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Effects of Mango Seed and Castor Seed Oils with Nanoparticle Additives on Friction and Wear Performance of Steel-Steel Contacts

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ABSTRACT

Investigation of the effects of mango (mangifera indica) seed oil and castor (ricinus communis) seed oil-based lubricants on friction and wear performance of steel-steel surface contacts was carried out in this study. Petroleum-based lubricants are hazardous and contaminate the environment. There is need to develop credible alternatives, which are biodegradable and environmentally friendly. The Soxhlet extraction method was used to extract vegetable oils from these seeds. The oils were subjected to laboratory analyses and formulations with nanoparticles additives. Friction and wear performance tests were carried out on the pin-on-disc apparatus according to ASTM G 99 standard. The addition of nanoparticles to pure mango seed oil and castor seed oil, respectively, improved their coefficient of friction by 21%, and 41%, respectively, and performed well in comparison to SAE20W50. Wear test results showed that pure mango seed oil and pure castor seed oil, and 1% titanium dioxide nanoparticle in mango seed oil have, respectively, 23%,7% and 36% better total wear performance than the reference commercial engine oil (SAE20W50). Among samples of castor oil formulated with nanoparticles, 2% aluminum oxide had the best wear performance, but the resulted wear mass loss was 20% higher than the result obtained from the SAE20W50l. Wear scars on the steel surfaces were analyzed with scanning electron microscope. The performance of these vegetable oils confirmed that they are excellent candidate lubricant oil-based stock that should be fully exploited and utilized.

KEYWORDS: Castor seed oil, Friction, Mango seed oil, Nanoparticles, Wear.

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1.0 INTRODUCTION

The failure of most components in machines is as a result of the lack of lubricants or inadequate lubrication of the surfaces in contact. This is usually followed with undesirable outcome of friction and wear. Mechanical component parts such as bearings, cams, internal combustion engines, gears, etc., operate on the principle of surface–surface contacts for the transmission of power and motion. At these contacts, enormous amounts of energy and materials are lost on the contacting surfaces through friction and wear. The main causes of friction and wear are the adhesion and deformation of surfaces in contact while in relative motion (Shafi *et al*., 2018). Friction and wear of contacting surfaces in motion occur due to microscopic interactions between surface asperities (Greenwood & Wu, 2002). The factors responsible for these interactions are mainly the nature of materials, geometry and the topography of the surfaces, including other conditions such as temperature, humidity and type of contacts (Patil *et al*., 2014). The other factors are speed, load, surface roughness and vibration of the parts in contact (Nikam *et al*., 2018). Proper application of lubrication reduces friction and wear of surfaces in contact during operation (Panchal *et al*., 2017).

Mineral oil has been used as lubricant base-oil in the automobile sector since 1890 (Kerley, 1981). It is usually a mixture of base stock and additives. The additive is about 0.2% to 30% in the base oil (Adhvaryu & Erhan, 2002). The base stock provides viscosity for low friction and wear (Odi-Owei *et al*., 1987), controls corrosion and oxidation, and promotes adequate surface for heat transfer (Erhan & Asadauskas, 2000). The additives enhance the

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existing desirable properties of the base stock and suppress the undesirable ones (Moser *et al*., 2011). Mineral oil resources are not renewable and hence, their future use as lubricant-based oil is uncertain due to the depletion of crude oil (Bahari *et al*., 2018). Petroleum based lubricants cause a lot of damages of environments (Ssempebwa & Carpenter, 2009). Bio-based lubricants are considered nowadays as suitable replacements for the mineral oil-based lubricants (Ruggiero *et al*., 2017). The ability of bio-based lubricants to degrade with no harm to the environment makes them acceptable alternatives to mineral oil-based lubricants (Erhan & Asadauskas, 2000).
Odi-Owei (1989) investigated the fatigue resistance, anti-wear and extreme pressure properties of some vegetable oils and fats using a four-ball and ball-cylinder machine. The study concluded that saturated fats (palm fats) with added anti-oxidants could make reliable greases that are suitable for extreme temperature applications. Bahari *et al*. (2018) investigated the performance of soybean and palm oil-based stock on friction and wear behaviour. The result showed that for the palm oil and soybean oil, the performance of the blended state is influenced by the vegetable oil component. Reddy *et al*. (2018) assessed the performance of vegetable oil as bio-lubricant for reciprocating compressor oil using a high frequency reciprocating ring tribometer. The results showed that the coefficient of friction and wear depth of the bio-lubricants compared well with those of the mineral oil-based lubricant.

Hassan and Khalefa (2018) evaluated the tribological characteristics of mustard oil using a four-ball tribometer and ASTM D4172-B standard (ASTM, 1999). The results showed that the blends of mustard seed oil with mineral oil performed better, with a lower wear scar diameter, than pure mineral oil and pure mustard seed oil. The main limitation of vegetable oil as lubricant is its susceptibility to thermal degradation and low oxidative stability (Thottackkad *et al*., 2012). This limitation can be minimized by the application of anti-oxidants as additives in the base oils or by chemical modification of the oils (Shafi *et al*., 2018).

This study is aimed at the investigation of friction and wear performance of steel surface contacts under mango seed and castor seed oil lubricant base stock. These oils were blended with nanoparticles of aluminum oxide, copper II oxide and titanium dioxide, with particle sizes of 13nm, 30-70nm and 30-50nm, respectively. The results were compared with those obtained for the commercial engine oil SAE20W50. The scope of this study included extraction of the vegetable oils, physicochemical analysis, blending with nanoparticle additives and friction and wear tests.

2. MATERIALS AND METHODS

Ground and oven dried castor seed and mango seed are shown in Plate 1. The Soxhlet apparatus, other laboratory apparatus, N-hexane and acetone were used for the extraction of the vegetable oils according to the method described in Gupta *et al*. (2012). The oil was weighed and Equation (1) was used to determine the oil yield.

$$\text{Oil yield (\%)} = \frac{\text{mass of oil}}{\text{mass of sample}} \times 100 \qquad (1)$$

Mango seed oil and castor seed oil were blended with 1%, 2%, and 3% copper II oxide, aluminum oxide, and titanium dioxide nanoparticles additives, respectively, as shown in Table 1. A total of 21 samples were prepared for the experiments.

Commercial grade mild steel with hardness of HRC 4.7 was machined into a pin of dimensions 100mm by 10mm with a 6mm spherical-end, and a bearing steel with hardness of HRC 31.7 was machined into a disc of dimension 30mm diameter (Figure 1). The friction and wear behaviour of the pin in contact with the disc was tested using a pin-on-disc set-up (Figure 2) with the various formulated vegetable oil-based lubricants according to ASTM G 99 standard (ASTM, 2000).

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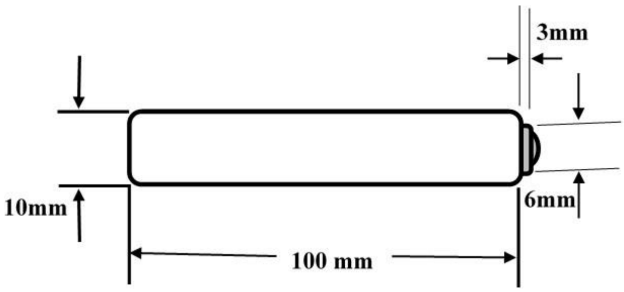
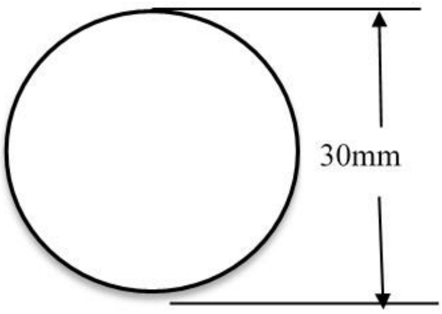
Plate 1: Oven Dried Cakes of (L-R) Castor Seed and Mango Seed

Table 1: Vegetable Oil-Based Lubricant Sample Formulation with Additives

SAE20-W50	Castor seed oil	Mango seed oil	Additive	%
D	A	E	-	-
	A1	E1	Aluminum oxide	1
	A2	E2	Copper II oxide	1
	A3	E3	Titanium dioxide	1
	A4	E4	Aluminum oxide	2
	A5	E5	Copper II oxide	2
	A6	E6	Titanium dioxide	2
	A7	E7	Aluminum oxide	3
	A8	E8	Copper II oxide	3
	A9	E9	Titanium dioxide	3



(a)



(b)

Figure 1: Schematic Drawings of (a) Steel Pin and (b) Steel Disc

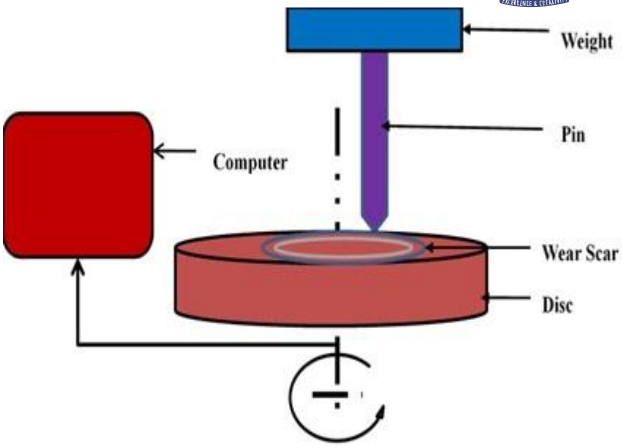


Figure 2: Schematic View of Pin and Disc Set-Up Under Test

The wear mass loss of the pin for each of the test runs was computed according to the equation

$$\text{Mass Loss } (M_L) = X_1 - X_2 \quad (2)$$

where X1 = Initial mass of the pin, X2 = Final mass of the pin after each run

Dimensional analysis method was used to determine the appropriate relationship between the wear mass loss (m), sliding speed (v), applied load (w), and shear strength (s) in accordance with the formalized procedure of Buckingham Pi theorem to arrive at the equation (Pritchard & Leylegian, 2011)

$$m = f\left(\frac{w^{1.5}}{s^{0.5}v^{2}}\right) \quad (3)$$

f is a dimensionless constant function. Excel Solver fitting tool was used to appropriately fit the functional relationship with the experimental results, and absorbed the constant, f, to arrive at the final mass loss model

$$Mass\ loss\ (m) = \frac{w^{1.2}}{s^{0.7}v^{0.3}} \quad (4)$$

Friction between two contacting surfaces in motion is a resistance force, which is proportional and perpendicular to applied load:

$$F = \mu N \quad (5)$$

where F = Frictional force, N = Normal load, μ = Coefficient of friction

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Equation (5) is the governing equation for the pin-on-disc experiment.

3. RESULTS AND DISCUSSION

The oil yield from castor seed was 30 percent while that from mango seed was 15 percent. The work of Dasari and Goud (2013) showed the yield for castor oil as 44%. There is little or no past research data on mango seed oil yield. The desirable physicochemical properties of the vegetable oils analysed are shown in Table 2.

Table 2: Physicochemical Properties of Vegetable Oils and SAE20W50

	Mango seed	Castor seed	SAE20W50
Acid value (mg/g)	40.33	2.24	2.47
Peroxide value (mg/g)	0.47	0.60	0.20
Free fatty acid	20.16	1.12	1.23
Viscosity (cP)	289.6	482.00	420.00
Relative density	0.9	1.06	1.14
Saponification value (KOH/g)	179.52	64.52	-

Owuna *et al*. (2019) showed similar acid values for vegetable oil. This is an indication that the mango seed oil may need further treatment for the reduction of its acid value before it can be used as a lubricant. The recommended factory upper limit of peroxide value for fresh vegetable oils is 3.0 mg/g (Popa *et al*., 2017). Viscosity is the most important physical property of lubricant base stock. The reference oil, SAE20W50, is a high-grade petroleum-based commercial lubricant brand, which is not saponifiable. Some proportions of moisture residues and other impurities in the extracted castor seed oil could have been the cause of the slightly higher value of its relative density. Very pure vegetable oils have average relative densities around 0.91(Noureddini *et al*., 1992), making them float on water. Further evaporation and filtration are required to purify the extracted vegetable oils.

3.1 Analysis of Coefficient of Friction for Vegetable Oil-Based Lubricated Contacts

Figure 3a presents the coefficient of friction of castor oil-based lubricant samples A1 to A9. Sample A4 (2% aluminium oxide in castor seed oil) has the lowest coefficient of friction, 0.0614. Compared to the other samples, sample A2 (1% copper oxide in castor seed oil) has the highest coefficient of friction, 0.1575. Figure 3b presents the coefficient of friction of mango seed oil-based lubricated contact pairs. The sample with the least coefficient of friction (μ=0.1134) is E3 (1% titanium dioxide in mango seed oil-based stock) while the sample with the highest coefficient of friction (μ=0.1595) is E4 (2% aluminium oxide in mango seed oil-based stock).

Figure 4 presents the lubricant oil samples with the least mean coefficient of friction in their respective groups of concentrations of additives as shown in Tables 1. This cross-group comparison shows that sample A4 (2% aluminium oxide in castor seed oil) had the least mean coefficient of friction (μ=0.0614). The mean coefficient of friction (μ=0.1278) for the reference oil, SAE20W50, is much higher than those for the vegetable oils and their blends with additives, except mango seed oil-based blend, E3 (1% titanium dioxide in mango seed oil) with its best formulation with coefficient of 0.1600. The coefficient of friction for the dry-run (X), that is, not lubricated with oil, is highest at 0.2400.

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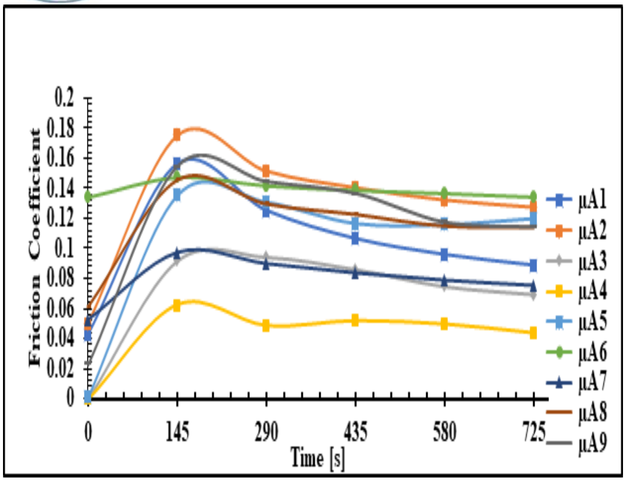
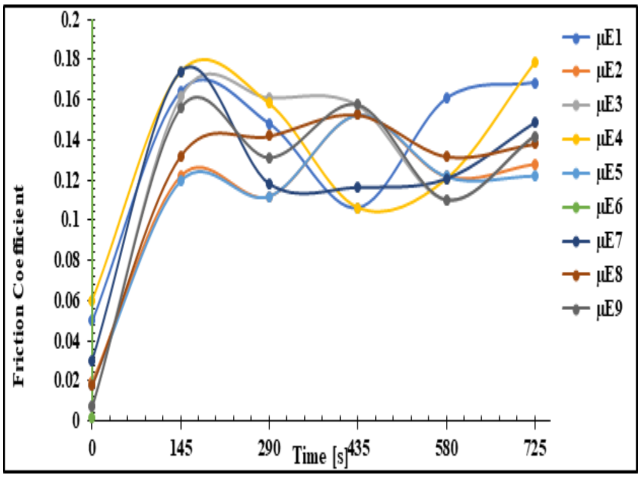


(a)



(b)

Figure 3: Coefficient of Friction Against Time for (a) Castor Seed and (b) Mango Seed Oil-Based Lubricated Contacts

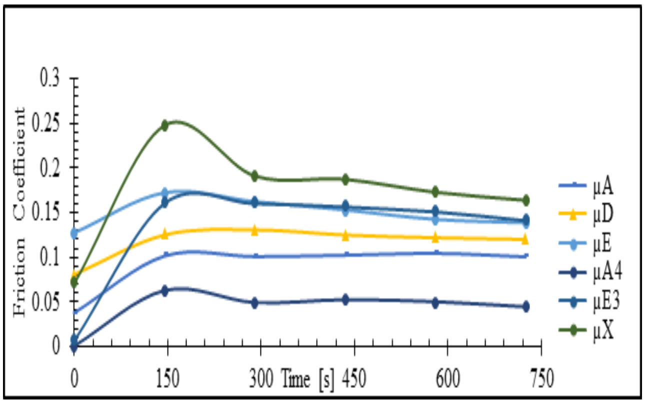


Figure 4: Coefficient of Friction Against Time for Optimum Performing Lubricant Oil Samples

All the graphs in Figures 3 and 4 exhibited similar trends. From the onset of the lubricated sliding contacts, the coefficient of friction increased briefly to a maximum point and then started to decrease until it nearly stabilized with respect to time. The initial sharp increase in coefficient of friction was possibly due to resistance to motion due to contact of the asperities between the two sliding surfaces under loading and motion conditions, thus generated frictional force. As the sliding continued, the highest peak asperities were sheared, more asperities made contacts with those on the other surface, thereby increasing friction, which led to mass loss of the softer surface of the sliding pair. Removal of one set of asperities created a new set of asperities (Greenwood & Wu, 2002) and this process continued until a mending effect occurred as the lubricant materials started filling up the spaces in the asperities, which reduced the friction to a steady state.

The mechanism of interaction of the blended pure vegetable oil specimens, A4 and E3 with the steel surfaces is a combination of the qualities of the pure oils and the nanoparticle additives. The nanoparticles of 2% aluminium oxide in castor seed oil (A4) and 1% titanium dioxide in mango seed oil (E3) acted as micro-ball bearings between the interacting steel surfaces. These micro-ball bearings easily filled the asperity spaces and also caused rolling effects, which decreased friction and wear of the surfaces. This is in agreement with Gundarneeya and Vakharia (2017).

In summary, the coefficient of friction of pure castor seed oil was reduced by 41% with the addition of 2% aluminium oxide nanoparticle while the corresponding coefficient of friction of pure mango seed oil was reduced by 21% with addition of 1% titanium dioxide nanoparticles additive.

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3.2 Analysis of Wear Mass Loss of the Pin for Vegetable Oil-Based Lubricated Contacts

Figure 5 shows the results for the mass loss of the pins lubricated with the respective formulated lubricants. The pin lubricated with oil sample E shows the greatest mass loss. This is followed by samples A3 and E1. The formulation samples E3 and E9 shows the least mass loss of the pins in comparison to D, the reference commercial engine oil (SAE20W50). Greatest mass loss was recorded by sample X, which, understandably, is a dry-run, hence, no lubricant oil was applied. The copper oxide, aluminium oxide and titanium dioxide nanoparticle additives in the base oil acted as abrasives on the contacting surfaces. The nanoparticles polished the steel surface, and the surface roughness of the steel contacts were reduced. This is an indication that the pin with the highest mass loss lost more surface material in the polishing process. Similar observations have been reported by Binu *et al*. (2014), and Gundarneeya and Vakharia (2017). The initial polishing of steel contacts by the nanoparticles-initiated loss of mass. It is therefore, inferred that the initial polishing effect could be the reason for the mass loss of the pins.

For the pin samples that did not show significant mass loss, it could be inferred that the abrasive action of the nanoparticles mended the contacting surfaces by filling in the valleys of their surfaces. This agrees with Odi-Owei and Roylance (1986),

who studied the effects of aluminium oxide particles as abrasive contamination in SAE 10 base oil. They concluded that the abrasive contaminant promoted a mending effect on contacting surfaces.

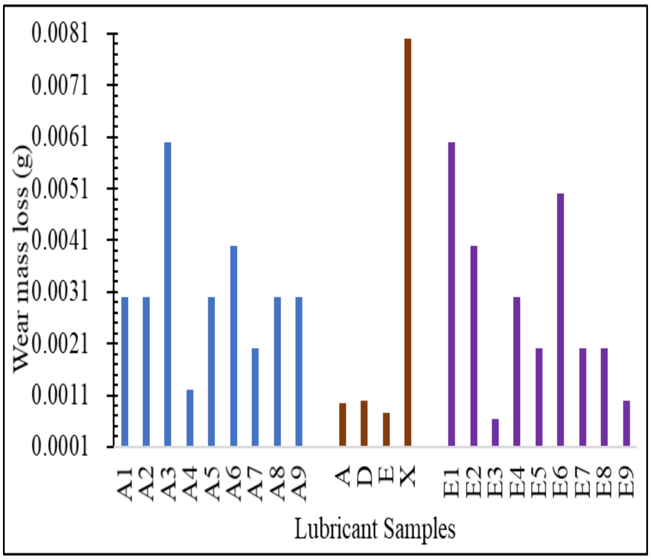

Figure 5: Wear Mass Loss of the Pin Lubricated in Lubricant Oil Samples

Figure 6 shows the results of the wear mass loss model compared with the experimental results. Wear mass loss decreased with increase in speed at constant applied load. Conversely, wear mass loss increased with increasing load at constant speed. This trend is in agreement with Chowdhury *et al*. (2011), Hekimoglu & Savaskan (2016), and Odi-Owei and Amandi (2017).

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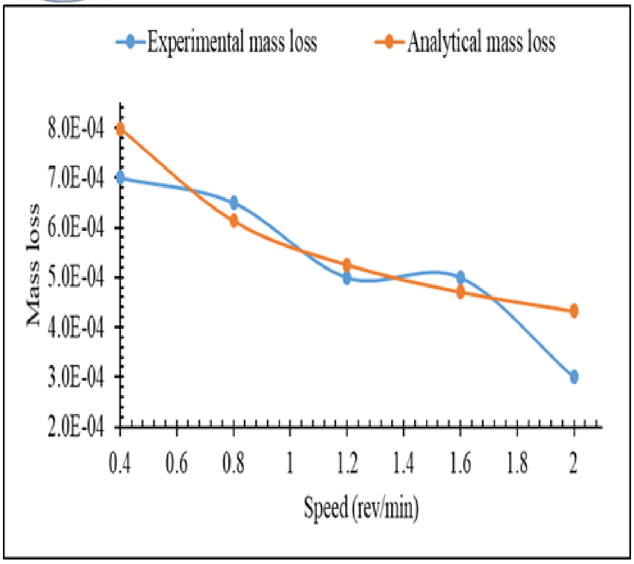
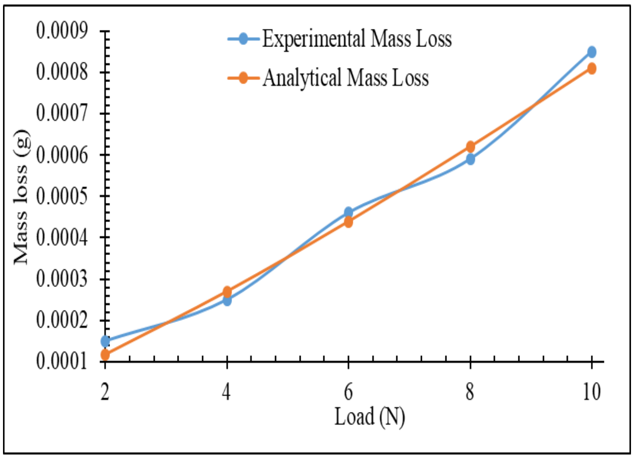


(a)

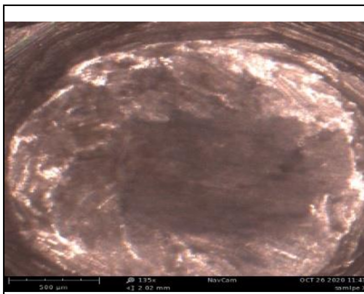


(b)

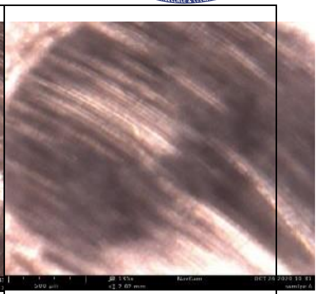
Figure 6: Wear Mass Loss of the Pin Lubricated in Lubricant Oil Samples Against (a) Sliding Speed and (b) Applied Load

3.3 Scanning Electron Microscopy (SEM) Analysis of Worn Pin Surfaces

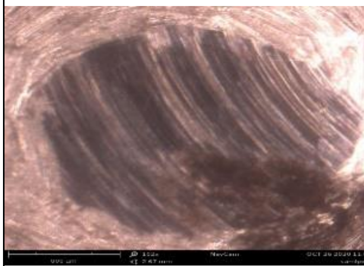
The results of the examination of the morphology of the worn surfaces of the pin at the pin-disc contact point lubricated with the respective test vegetable oil-based lubricant samples are shown in Plate 2 (a –f). The analysis of the topography of the wear scar on the pin surfaces shows the nature of wear influenced by the respective test lubricants protecting the surfaces in the regime of boundary lubrication contacts.



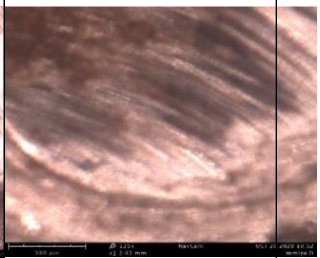
Dry-contact



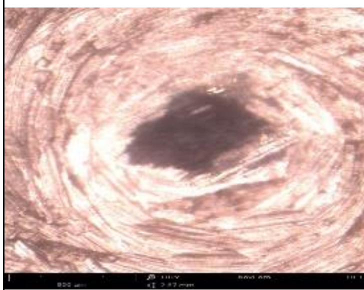
Pure castor seed oil



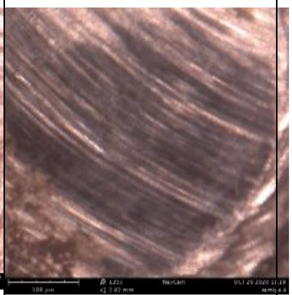
Pure mango seed oil



(d) Engine oil (SAE20W50)



(e) Mango seed oil + 1%TiO2



(f) Castor seed oil +2 % Al2O3

Plate 2: Scanning Electron Microscopy (SEM) Micrographs of the Worn Pin Surfaces Lubricated with the Test lubricants (a – f)

The SEM micrograph picture (a) in Plate 2 is a wear scar from the dry-run; the pin-disc contact was not lubricated by any of the test lubricants. The dry-run test was used to highlight the significant effects of lubrication. The deep pit on the pin shows there was a localized loss of materials there. In the absence of lubricant, under high speed and loading conditions, a localized temperature increase could have caused some asperities to become welded together and create micro-joints. These micro-welded joints could have ruptured from

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the pin and transferred some materials out of the point, leaving micro-pits and scuffed surfaces behind. This was a typical adhesive wear mechanism. The other micrograph pictures of wear scar, (b) - (f), are basically showing what appears more as abrasive wear scar on the lubricated pin-disc contact point. The shallow grooves on the abrasive wear scar can be seen on the contact point. This could have been caused by ploughing and cutting away of surface materials of the pin by the hard nanoparticles' additives in the vegetable oil-based lubricants. These nanoparticles oxides of aluminium and titanium acted as third bodies between the contact pair.

4. CONCLUSION

This study investigated the effects of mango and castor seed oils with nanoparticle additives on friction and wear performance of steel-steel surface contacts with a view to mitigating problems of friction and wear of machine component parts. This overall aim was achieved.

This work confirmed that:

(i) Mango seed oil had a very high acid value of 40mg/g compared to castor seed oil and SAE20W50 with acid values of 2.24 mg/g and 2.47mg/g, respectively. Mango seed oil easily became solidified at relatively low room temperature.

(ii) 1% & 3% titanium dioxide nanoparticles in mango seed oil had better anti-wear properties than the reference engine oil (SAE20W50). Similarly, 2% aluminium oxide nanoparticles in castor seed oil, had better anti-friction properties than the reference engine oil (SAE20W50). Nanoparticles' additives improved the coefficient of friction of pure castor oil by 41%, and pure mango seed oil by 21%, respectively.

(iii) Wear mass loss of the softer of two contacting surfaces in motion is a function of the sliding speed, the applied load and the shear stress of the softer surface.

Castor and mango seed oils have great potentials for use as base stock for the formulation of engine oils, especially, for their anti-wear and anti-friction properties.

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NOMENCLATURE

Abbreviation	Meaning
Al_2O_3	Aluminum Oxide
ASTM	American Society for Testing and Materials
CuO	Copper II Oxide
HRC	Hardness Rockwell C
MPa	Mega Pascal
Nm	Nanometer
N	Newton
SAE	Society of Automotive Engineering
SEM	Scanning Electron Microscope
TiO_2	Titanium II Dioxide

Symbols	Description	Unit
μ	Coefficient of Friction	-
N	Normal Load	N
S	Shear Strength	Nm^{-2}
V	Sliding Velocity	ms^{-1}
ŋ	Dynamic Viscosity	N/m^2s
W	Applied Load	N