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Tribological characteristics of palm olein under conditions of elevated temperature and effect of addition molybdenum disulfide at high load

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KEYWORDS

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Engine oil

ABSTRACT

This study evaluates the performance of palm olein lubricant at high temperatures and under high loads, enhanced with Molybdenum disulfide (MoS_2) nanoparticles. Using a linear reciprocating tribometer to simulate engine motion, the lubricant is assessed based on coefficient of friction (COF), wear scar diameter (WSD), wear volume, surface roughness, and topography. Results show that increasing temperature and load raises COF, WSD, and wear volume for engine oil, plain palm olein, and palm olein + MoS_2. At 120°C and 150°C, palm olein has a higher COF than engine oil, but its wear performance patterns are similar. Palm olein demonstrates better surface roughness and topography, especially at low temperatures. At 100°C under high loads, palm olein mixed with MoS_2 outperforms engine oil and plain palm olein. The addition of 0.05% MoS_2 nanoparticles significantly reduces COF and WSD across various loads, with reductions of up to 7.35% and 12.34%, respectively. This improvement is attributed to palm olein's fatty acid composition and the enhanced tribological properties from MoS_2. Future research should optimize MoS_2 concentrations in palm olein and assess its long-term performance in engine applications.

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1.0 INTRODUCTION

The demand for high-quality machinery and tools has risen significantly with the expansion of the industrial sector and the pursuit of higher standards of living. These machinery and tools need lubrication as a fundamental requirement for optimal performance and smooth operation (Golshokouh et al., 2013). The industrial revolution and the ever-increasing sales of vehicles have caused a massive surge in the need for lubricants (Yahaya et al., 2023). In 2019, lubricants were utilized at a rate of 36.8 MMT, with demand growing by around 2.1% year, according to a worldwide market study (Afifah et al., 2021). From 2021–2028, the worldwide lubricants market is projected to expand from an initial 2020 valuation of 125.81 billion USD, a compound annual growth rate (CAGR) of 3.7%. Due to the abrupt changes in lubricating costs caused by the fast depletion of fossil fuels, the lubricant market is an important part of the national economy. The loss of heat as a result of rubbing surfaces accounts for one-third of mechanical energy, according to tribological research studies. The piston assembly, gearbox, bearings, crankshaft and camshaft mechanism, valve train, etc., are responsible for one-third of the energy losses in the automotive industry (Samion et al., 2024; Opia et al., 2021). Lubricants are a great way to decrease friction and save energy by 40-50% (Jabal et al., 2014). The lubricant industry is expected to reach 52.36 billion by 2025.

The use of mineral or synthetic oils as lubricants has been the subject of many recent investigations. While mineral oils have been around for many years and have been used to improve tribological qualities, concerns about their non-biodegradability and the depletion of mineral oil deposits have led researchers and scientists to look into other energy sources. A number of studies have shown that vegetable oils might be a viable substitute for mineral oils (Paiman et al., 2024; Syahrullail et al., 2013). Vegetable oils are a great alternative to mineral oils since they are renewable, biodegradable, nontoxic, and have excellent low temperature qualities (Abdul Sani et al., 2017; Sani et al., 2017). While there are many benefits to using lubricants made from vegetable oils, one major drawback is their weak oxidation stability. Since unsaturated double bonds are significant sites for oxidation, the amount of unsaturated fatty acids in vegetable oils determines their oxidative stability (Azman and Samion, 2019; Azman and Samion, 2018).

To make a based oil suitable for high-performance lubricants, which it is not naturally capable of producing, a number of additives are added to it (Golshokouh et al., 2013). Lubricants cannot fulfil high-performance demands without additives, which are substances mixed with base oil to impart the lubricating oil's unique properties (Nyholm and Espallargas, 2023). Adding different additives to bio lubricants may fix their drawbacks, but it will affect how biodegradable, expensive, and poisonous the lubricants are (Pichler et al., 2023; Syahrullail et al., 2005). The additives are categorized as follows: anti-oxidants (AW), viscosity modifiers (EP), friction modifiers (FW), anti-foam agents (AF), corrosion inhibitors (PPD), dispersants (DPD), detergents (Singh et al., 2021). One long-term answer to these problems is nano lubrication, which involves adding nanoparticles to lubricants. Since the introduction of sophisticated nanoparticles with exceptional capabilities resulting from a high surface-to-volume ratio, nano lubrication has attracted a great deal of attention. Some examples of nano additives include metals, metal oxides, carbon nanoparticles, sulphides, nanocomposites, and rare earth compounds, according to a 2019 study by Azman and Samion (2019).

By using nano additions composed of molybdenum and titanium, base oils have the potential to improve their tribological properties, especially when subjected to very high levels of mechanical stress. Nano-MoS2 or its particles are said to offer outstanding rubbing capabilities, as stated by Li et al., (2022). Nanotechnology is responsible for the incorporation of nanoparticles, which are used to compensate for the deficiencies of biolubricants. Waqas et al. (2021) found that the use of biolubricant that contains friction modifier nanoparticles resulted in a considerable reduction in friction. Because of their ability to enhance the tribological properties of base oil, metal nanoparticles have become an extremely desirable addition over the course of the decades.

The aims of this article are to find out more about How significant of an impact does the addition of MoS2 nanoparticle additive have on the tribological performance of palm olein when it is subjected to higher loads using the linear reciprocating tribotester.

2.0 MATERIALS AND METHOD

2.1 Lubricants Sample

Palm olein (PO) is the based lubricant as lubricating oil. Unsaturated fatty acids make up 53.4% of PO, whereas saturated fatty acids make up 46.6%. PO has a predominant amount of saturated palmitic acid, which accounts for 40.9% of its total fatty acid. Palm oil is ideal as a lubricant because of its high concentration of monounsaturated fatty acids, which provide it decent oxidation stability. Table 1 shows the fatty acid composition of palm olein and the properties of the base oil and additive of the sample. The research used MoS_2 as an additive, with a particle size ranging from 1 to 3 µm.

Table 1: Physicochemical and Fatty acid composition of sample lubricant.

FAC (% by gas chromatography)	**PO**	**EO**
Caprylic acid (C8:0)	-	-
Capric acid (C10:0)	-	-
Lauric acid (C12:0)	0.2	-
Myristic acid (C14:0)	1.1	-
Palmitic acid (C16:0)	40.9	-
Stearic acid (C18:0)	4.2	-
Oleic acid (C18:1)	41.5	-
Linoleic acid (C18:2)	11.6	-
Linolenic acid (C18:3)	0.3	-
Arachidic acid (C20:0)	0.2	-
Eicosenoic acid (C20:1)	-	-
SFA	46.6	
MUFA	41.5	-
PUFA	11.9	-
Density (kg/m3) @ 25°C	0.890	0.865
KV (mm2/s) @ 25°C	46.74	201.32
KV (mm2/s) @ 40°C	35.00	106.00
KV (mm2/s) @ 100°C	14.4	14.27
Viscosity index, (VI)	426	137

2.2 Dispersion of Additives

The concentration of MoS2 was apportioned into 0.5. wt%. The additive was progressively added using an overhead stirrer set to 800 rpm for stirring. To ensure homogeneity, the stirrer was turned up to 2200 rpm after the addition had been well mixed. The stirring process took around 60 minutes.

2.3 Experiment Set-Up

The linear reciprocating tribometer is used to examine the lubricants' tribological qualities in this investigation. For this investigation, we relied on a linear reciprocating tribometer because of its adaptability to different working conditions, including temperature and load. A linear reciprocating tribometer requires precise regulation of the following parameters during setup: applied load, temperature, sliding speed, testing period, and stroke length. Table 2 shows the experiment parameters testing and Figure 1 shows the experiments set-up using linear reciprocating tribotester.

Table 2: Experiment parameters and additive properties.

Parameters	**Measurement**	
	Test 1	**Test 2**
Load (N)	35	50, 100, 150 and 200
Speed (Hz)	2	2
Temperature (˚C)	40, 60, 100, 120 and 150	100
Time (min)	10	10
Stroke (mm)	10	10
Ball	10mm diameter Chrome alloy steel AISI E-5120	
Plate	20x20mm Steel	
Additives	Morphology	Hexagonal with sharp edges
	Size	1-3µm
	Color	Grey
	Purity	98.5%

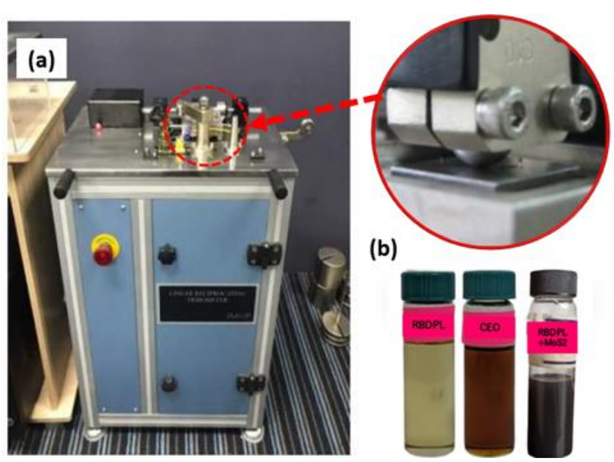


Figure 1: Experimental set up (a) linear reciprocating tribometer and (b) sample lubricant.

3.0 RESULTS AND DISCUSSION

3.1 Effect of Palm Olein Lubricant with High Temperatures

Figure 2 illustrates the contrasting impact of temperature on the coefficient of friction (COF) values of palm olein (PO) and engine oil (EO). At temperatures below 100°C, the COF of PO is lower than EO. The COF values for PO and EO at a temperature of 40°C are 0.054 and 0.120, respectively. The EO has its highest COF at a temperature of 40°C. Even at a temperature of 60°C, the COF of PO is still lower than EO. At a temperature of 100°C, the COF for PO reached its lowest value in this experiment, but the COF for the EO continued to reduce.

The favorable lubricity quality of PO is attributed to its chemical structure, which contains a significant amount of long fatty acids and polar COOH groups (Hidayati et al., 2024). The long fatty acid molecules possess a high molecular weight and viscosity, enabling them to form a thick and robust lubricating film. This film acts as a boundary lubrication, effectively safeguarding the surfaces in contact by establishing strong interactions with the metallic surface that reduces friction (Syahrullail et al., 2011). The lubricating coating reduces mating surface resistance and smoothes sliding. Reducing surface roughness forces reduces energy conversion into heat or disturbance rather than motion (Jason et al., 2020). Conversely, the EO's COF value should drop, indicating thermal stability. Due to its excellent composition, the oil contains antiwear compounds. (Tonk, 2021).

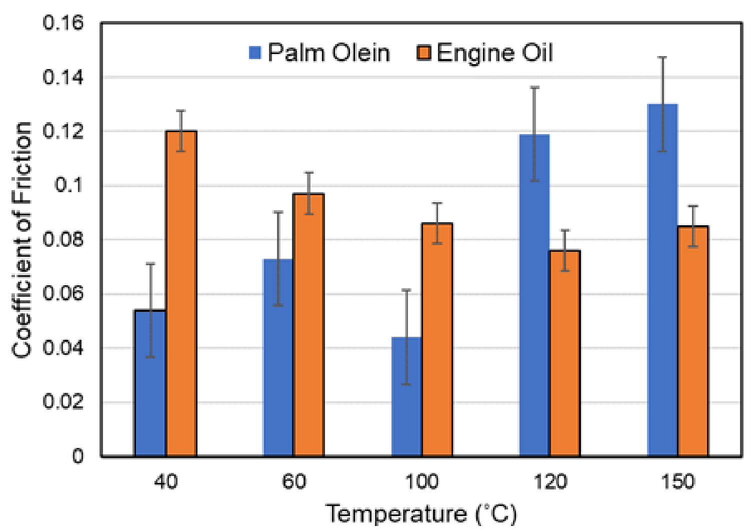


Figure 2: COF value of Palm olein (PO) and Engine oil (EO).

PO COF increases significantly at 120°C. This increase gets the COF value very near to the maximum EO value, with a difference of 0.001. The substantial rise in temperature is a result of the inadequate thermal and oxidative stability of PO when exposed to high temperatures (Zhang et al., 2021). The stability of the lubricating film provided by the fatty acid chain is influenced by various operating conditions (Zhang et al., 2023). This film prevents direct metal-to-metal contact and offers a sliding surface, thereby protecting the surface. The rise in temperature has a cascading effect on the protective coating and viscosity of lubricants. At elevated temperatures, PO undergoes decomposition and experiences a reduction in weight due to the formation and rupture of chemical and physical bonds (Hussin et al., 2022), leading to the breakdown of boundary lubrication.

Temperature has a reverse impact on viscosity. Raising the temperature will decrease the viscosity. Due to its low viscosity, there is a greater likelihood of metal-to-metal contact, which leads to increased shear stress. This, in turn, reduces the protective coating and ultimately causes the breakdown of the boundary lubricant (Cyriac et al., 2022). However, the presence of palmitic acid and the fatty acid content in super olein leads to corrosive wear due to oxidation (Opia et al., 2023). While the extended length of fatty acid chains in PO may enhance its tribological performance as previously indicated, it is important to note that it has a limitation in terms of oxidation stability (Chan et al., 2018).

3.2 Impact of A Nanoparticle Additive on Palm Olein Under High-Load Conditions

This experiment involves subjecting palm olein to high stress conditions after adding a 0.05% MoS_2 nanoparticle addition to it. Figure 3 illustrates that the COF value of both PO and PO with additional molybdenum disulfide (PO+MoS_2) increases as the applied load increases. The COF of the engine oil increases when subjected to a load of 100N but decreases when the force is increased to 150N. The results indicate that the COF value for PO+MoS_2 is consistently the lowest across all applied loads, followed by PO. The COF value of EO is consistently the greatest under all applied loads. The current result aligns with the earlier experiment, where the COF for PO was shown to be lower than the COF for EO in conditions of 100°C and below.

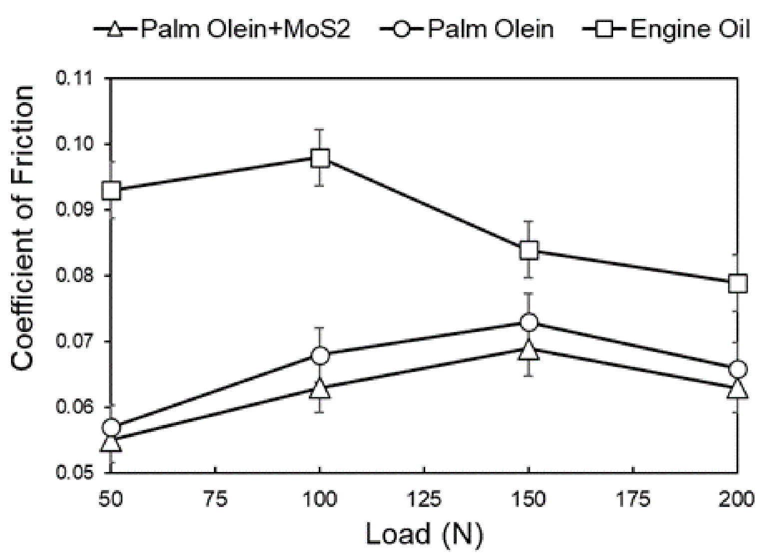


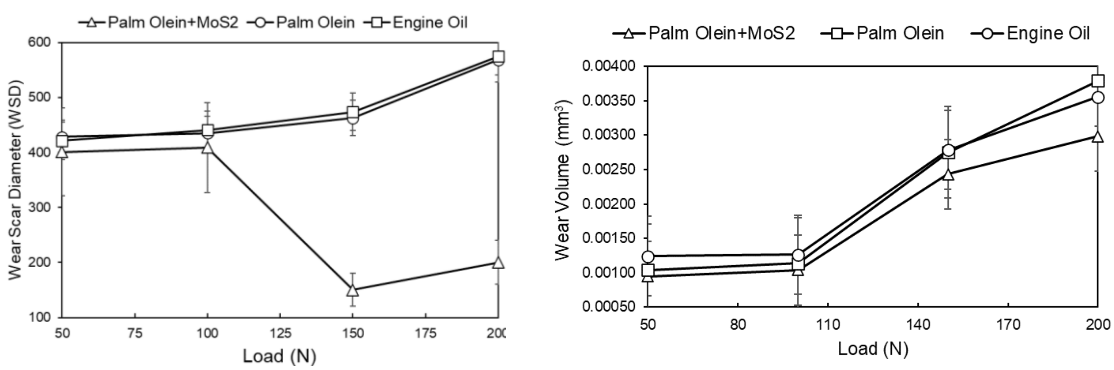
Figure 3: COF value for all samples.

Furthermore, the use of a nanoparticle component enhances the wear resistance capabilities of palm oil. The reduced COF value of PO is seen when nanoparticle additives are introduced, in comparison to PO. The addition of 0.05% MoS_2 nanoparticle additive to PO resulted in a reduction of the COF by 3.51% at a 50N load, 7.35% at a 100N load, 5.48% at a 150N load, and 4.55% at a 200N load. The improvements are rather little in comparison to a work conducted by Gulzar et al., (2015), in which 1%wt of MoS_2 nanoparticles additives were included into chemically modified PO resulting in an improvement of over 10% on average. Nevertheless, the addition of MoS_2 nanoparticles seems to have effectively enhanced surface protection by functioning as a friction modulator (Mao et al., 2024). Nanoparticles adhere to the surface they come into touch with, forming a protective coating (Ye et al., 2021). The successful deposition of nanoparticles on the surfaces in contact is linked to the efficient dispersion of additives on the surface, which is facilitated by the increased surface area to volume ratio.

The lower COF value of PO is attributed to the concentration of fatty acid, which enhances the strength of the lubricating film. The extended, polar fatty acid chains provide a lubricant coating of exceptional strength, which forms strong bonds with metallic surfaces, resulting in a significant reduction in both friction and wear (Gusain et al., 2020). The findings indicate that the lubricating layer formed by the fatty acid in the PO component remains stable and robust when subjected to both low and high applied loads.

3.3 Wear Scar Diameter, Volume analysis and Wear Observation

Figure 4(a) shows that the size of the scar in the wear scar diameter (WSD) grows as the load increases, regardless of the lubricant used, however the wear is reduced significantly at 150N and 200N. As stated before, an increase in load will exert more force on the lubricant, leading to a decrease in its tribological performance and a subsequent reduction in viscosity. The thickness of the lubricating coating between the mating surfaces decreases, leading to an increase in the contacting surface area and therefore a bigger WSD. The result for sample PO+MoS2 shows slightly different, where According to Illie and Crestescu (2022), MoS2 exhibits superior wear resistance in which the microstructure of the protective layer functions as an intermediary lubricant, minimizing friction and preventing surface damage.



(a) (b)

Figure 4: Analysis of (a) Wear scar diameter and (b) Wear volume of all specimens.

The wear volume obtained in Figure 4(b) is similar to the WSD. A greater WSD may indicate a higher amount of material being removed from the surface, which corresponds to an increased wear volume. Similar to the relationship between WSD, wear volume also rises in direct proportion to the increase in load. The combination of PO+MoS_2 exhibits the lowest wear volume under all load conditions, with a particularly considerable reduction under a 200N load as compared to using either PO or EO. The wear volume of PO is smaller than that of EO under stress conditions of 50N, 100N, and 150N. At a force of 200N, the rate at which the volume of PO wears is somewhat more than that of EO. One possible explanation for this phenomenon is that PO has a limited thermal and oxidative stability when exposed to high temperatures (Yahaya and Samion, 2022).

The optical micrograph (Figure 5) clearly shows that the worn ball surface lubricated with PO+MoS_2 is the smoothest under all applied loads. The smooth surfaces may be attributed to the presence of nanoparticle MoS_2 that has precipitated onto them. One possible explanation is that the nanoparticle additives in the PO lubricant are distributed evenly, leading to the development of aligned tribofilms (Gulzar et al., 2015). The scars from PO+MoS_2 were oval at all loads. Low scar with 50N load and pits. Darker wear appears at 100N load. One side has some serrated edge damage. With 150N load, scar surface color faded, but damage remains as growth with more serrated edges on both sides. The scar center has darker lines at 200N, indicating more damage. Even at 50N EO load, the scar surface remained black. The darkest surface is at 100 N load, yet there are no sharp edges. Scarring is worst at 150N. A dark scar and multiple serrated edges on both sides indicate extensive edge damage. High load, increased fusion welding area, and adhesive wear induced metal peeling and black spots (Gupta et al., 2023).

The wear line formed by PO+MoS_2 is the smoothest and the wear worn surface is considerably less, as seen in Figure 5 of the optical micrograph on the plate. This is due to the excellent lubricating protective layer that nanoparticles have created. When a plate is worn, the rougher and darkest part is usually the area that has been lubricated with EO. The PO worn surface is noticeably darker than EO at 150N. Increased mating metal adhesion may be the result of a combination of factors, including the breakdown of the lubricating layer and rising temperatures. Under 200N, the PO and PO+MoS_2 surfaces show low wear and a smooth surface than under lower loads. At load below 200 N, the ball's surface may get damaged, causing the material to become serrated at the edges and reducing the amount of material that meets the surface in the center. According to Shrestha et al. (2020), the contact surface's smooth surfaces are associated with nanoparticle precipitation.

The application of a significant load resulted in a substantial shear force acting on the lubricant, leading to the disruption of the lubrication layer formed by the palm oil fatty acid chain. A greater load is being borne by the rough areas on the mating surface and direct contact between metal surfaces is present and has taken place. Under elevated temperatures, palm oil is susceptible to oxidation, which subsequently impacts the viscosity and lubricity of the lubricant (Murru et al., 2021). Additionally, an increase in load leads to a rise in temperature, which exposes the unsaturated double bond in fatty acid molecules to a chemical process that initiates oxidation. The peroxides and other derivative products of oxidation will undergo constant reactions with the metal surface, resulting in brittleness and weakening. According to Zulhanafi and Syahrullail, (2019), there is an increase in wear and widening of the WSD.

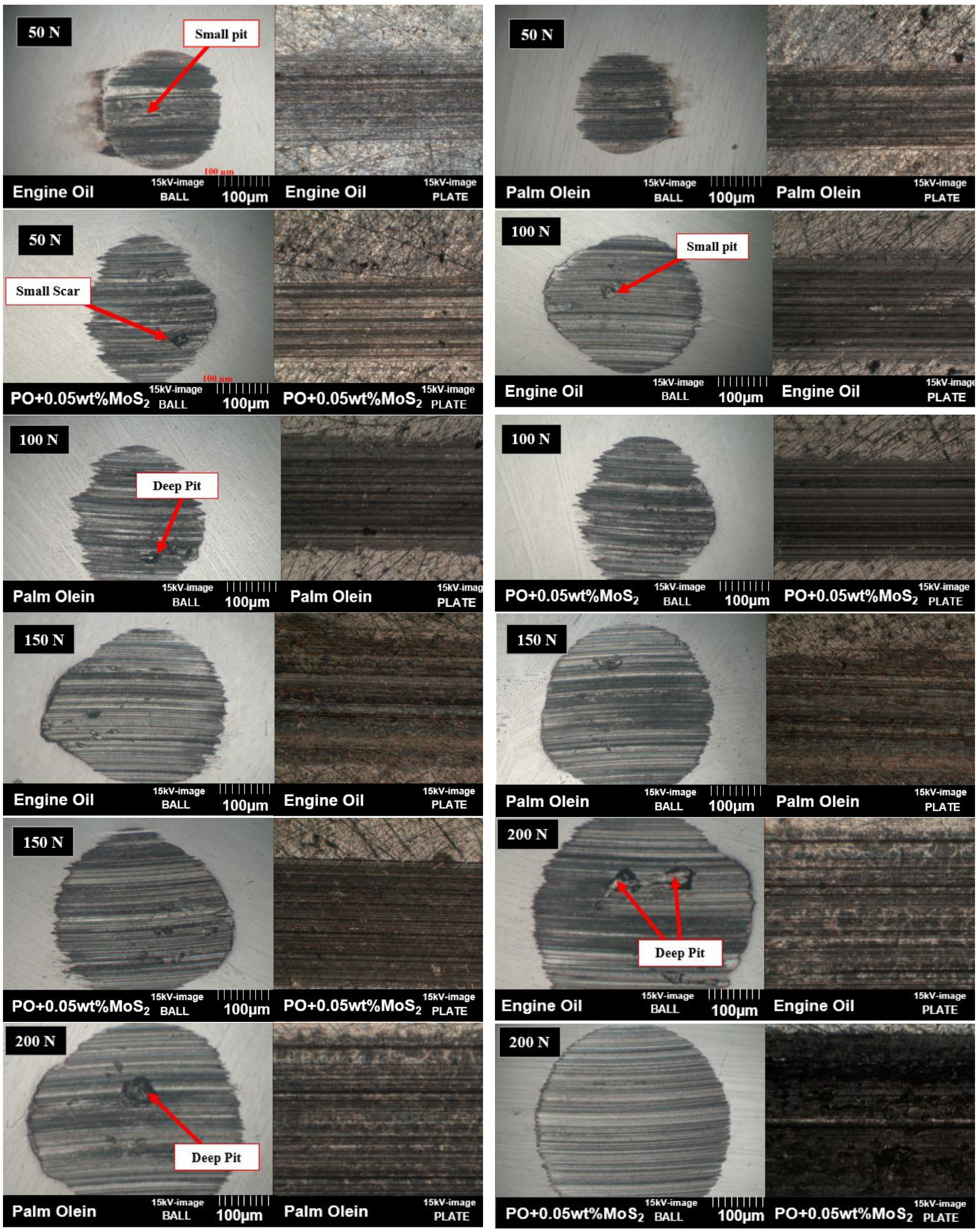


Figure 5: Optical micrograph under 100× for all specimens.

The nanoparticles effectively adhere to and spread throughout the surface, creating a protective barrier that reduces direct contact between metals. The force is decreased by 6.41% at a weight of 50N, 5.98% at a load of 100N, and 7.94% at a load of 150N. Additionally, at a load of 200N, the force is reduced by 12.34%. WSD of the PO is smaller than the EO, however, the difference is insignificant. The molecular structure of MoS_2 gives it a great load-bearing capability. Lubricants that include it assist to disperse loads more uniformly across contact surfaces, which in turn reduces wear and tension in specific areas. In addition, the interlayer van der Waals forces in MoS_2 are somewhat modest. When combined with a lubricant, these layers reduce wear and friction by sliding over one another. According to Lin et al., (2021), adhesive wear may be decreased with the addition of MoS_2 by reducing the adhesion between the contact surfaces. Combining MoS_2 with PO components may have a synergistic impact that improves the lubricating performance. A more persistent and efficient lubricating coating might be formed, for instance, by interacting with the fatty acids in PO+MoS_2.

3.4 Surface Roughness Analysis

The roughness of EO, PO, and PO+MoS_2 surfaces increases with load (Figure 6). Compared to the other two lubricants, PO+MoS_2 had the lowest range of high and low peak roughness values, indicating smoother surfaces. A rough texture with sharp protrusions resembling teeth appears on the EO at 50N. The difference between high and low peak values is about 4μm. Difference between highest and lowest peaks is about 3μm. Stress of 150N increases surface roughness. High and low peaks show a larger variation of around 10μm. The range widens to around 12μm when exposed to 200N of stress. Multiple peaks appeared at 150N and 200N loads. PO has a narrower high-low peak range than EO, indicating a smoother surface. Under 50N load, the high and low peak amplitude is around 4μm, making it the smoothest option compared to EO and PO+MoS_2. Additionally, peaks are less abrupt. The high and low peaks had an amplitude of around 3μm at 100N force, with multiple sharp peaks noted. Similar to EO, high and low peaks rise significantly at 150N. With 150N force, the range is about 6μm, with many peaks. The amplitude of high and low peaks at 200N varies from 6μm to 11μm, with both low and high sharpness. When loaded with 50N, the PO+MoS_2 exhibits a low and high peak range of 5-7μm. Few sharp edges were found. Among the three alternatives, the surface-treated PO+MoS_2 had the smoothest surface. High Ra and rough surface are due to load-induced friction and abrasion. All three lubricants transition at 100N. Surface roughness is lower at 100N than 50N. The surface roughness increases at 150N and peaks at 200N. The running-in condition may explain the 100N transition. A 100N load may cause the lubricating layer to break down, causing stability breakdown. This load condition may increase heating, decreasing viscosity and friction. Surface protection is achieved with this reduction. At 150N, wear debris is transferred and implanted into mating surfaces, causing rough surface topography. Adhesion between surfaces increases wear. Increased temperature breaks down the lubricating layer and accelerates wear (Yang et al., 2013).

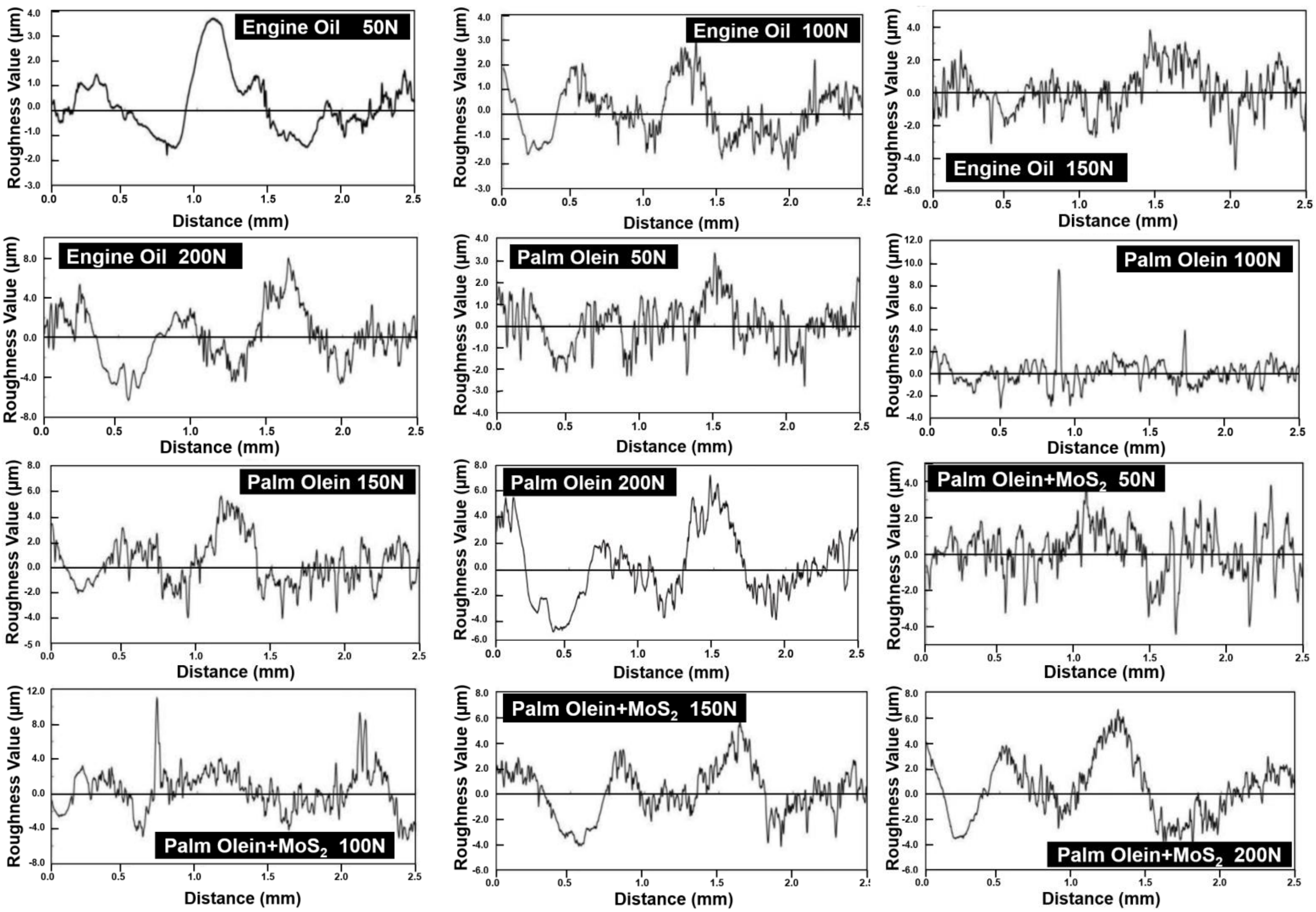


Figure 6: Surface Roughness sample of Engine oil, palm olein and Palm Olein + MoS_2.

CONCLUSIONS

The results suggest that at low temperatures (100°C and below), PO outperforms EO in terms of tribological qualities, such as a lower COF value, smaller WSD, and smoother surface roughness. On the other hand, PO performance suffered a dramatic decline when exposed to temperatures between 120°C and 150°C. When compared to EO, PO has a higher Ra value and a coarser surface roughness level. PO is not very stable when exposed to heat or oxidation. PO loses its protective properties and the lubricating coating it forms on surfaces when heated too much. Additionally, fatty acid has a role in the high-temperature oxidation of palm olein. The surface's roughness increases due to corrosive wear. Improved tribological characteristics and a noticeable decrease in friction are achieved by adding MoS_2 nanoparticle addition to PO. PO+MoS_2 outperforms both PO and EO when subjected to high loads of 50N, 100N, 150N, and 200N, respectively. WSD is decreased by 6.41% at 50N load, 5.98% at 100N load, 7.94% at 150N load, and 12.34% at 200N load when 0.05% MoS_2 nanoparticle additive is applied to palm olein. COF is reduced by 3.51% at 50N load, 7.35% at 100N load, 5.48% at 150N, and 4.55% at 200N load.

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REFERENCES

Abdul Sani, A. S., Rahim, E. A., & Samion, S. (2017). Tribological performance of modified jatropha oil containing oil-miscible ionic liquid for machining applications. Journal of Mechanical Science and Technology, 31, 5675-5685.

Afifah, A. N., Syahrullail, S., Azlee, N. I. W., & Rohah, A. M. (2021). Synthesis and tribological studies of epoxidized palm stearin methyl ester as a green lubricant. Journal of Cleaner Production, 280, 124320.

Azman, N. F., & Samion, S. (2019). Dispersion stability and lubrication mechanism of nanolubricants: a review. International journal of precision engineering and manufacturing-green technology, 6, 393-414.

Azman, N. F., Samion, S., & Sot, M. N. H. M. (2018). Investigation of tribological properties of CuO/palm oil nanolubricant using pin-on-disc tribotester. Green materials, 6(1), 30-37.

Chan, C. H., Tang, S. W., Mohd, N. K., Lim, W. H., Yeong, S. K., & Idris, Z. (2018). Tribological behavior of biolubricant base stocks and additives. Renewable and Sustainable Energy Reviews, 93, 145-157.

Cyriac, F., Yi, T. X., Poornachary, S. K., & Chow, P. S. (2022). Boundary lubrication performance of polymeric and organic friction modifiers in the presence of an anti-wear additive. Tribology International, 165, 107256.

Golshokouh, I., Golshokouh, M., Ani, F. N., Kianpour, E., & Syahrullail, S. (2013). Investigation of physical properties for jatropha oil in different temperature as lubricant oil. Life Science Journal, 10(8), 110-119.

Golshokouh, I., Syahrullail, S., Ani, F. N., & Masjuki, H. H. (2013). Investigation of palm fatty acid distillate as an alternative lubricant of petrochemical based lubricants, tested at various speeds. International Review of Mechanical Engineering, 7(1), 72-80.

Gulzar, M., Masjuki, H. H., Varman, M., Kalam, M. A., Mufti, R. A., Zulkifli, N. W. M., ... & Zahid, R. (2015). Improving the AW/EP ability of chemically modified palm oil by adding CuO and MoS2 nanoparticles. Tribology International, 88, 271-279.

Gupta, M. K., Demirsöz, R., Korkmaz, M. E., & Ross, N. S. (2023). Wear and friction mechanism of stainless steel 420 under various lubrication conditions: a tribological assessment with ball on flat test. Journal of Tribology, 145(4), 041703.

Gusain, R., Khan, A., & Khatri, O. P. (2020). Fatty acid-derived ionic liquids as renewable lubricant additives: Effect of chain length and unsaturation. Journal of Molecular Liquids, 301, 112322.

Hidayati, S., Nurainy, F., Suroso, E., Sartika, D., & Hadi, S. (2024). Effect Of Heating Time On Changes In Physicochemical Properties And Fatty Acid Composition Of Red Palm Oil. African Journal of Food, Agriculture, Nutrition and Development, 24(1), 25628-25644.

Hussin, M. H., Abd Latif, N. H., Hamidon, T. S., Idris, N. N., Hashim, R., Appaturi, J. N., ... & Sedliačik, J. (2022). Latest advancements in high-performance bio-based wood adhesives: A critical review. Journal of Materials Research and Technology, 21, 3909-3946.

Ilie, F., & Cristescu, A. C. (2022). A study on the tribological behavior of molybdenum disulfide particles as additives. Coatings, 12(9), 1244.

Jabal, M. H., Ani, F. N., & Syahrullail, S. (2014). The tribological characteristic of the blends of Rbd palm olein with mineral oil using four-ball tribotester. Jurnal Teknologi, 69(6), 11-14.

Jason, Y. J. J., How, H. G., Teoh, Y. H., & Chuah, H. G. (2020). A study on the tribological performance of nanolubricants. Processes, 8(11), 1372.

Li, Z., Hu, K., Xu, Y., Hu, E., & Hu, X. (2022). Dispersion and tribological properties of nano-MoS2/sericite particles in di-n-butyl adipate synthesized by their own catalysis. Tribology International, 174, 107760.

Liu, C., Yin, Y., Tong, B., & Zhang, G. (2021). Tribological properties of MoS2 powder-lubricated interface. Industrial Lubrication and Tribology, 73(6), 839-845.

Mao, C., Zhang, Y. C., Lei, H., Jia, X., Chen, F., Yao, W., ... & Chen, W. (2024). Boosting tribo-catalytic degradation of organic pollutants by BaTiO3 nanoparticles through metallic coatings. Applied Surface Science, 160172.

Murru, C., Badía-Laíño, R., & Díaz-García, M. E. (2021). Oxidative stability of vegetal oil-based lubricants. ACS Sustainable Chemistry & Engineering, 9(4), 1459-1476.

Nyholm, N., & Espallargas, N. (2023). Functionalized carbon nanostructures as lubricant additives–A review. Carbon, 201, 1200-1228.

Opia, A. C., Abdollah, M. F. B., Hamid, M. K. A., & Veza, I. (2023). A Review on Bio-Lubricants as an Alternative Green Product: Tribological Performance, Mechanism, Challenges and Future Opportunities. Tribology Online, 18(2), 18-33.

Opia, A. C., Hamid, M. K. A., Syahrullail, S., Johnson, C. A., Rahim, A. B., & Abdulrahman, M. B. (2021). Nano-particles additives as a promising trend in tribology: A review on their fundamentals and mechanisms on friction and wear reduction. Evergreen 8 (4), 777-798.

Paiman, Z., Samion, S., Yazid, M. N. A. W. M., & Rasep, Z. (2024). Friction and wear characteristics of palm mid olein base stock with Tertiary Butyl-Hydroquinone and Ethylene Vinyl Acetate as bio-based lubricant. Jurnal Tribologi, 41, 10-23.

Pichler, J., Maria Eder, R., Besser, C., Pisarova, L., Dörr, N., Marchetti-Deschmann, M., & Frauscher, M. (2023). A comprehensive review of sustainable approaches for synthetic lubricant components. Green Chemistry Letters and Reviews, 16(1), 2185547.

Samion, S., Hanafi, M. S., Yahaya, W. M. A. W., Abas, A., Paiman, Z., Abdollah, M. F., Hilmi, A., Nurin Wahidah, M.Z., (2024). Exploring the performance of TMP trioleate esters in real-world automotive engines: A tribological analysis. Jurnal Tribologi, 42, 265-277.

Sani, A., Sahab, A., Abd Rahim, E., Talib, N., Kamdani, K., & Rahim, M. Z. (2017). Performance Evaluation of Palm-Olein TMP Ester Containing Hexagonal Boron Nitride and an Oil Miscible Ionic Liquid as Bio-Based Metalworking Fluids. Journal of Mechanical Engineering (JMechE), (1), 223-234.

Shrestha, S., Wang, B., & Dutta, P. (2020). Nanoparticle processing: Understanding and controlling aggregation. Advances in colloid and interface science, 279, 102162.

Singh, A., Verma, N., Mamatha, T. G., Kumar, A., Singh, S., & Kumar, K. (2021). Properties, functions and applications of commonly used lubricant additives: a review. Materials Today: Proceedings, 44, 5018-5022.

Syahrullail, S., Azwadi, C. S. N., & Ing, T. C. (2011). The metal flow evaluation of billet extruded with RBD palm stearin. International Review of Mechanical Engineering, 5(1), 21-27.
Syahrullail, S., Nakanishi, K., & Kamitani, S. (2005). Investigation of the effects of frictional constraint with application of palm olein oil lubricant and paraffin mineral oil lubricant on plastic deformation by plane strain extrusion. Japanese journal of tribology, 50(6), 727-738.
Syahrullail, S., Wira, J. Y., Wan Nik, W. B., & Fawwaz, W. N. (2013). Friction characteristics of RBD palm olein using four-ball tribotester. Applied Mechanics and materials, 315, 936-940.
Tonk, R. (2021). The science and technology of using nano-materials in engine oil as a lubricant additives. Materials Today: Proceedings, 37, 3475-3479.
Waqas, M., Zahid, R., Bhutta, M. U., Khan, Z. A., & Saeed, A. (2021). A review of friction performance of lubricants with nano additives. Materials, 14(21), 6310.
Yahaya, A., & Samion, S. (2022). Friction condition of aluminum alloy AA6061 lubricated with bio-lubricant in cold forging test. Industrial Lubrication and Tribology, 74(4), 378-384.
Yahaya, A., Samion, S., Abidin, U., & Abdul Hamid, M. K. (2023). Different Behaviors of Friction in Open and Closed Forging Test Utilizing Palm Oil-Based Lubricants. Lubricants, 11(3), 114.
Yang, S., Reddyhoff, T., & Spikes, H. (2013). Influence of lubricant properties on ARKL temperature rise and transmission efficiency. Tribology transactions, 56(6), 1119-1136.
Ye, Z., Li, S., Zhao, S., Deng, L., Zhang, J., & Dong, A. (2021). Textile coatings configured by double-nanoparticles to optimally couple superhydrophobic and antibacterial properties. Chemical Engineering Journal, 420, 127680.
Zhang, X., Li, C., Zhou, Z., Liu, B., Zhang, Y., Yang, M., Gao, T., Liu, M., Zhang, N., Said, Z. and Sharma, S., (2023). Vegetable oil-based nanolubricants in machining: from physicochemical properties to application. Chinese Journal of Mechanical Engineering, 36(1), 76.
Zhang, Z., Ye, J., Lee, W. J., Akoh, C. C., Li, A., & Wang, Y. (2021). Modification of palm-based oil blend via interesterification: Physicochemical properties, crystallization behaviors and oxidative stabilities. Food Chemistry, 347, 129070.
Zulhanafi, P., & Syahrullail, S. (2019). The tribological performances of Super Olein as fluid lubricant using four-ball tribotester. Tribology International, 130, 85-93.