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Tribological performance of super olein added with Butylated Hydroxyanisole (BHA) and Butylated Hydroxytoluene (BHT) by using pin on disc tribotester for hydrogen engine lubrication

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KEYWORDS

Vegetable oils
Super olein
Antioxidant
Tribological
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ABSTRACT

The transition to hydrogen engines presents new tribological challenges, particularly concerning lubricant oxidative stability due to high water vapor generation and the absence of carbon-based soot. This study explores the potential of super olein-based biodegradable lubricants enhanced with antioxidants for hydrogen engine applications. Given that hydrogen combustion accelerates oil oxidation and affects lubricant performance, the oxidative stability of super olein was improved by blending it with 0.3% Butylated Hydroxytoluene (BHT) and Butylated Hydroxyanisole (BHA). Tribological performance was evaluated using a pin-on-disc tribotester under varying loads (0.5–1.5 kg) and speeds (0.5–1.5 m/s) following ASTM G99 standards. Results showed that super olein with BHT and BHA reduced the coefficient of friction by 6.23% and 18.74%, respectively, compared to industrial oil. However, industrial oil exhibited smaller wear scar diameters, lower surface roughness, and superior wear resistance, highlighting the need for further optimization of bio-based lubricants for hydrogen engines. Enhancing antioxidant formulations in biodegradable lubricants can improve oxidative stability, ensuring reliable lubrication and extended maintenance intervals in hydrogen-powered vehicles.

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1.0 INTRODUCTION

Hydrogen engines have gained attention as a promising alternative to conventional internal combustion engines due to their potential for near-zero carbon emissions and high thermal efficiency (Bao et al., 2022). However, the transition to hydrogen as a fuel introduces several tribological challenges, particularly concerning lubricant oil oxidative stability. Unlike traditional hydrocarbon fuels, hydrogen combustion generates high water vapor content (Onorati et al., 2022), which can lead to increased oil dilution (Lubes and Greases, 2024) and accelerated oxidation (Chen et al., 2021), affecting lubricant performance and engine longevity. The oxidative stability of lubricants is crucial in hydrogen engines, as oxidation can cause viscosity breakdown (Sejkorová et al., 2021), sludge formation (Ziółkowska, 2019), and the generation of acidic by-products (Higgins et al., 2019) that contribute to component wear. Additionally, the absence of carbon-based soot in hydrogen combustion alters the tribological environment (Mohd Nor, 2020), requiring specially formulated lubricants to maintain proper film strength and wear protection. The high combustion temperatures and potential for pre-ignition in hydrogen engines further stress lubricants (Wang et al., 2025), demanding advanced additives and base oil formulations to enhance thermal and oxidative resistance (Paiman et al., 2024). Research into bio-based and synthetic lubricants with superior antioxidant properties is ongoing to address these challenges, ensuring reliable operation and extended maintenance intervals for hydrogen-powered vehicles. By improving lubricant oil stability, advancements in tribological technology will play a key role in optimizing the efficiency and durability of hydrogen engines, supporting their adoption as a sustainable transportation solution.

1.1 Bio-based Lubricant

The growing demand for renewable and biodegradable lubricants, such as bio-based oils, stems from increasing environmental concerns and regulatory restrictions (Paiman et al., 2024). Traditionally, mineral oils have been the most common lubricant base fluid, but their environmental impact has raised concerns, leading to a shift towards biodegradable alternatives like vegetable oils and synthetic-based oils (Zulhanafi et al., 2019). The rapid industrialization and rising energy demands have further increased the consumption of petroleum-based lubricants, with an estimated 30 to 40 million tonnes used annually, of which 55% is released into the environment, causing significant ecological harm (Syahir et al., 2017). As petroleum resources deplete and environmental hazards rise, the development of bio-based lubricants has become a priority (Shah et al., 2021). Derived from renewable sources such as vegetable oils and animal fats, bio-based lubricants offer advantages like high lubricity, a high viscosity index, good shear resistance, and biodegradability (Zulhanafi et al., 2021). However, their widespread adoption is limited by challenges such as poor low-temperature performance and oxidative stability, which can be improved through additives and chemical modifications (Negi et al., 2021). Barbera et al., 2022 concluded that lubricants are made up of 70 – 100% base oil and 0 – 30% of additives or surfactants. The transition to bio-based lubricants requires collaboration among manufacturers, environmental organizations, and government agencies to develop sustainable and economically viable biotechnologies. Such efforts will promote a greener future by encouraging the adoption of bio-lubricants in various industries while balancing performance and environmental sustainability.

1.2 Oxidative Stability of the Bio-based Lubricant

Oxidative stability is a critical factor in the performance of lubricants, particularly for vegetable oil-based lubricants, which are more susceptible to oxidation due to their high content of unsaturated fatty acids (Negi et al., 2021). Oxidation occurs when oxygen reacts with the weakest components of the base oil, leading to the formation of acids, sludge, and increased viscosity, ultimately degrading the lubricant's effectiveness (Zulhanafi et al., 2023). This process accelerates at higher temperatures and in the presence of contaminants such as water and metal particles. To enhance oxidative stability, manufacturers incorporate antioxidant additives, which function by interrupting the oxidation chain reaction and stabilizing free radicals. Common antioxidants, such as Butylated Hydroxyanisole (BHA), Butylated Hydroxytoluene (BHT), Propyl Gallate (PG), and Tertiary Butyl Hydroquinone (TBHQ) (Norazman et al., 2024), donate hydrogen to free radicals, preventing further oxidation (Santos-Sánchez et al., 2019). While blending vegetable oil-based lubricants with synthetic esters or mineral oils can improve stability, it may compromise their environmental benefits (Hamnas and Unnikrishnan, 2023). Therefore, optimizing antioxidant formulations is essential for maintaining the longevity and performance of bio-based lubricants while ensuring sustainability. The general aim of this experiment is to evaluate the tribological performance of super olein-based lubricants enhanced with antioxidant additives (BHA and BHT) and its molecular structures are shown in Figure 1 by assessing their friction and wear characteristics using a pin-on-disc tribotester.

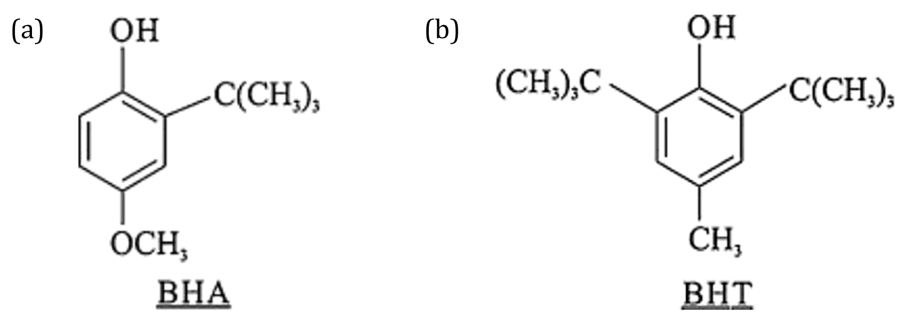

Figure 1: Chemical structure of (a) BHA (b) BHT. Adapted after Freitas and Fatibello-Filho, 2010.

2.0 METHODOLOGY

The testing will be conducted following the ASTM G99 standards, which outline the Standard Test Method for Wear Testing at room temperature. According to the standard, prior to the test, both the pin and the disk will be thoroughly cleaned using acetone to eliminate any foreign particles on the surface that could potentially cause scratches and impact the test results.

2.1 Lubricant Properties

The lubricant was formulated using super olein as the base oil, with BHT and BHA added as additives at a concentration of 0.3% by weight, and its performance was compared to industrial oil which is fully synthetic advanced engine oil 0W/20. The properties of super olein and industrial oil are listed in Table 1.

Table 1: Lubricant Properties.

Properties	Super Olein	Industrial Oil
Specific gravity	0.9000	0.8660
Kinematic viscosity (mm^2/s)		
@ 40°C	33.3	108.2
@ 100°C	12.05	14.10
Viscosity index (VI)	378	132
Colour	3.3R 33Y	1.2.5
Free Fatty Acid (FFA%)	0.087	-
Peroxide Value (PV)	1.27	-
Pour Point (°C)		-30
Flash Point (°C)		227
Iodine Value (IV)	64.57	-
Slip Melting Point (°C)	15.2	-
Cloud Point (°C)	3.8	-

2.2 Types of Analysis

Five key analyses will be conducted: viscosity, oxidative stability, coefficient of friction, wear performance, and physical wear characterization.

2.2.1 Oxidative Stability Test

In this study, the oxidative stability of the lubricant was enhanced through the incorporation of the phenolic antioxidant butyl-hydroxytoluene (BHT) and butyl-hydroxy anisole (BHA) at a concentration of 0.3%wt. BHA was in powder form with a particle size around 5–10 µm, while BHT was in bead form with a diameter of 100–300 µm, and it was mixed into the base oil using a motorized stirrer with mild heating at approximately 45 °C to facilitate uniform dispersion. Visual inspection revealed that the mixture was clear and free of any cloudiness or sedimentation. No visible opacity or phase separation was observed during storage, indicating a homogeneous and stable formulation. The oxidative stability of the formulated samples was assessed based on oxidative induction time (OIT) using a Differential Scanning Calorimeter (DSC), in accordance with the ASTM E1858 standard.

2.2.2 Viscocity Analysis

In this experiment, a rotational viscometer was used to measure the viscosity of the lubricant. The density of the lubricant was initially determined using a hydrometer. The lubricant was then poured into a 250 ml beaker and placed on a heater with a magnetic stirrer. The heating and stirring process was conducted slowly until the temperature reached 100°C, following the guidelines of ASTM D2983. The viscometer automatically recorded the viscosity readings during the test. Once the lubricant reached 100°C, it cooled down naturally to the room temperature, and viscosity values were also recorded during the cooling process. The average viscosity values for each temperature were then calculated to obtain the final readings. Periodic observations and viscosity measurements confirmed that the formulation remained homogeneous and within acceptable rheological limits throughout the idle period.

2.2.3 Coefficient of Friction

A pin-on disc tribotester can be used to evaluate the friction properties of lubricants and other materials. The device simulates the conditions of a sliding contact by pressing a pin against a rotating disc, with lubricant applied to the contact area. The frictional force created between a pin and rotating disk is measured using load cell. Strain gauge load cell used in wheat Stone Bridge is mounted to the side of the pin holding lever arm, and their electrical output is proportionate to the load acting column. The tribotester can measure the friction force that were shown in the digital display. Figure 2 shows the schematic diagram of the pin on disc and the friction coefficient is calculated by using Equation (1).

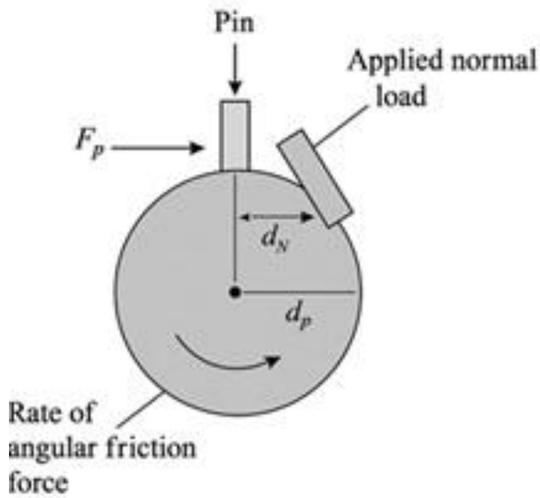

Figure 2: Schematic diagram of the pin on disc tribotester.

$$\mu = \frac{F_p d_p}{F_N d_N} \tag{1}$$

where, μ is coefficient of friction, F_p is rate of angular friction force, F_N is applied normal load, d_p is the distance between center to the pin and d_N is between center to normal force.

2.2.4 Wear Performance

An LVDT (Linear Variable Differential Transformer) sensor is a type of displacement sensor used in a pin-on-disc tribotester. It is connected to a display monitor to measure the pin's wear rate. The weight loss of the hemispherical pin was recorded before and after the experiment. Using the weight loss data obtained during the experiment, the wear rate was determined according to Equation (2).

$$Q\left(\frac{mm^3}{m}\right) = \frac{\Delta V}{S} \tag{2}$$

where Q is wearing rate, V is volume loss, and S is sliding distance.

2.2.5 Physical Wear

Wear scar diameter was measured by using high-definition microscope equipped with i-Solution software. Meanwhile the surface topography of the wear was examined by using Variable Pressure Scanning Electronic Microscopy (VPSEM) with 420x magnificent. This was used to identify the type and mechanism of physical wear behaviour.

2.3 Pin-on-Disc

Pin-on-disk tester (DUCOM-TR 20-LE) as shown in Figure 3 was used to forecast the wear and friction behaviour of the material. The device typically consists of a pin, which pressed against a rotating disk or flat surface. The pin is typically made of harder material than the disk and is used to simulate a specific type of wear or sliding motion. The device can be used to measure friction and wear under various conditions, such as different loads, speeds and temperature. The technical specifications of the DUCOM-TR 20-LE Pin on Disk Tester is listed in Table 2.

Table 2: Pin-on-disk tribotester specification.

Specification	Ranges
Normal load	2 N to 1000 N
Speeds	0.3 rpm to 3000 rpm

The testing will be conducted following the ASTM G99 standards, which outline the Standard Test Method for Wear Testing at room temperature. According to the standard, prior to the test, both the pin and the disk will be thoroughly cleaned using acetone to eliminate any foreign particles on the surface that could potentially cause scratches and impact the test results.

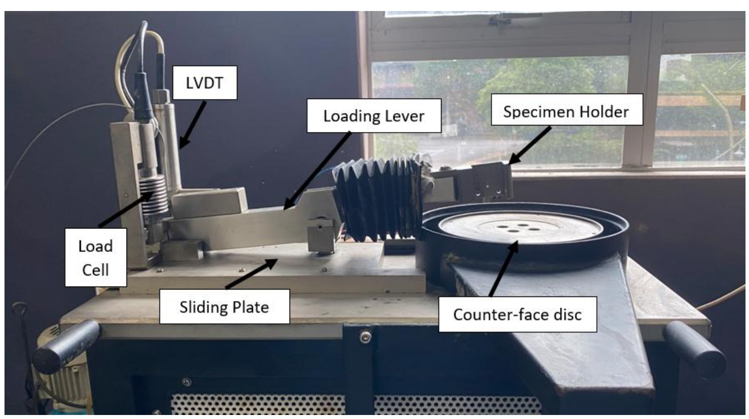

Figure 3: Pin-on-disc tribotester part.

The pin-on-disc method was utilized to investigate both wear and coefficient of friction. A pin was firmly pressed against a rotating disc, which was connected to a specific weight through a beam and two pulleys. A grooved disc was used, and lubricating oil was applied on its surface. The wear track was set at 40 mm by adjusting the sliding position and remained fixed throughout the experiment. To ensure the lubricant remained in place during high-speed rotation, a modified disc with a groove measuring 10 mm in width and 5 mm in depth was employed, preventing the lubricant from splashing out. The lubricant was manually applied to the modified disc surface.

2.4 Experimental Conditions

The experimental conditions for the pin-on-disc tribotester test are summarized in Table 3.

Table 3: Experimental condition for the pin on disc test.

Details	Description
Applied load	0.5 kg; 1 kg; 1.5kg
Sliding speed	0.5 m/s; 1 m/s; 1.5 m/s
Duration	1 hour
Temperature	Ambient temperature
Pressure level	Atmospheric pressure
Standard	ASTM G99
Amount of lubricants	5 ml

3.0 RESULTS AND DISCUSSION

3.1 Viscosity Profile of SPL+BHT, SPL + BHA and Industrial Oil

Before conducting the experiment, the density and kinematic viscosity of three lubricants, namely SPL + BHT, SPL + BHA and industrial oil, were measured to assess the effect of temperature on the kinematic viscosity of lubricating oil as shown in Figure 4. The temperature ranges from 30°C to 40°C was specifically selected as it represents the operating conditions of the experiment. The results indicated that all three lubricants exhibited similar viscosity profiles within this temperature range, demonstrating comparable resistance to flow and shear. Given the minimal differences observed, these lubricants can be considered to possess similar viscosity behavior, making them suitable for subsequent tribological testing. According to Liu et al. (2022), the decrease in viscosity with increasing temperature is primarily attributed to the weakening of intermolecular forces and the enhancement of molecular motion, which facilitates the easier flow of liquid molecules. The properties of lubricants at different temperatures are listed in Table 4.

Table 4: Properties of lubricants at different temperatures.

Properties	SPL + BHT	SPL + BHA	Industrial Oil
Density, ρ (kg/m^3)	0.8900	0.9000	0.8900
Kinematic viscosity, ν at 40°C (cSt)	35.1	36.9	32.7
Kinematic viscosity, ν at 100°C (cSt)	6.17	7.81	6.07

3.2 Oxidative Stability Test

The oxidative stability tests were carried out by using Differential Scanning Calorimetric (DSC) to observe the performance of BHT and BHA incorporated with SPL. In this study, the oil induction time (OIT) was used as the primary metric to evaluate the oxidative stability. OIT is defined as the duration in which a stable heat flow is observed before the onset of exothermic oxidation reactions, thus serving as a direct indicator of lipid or oil oxidative stability. The oxidation experiments were carried out in isothermal mode. For each test, approximately 12 mg of the liquid sample was dispensed into a DSC aluminum pan using a Pasteur pipette. The pan was hermetically sealed but equipped with a pin hole to allow the purging and entry of gases, ensuring effective oxidation.

Initially, the sample was heated at a constant rate of 10 °C/min under a nitrogen (N_2) atmosphere until reaching the target isothermal temperature of 180 °C (T_1). At this point, the atmosphere was switched to pure oxygen, and the sample was maintained under constant heat flow. The OIT was determined as the time interval from the introduction of oxygen (T_1) until a deviation in the heat flow signal was observed (T_2), indicating the onset of oxidation or the initiation stage of the degradation process. During this induction period ($T_2 - T_1$), no significant chemical reaction occurs. A longer induction time suggests a greater resistance of the lubricant to oxidative degradation.

It was observed that SPL+BHT formulation exhibited a longer induction time of 65 minutes, compared to 53 minutes for the SPL+BHA under the same isothermal conditions at 180 °C as shown in Figure 5(a) and 5(b). BHT is more thermally stable and sterically hindered chemical structure, which allows it to form a highly stable phenoxy radical that effectively terminates oxidation chain reactions. Unlike BHA, BHT is less volatile and less prone to thermal degradation, enabling it to maintain antioxidant activity at elevated temperatures over extended periods. Additionally, BHT has better solubility in lipid-based systems, allowing more efficient dispersion and interaction with free radicals in the lubricant matrix, thereby enhancing the lubricant's resistance to thermal oxidative breakdown. Furthermore, as shown in Figure 5(c), for the industrial oil, the end of the induction period (T_2) was not observed even after 60 minutes of analysis, indicating that this oil is well formulated to have superior oxidative stability and suitable to be used at high temperature applications.

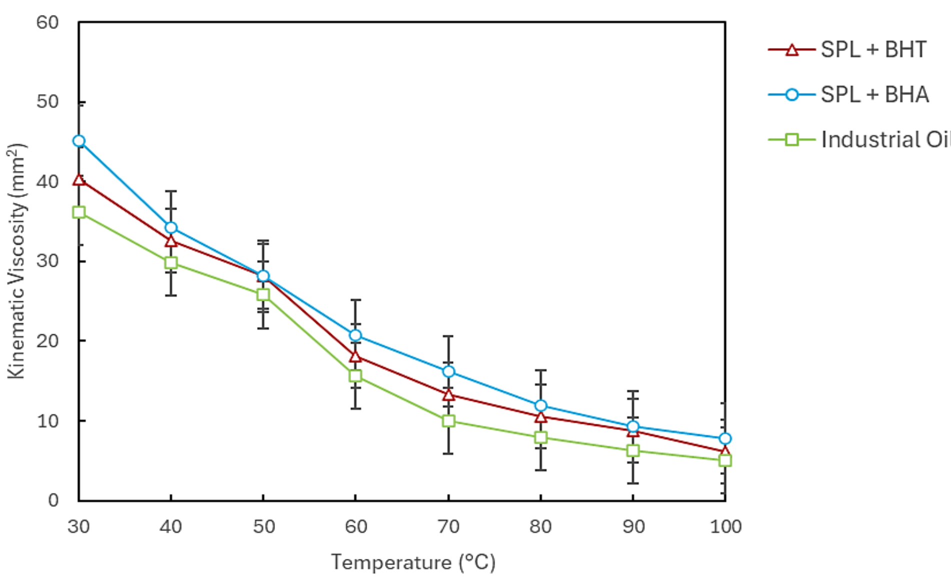

Figure 4: Viscosity profile of SPL + BHT, SPL + BHA and industrial oil.

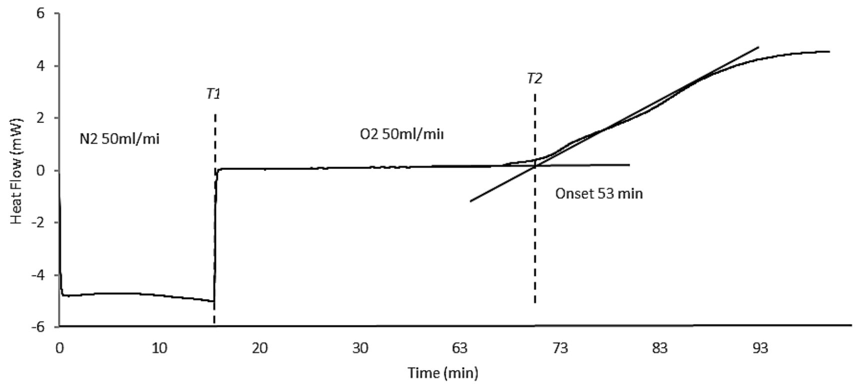

Figure 5(a): OIT for SPL+BHA

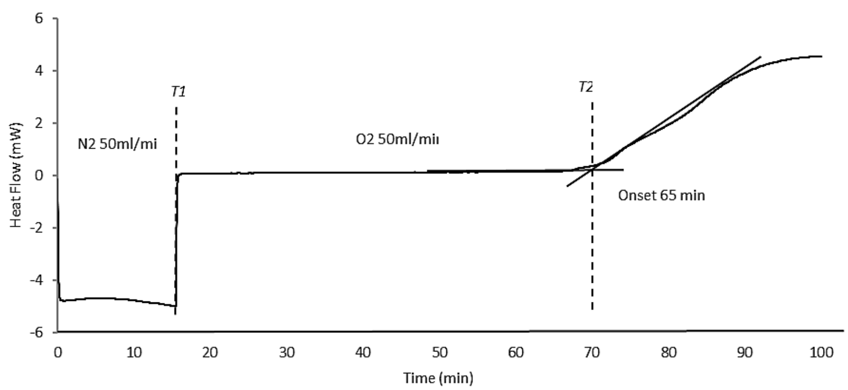

Figure 5(b): OIT for SPL+BHT

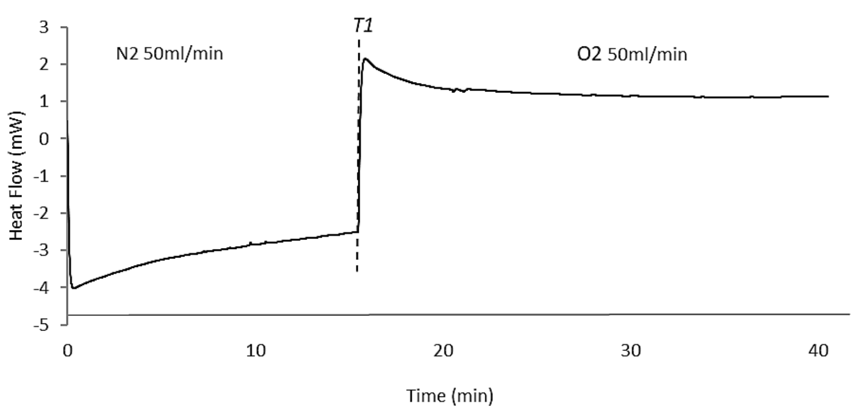

Figure 5(c): OIT for Industrial oil

3.3 Analysis on Friction Coefficient

Figures 6(a), 6(b) and 6(c) present the coefficient of friction measurements for different loads and sliding speeds associated with three lubricant types: Super Olein with Butylated Hydroxytoluene (SPL + BHT), Super Olein with Butylated Hydroxyanisole (SPL + BHA), and industrial oil. These measurements specifically illustrate the resistance to sliding motion between two contact surfaces.

At a load of 0.5 kg, the SPL + BHT lubricant exhibited a lower coefficient of friction compared to SPL + BHA and industrial oil at a sliding speed of 0.5 m/s. This finding suggests that SPL + BHT provided enhanced lubrication, reducing frictional resistance under these conditions. As the sliding speed increased to 1.0 m/s, a slight increase in the coefficient of friction was observed for both SPL + BHT and SPL + BHA, indicating a marginal rise in frictional resistance. In contrast, industrial oil displayed a minor decrease in the coefficient of friction at this speed, implying improved lubrication performance and reduced resistance.

At the highest tested speed of 1.5 m/s, a significant increase in the coefficient of friction was recorded for both SPL + BHT and SPL + BHA. Among the lubricants tested, SPL + BHA exhibited the highest coefficient of friction, indicating an increase in resistance to sliding as speed increased. Conversely, industrial oil maintained a relatively stable coefficient of friction across all sliding speeds, suggesting consistent lubrication properties. This stability can be attributed to the homogeneity of the lubricant, which plays a significant role in the tribological behavior of the system. When the lubricant is homogeneous, it ensures uniform coverage of the sliding surfaces, thereby contributing to the maintenance of a stable coefficient of friction throughout the operation.

As the applied load increased, all lubricants exhibited a rise in frictional forces. This trend can be attributed to the elevated pressure on the contact surfaces, which leads to thinning or rupture of the lubricating film. Consequently, metal-to-metal contact between the pin and disc becomes more pronounced, resulting in an increased coefficient of friction. However, in certain instances, a reduction in the coefficient of friction was observed despite increasing speed and load. This phenomenon can be explained by surface wear and its impact on the topography of the pin and disc surfaces (Dou et al., 2022). Even in the absence of lubricant, the accumulation of solid particles on the sliding surfaces can influence lubrication quality. These particles, often generated by surface wear or introduced through external contamination, may form a thin film on the contact surfaces, thereby altering the microtopography and affecting the frictional behavior (He et al., 2023). Depending on their size, composition, and interaction with the mating surfaces, these solid particles may either increase or decrease friction (Sellami et al., 2020). In certain cases, they can act as a third-body lubricant, modifying the tribological properties and potentially contributing to friction reduction (Shi et al., 2018). During the sliding process, material removal due to wear can lead to the gradual smoothing of surface asperities. As a result, the contact interface becomes smoother, reducing asperity interactions and ultimately lowering frictional resistance. The reduction in the coefficient of friction due to wear-induced surface smoothing is possible when a balance is achieved between the wear rate and surface adaptation. Over time, as asperities are flattened, the frictional force decreases, leading to a reduction in the coefficient of friction (Chowdhury, 2011). Additionally, variations in frictional behavior can be influenced by the temperature of the lubricant, as thermal effects at the interface play a crucial role in determining frictional characteristics (Manoharan et al., 2019). Another important factor affecting tribological performance is the particle size of additives. Smaller particles tend to disperse more uniformly within the lubricant, promoting the formation of stable tribofilms that help reduce friction and wear. In contrast, larger particles may agglomerate or fail to effectively penetrate micro-contact zones, potentially resulting in inconsistent film formation or even increased abrasion (Wang et al., 2022).

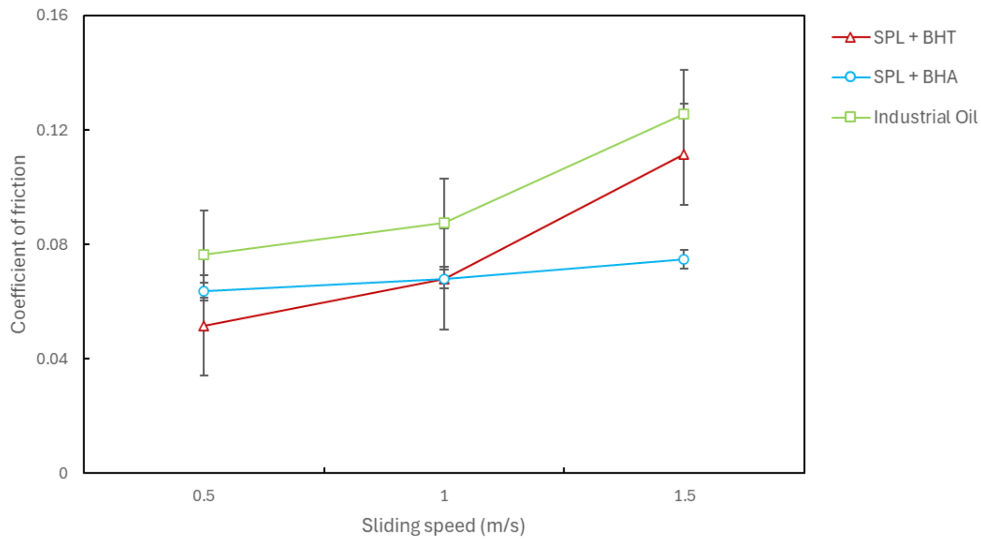

Figure 6(a): Friction coefficient trends at load of 0.5 kg.

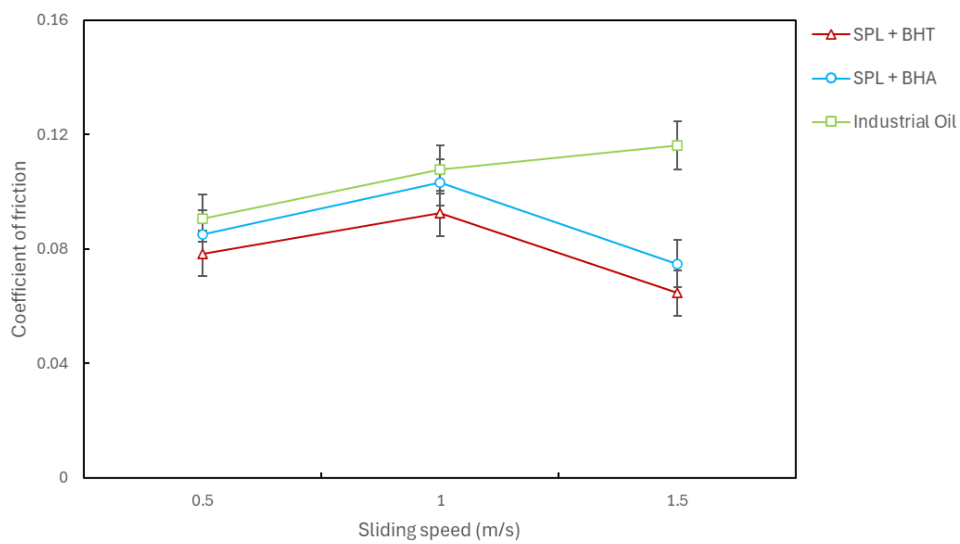

Figure 6(b): Friction coefficient trends at load of 1.0 kg.

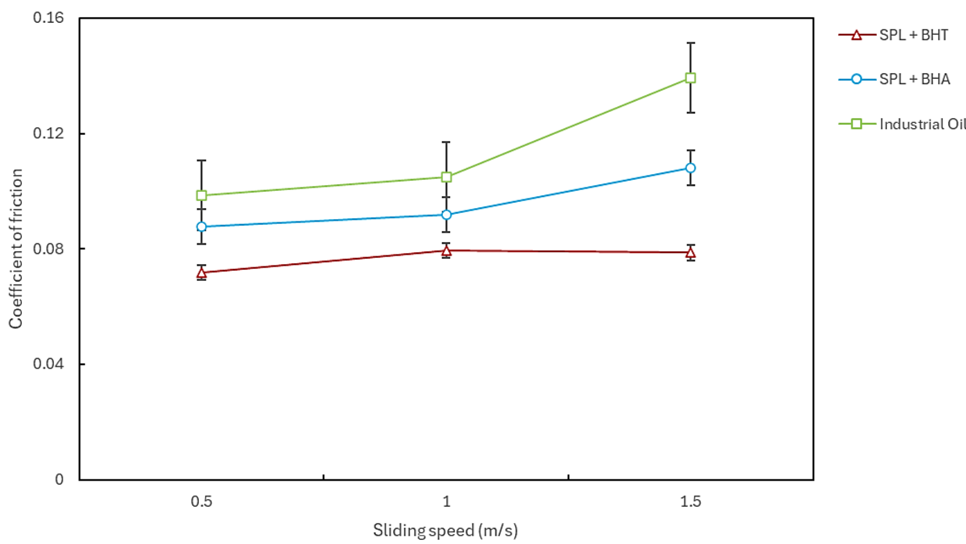

Figure 6(c): Friction coefficient trends at load of 1.5 kg.

3.4 Analysis on Wear Scar Diameter

Figures 7(a), 7(b) and 7(c) illustrate the wear scar diameter (WSD) analysis for all tested lubricants. The findings indicate that industrial oil exhibited minimal variation in WSD with increasing sliding speed and applied load. This suggests that industrial oil effectively maintained lubrication and wear protection under different testing conditions. However, it is important to note that despite its stable WSD performance, industrial oil exhibited a higher coefficient of friction in the previous analysis, implying that greater force was required to sustain the sliding motion compared to the other lubricants.

In contrast, both SPL + BHT and SPL + BHA exhibited lower coefficients of friction than industrial oil, indicating enhanced lubrication properties. However, despite this advantage, these lubricants demonstrated higher WSD values compared to industrial oil. This inverse relationship between friction reduction and wear protection can be explained by the principles discussed in Bowden and Tabor's study on metallic wear (Bowden and Tabor, 2001), can be attributed to the elevated shear strength of the oil absorbed on the pin's surface and the effects of chemical attack caused by fatty acids present in super olein. This implies that even though they reduced friction, they were not as effective in preventing wear and damage to the surfaces in the testing conditions. As discussed in the previous analysis, the presence of fatty acids interacting with metal surfaces causes the deterioration of a thin soap film layer, resulting in substantial damage to the contacting surfaces. Furthermore, as the sliding speed and applied load increase, the contact surface area expands, leading to a rise in temperature (Zulkifli et al., 2016). According to Mobarak et al., 2014, elevated sliding speeds accelerate the oxidation process, further influencing the lubrication performance.

The contrasting results for SPL + BHT and SPL + BHA, where they exhibited lower coefficients of friction but higher WSD, suggest that their ability to reduce friction does not necessarily translate into effective wear protection. This discrepancy may be attributed to the specific additives used in the lubricants and their interactions under varying operating conditions.

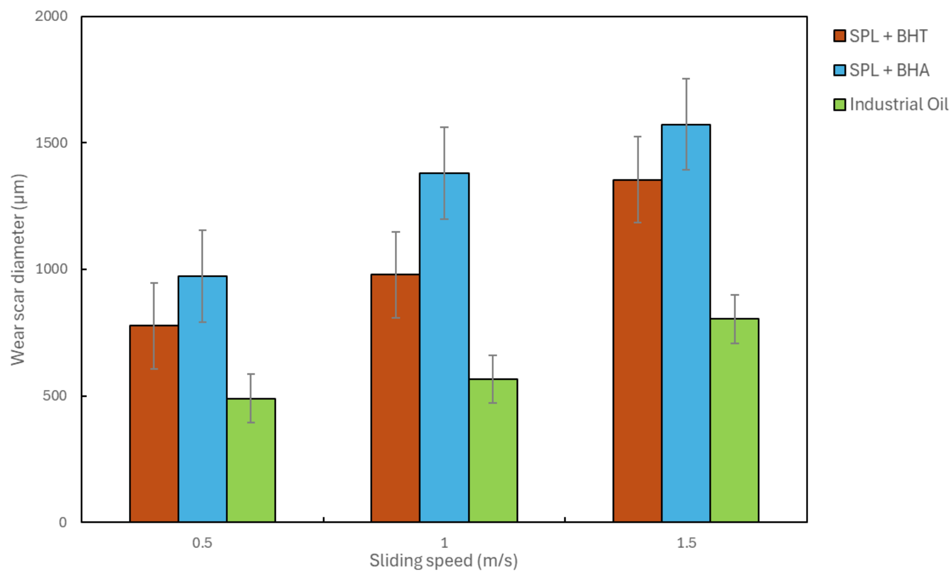

Figure 7(a): The trends of WSD at load of 0.5 kg.

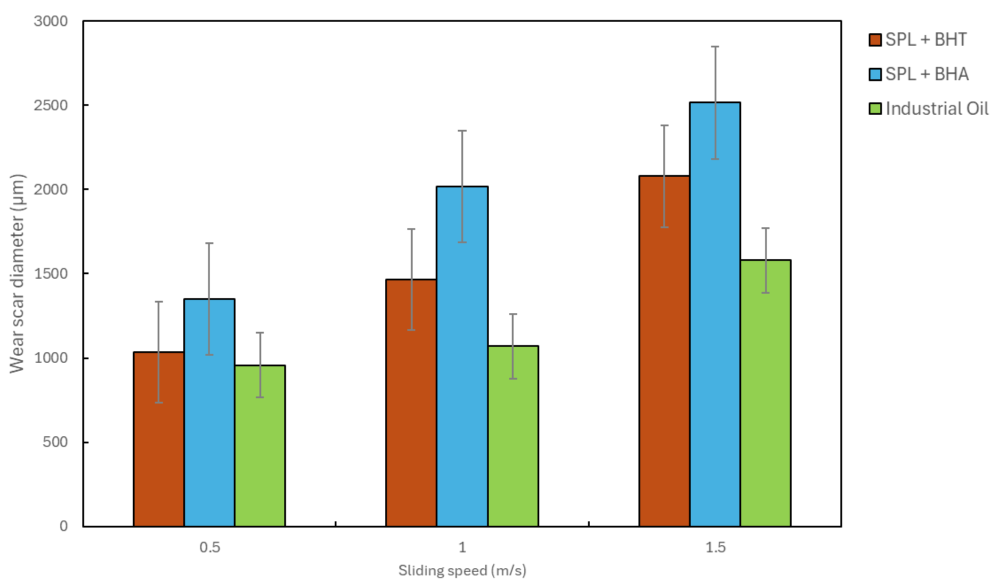

Figure 7(b): The trend of WSD at a load of 1.0 kg.

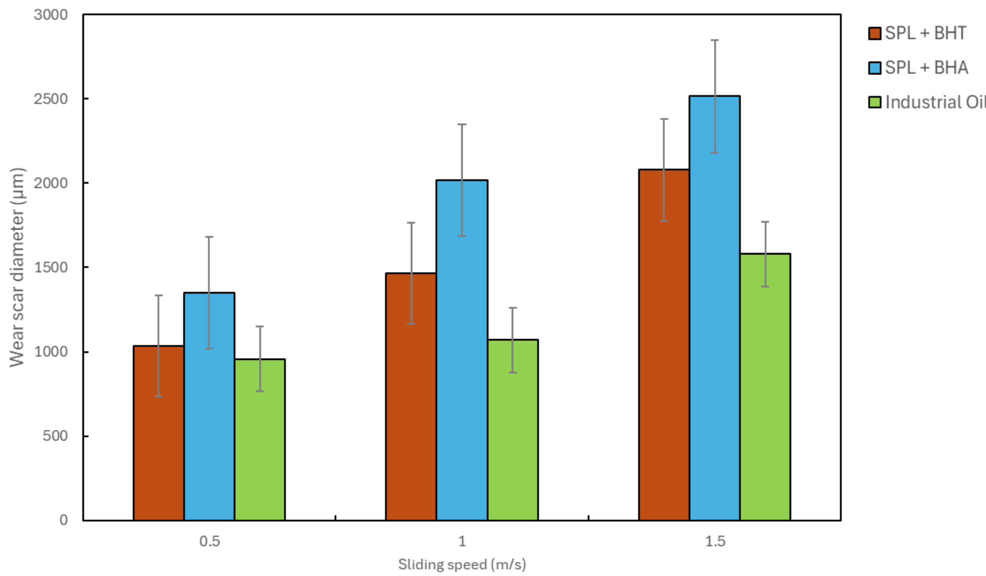

Figure 7(c): The trend of WSD at a load of 1.5 kg.

3.5 Analysis on Surface Roughness

Surface roughness is a critical parameter in characterizing surface modification (Butt et al., 2021; Najar et al., 2016), as it provides insights into the wear performance and lubrication efficiency of different lubricants. Various parameters exist for measuring surface texture, with arithmetic surface roughness (*Ra*) being the most used parameter (Yang et al., 2024). Surface roughness measurements were conducted using a surface roughness profiler, with the cut-off length set between 0.5 and 1.0 mm. The area exhibiting the predominant wear scar was selected for analysis to ensure the measurement captured the most representative wear features. The arithmetic surface roughness (*Ra*) values of the pin surface were measured after each test and are presented in Figures 8(a), 8(b) and 8(c). The results indicate that the pins lubricated with industrial oil exhibited the lowest Ra values across all normal loads compared to those lubricated with SPL + BHT and SPL + BHA. The lower Ra values suggest that industrial oil effectively maintained a smoother pin surface, minimizing surface irregularities such as scratches, grooves, and asperities. A smoother surface is typically associated with reduced friction and wear during sliding contact.

The ability of industrial oil to produce a smoother pin surface can be attributed to its superior lubricating properties, including the formation of a stable and uniform lubricating film. This film acts as a protective barrier, reducing direct metal-to-metal contact and minimizing surface damage. In contrast, SPL + BHT and SPL + BHA exhibited higher Ra values, indicating rougher pin surfaces. This suggests that these lubricants were less effective in preventing surface irregularities and mitigating wear during testing conditions.

The observed differences in surface roughness highlight the varying effectiveness of the tested lubricants in maintaining surface integrity and reducing wear. While industrial oil demonstrated superior surface protection, SPL + BHT and SPL + BHA exhibited higher wear-related surface roughness, reinforcing their limited capability in preserving surface quality under the applied test conditions.

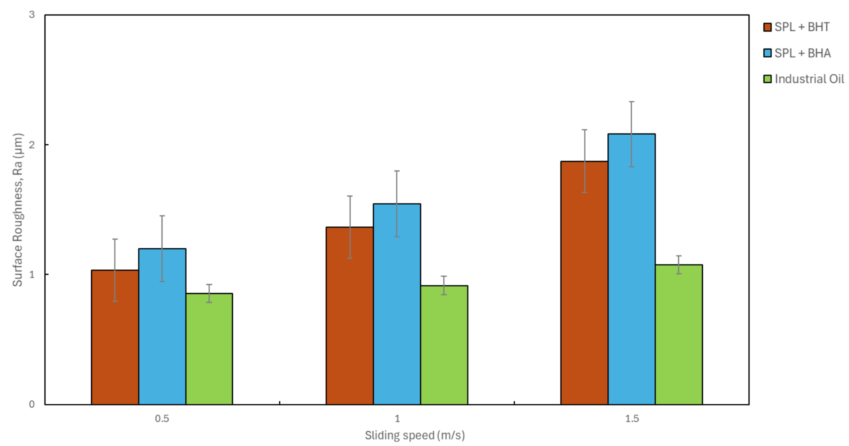

Figure 8(a): Surface roughness trend at load of 0.5 kg.

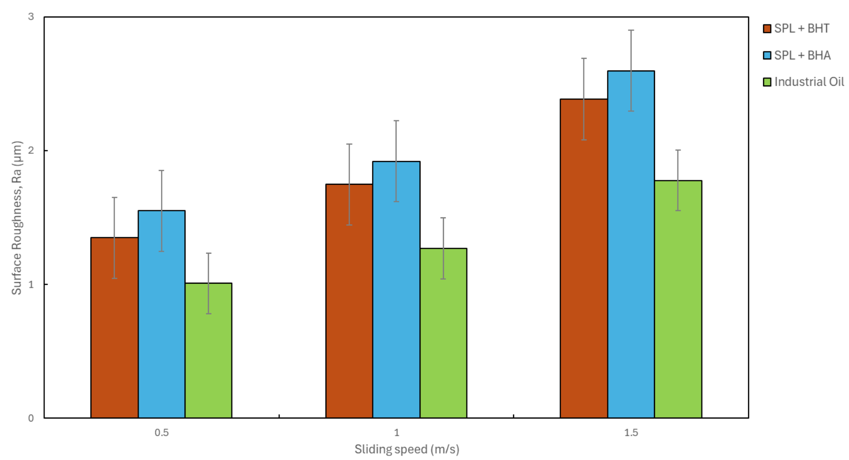

Figure 8(b): Surface roughness trend at load of 1.0 kg.

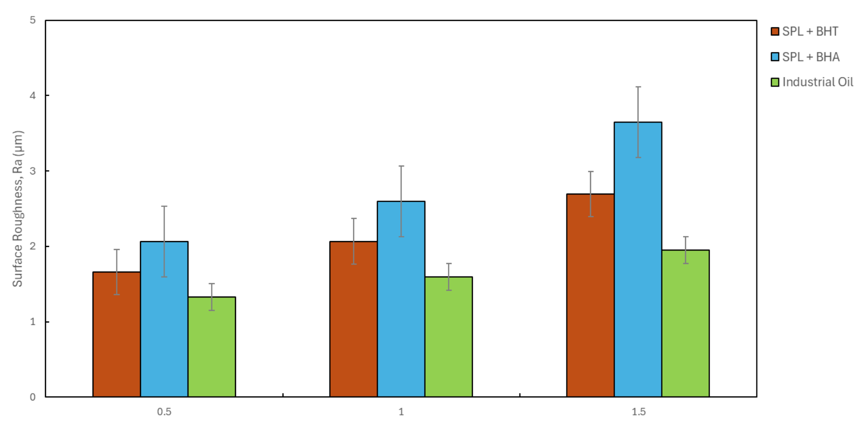

Figure 8(c): Surface roughness trend at load of 1.5 kg.

3.6 Physical Wear Observations

The surface topography analysis of the pins under various lubrication conditions, conducted using VPSEM with 420x magnificent, provides critical insights into the wear patterns and characteristics of each lubricant. This analysis was performed at a constant sliding speed of 1.5 m/s with load of 0.5 kg and 1.5 kg.

The wear scars shown in Figures 9(a) and 9(b) represent the surfaces of pins lubricated with industrial oil. Despite the higher load in Figure 9(b), the SEM image reveals a smoother wear surface with fewer and shallower grooves compared to Figure (a), which exhibits more prominent abrasive tracks and deformation. This suggests that the industrial oil maintains effective lubrication even under increased load, likely due to the formation of a robust boundary lubrication film supported by anti-wear additives. The observed wear mechanism in both cases is predominantly mild abrasive wear, but the improved surface finish at the higher load implies that the lubricant's performance is load-responsive, potentially enhancing film strength or additive activation under greater contact stress.

The wear scars for the pin surfaces lubricated with super olein (SPL) blended with antioxidant BHT were shown in Figure 10(a) and 10(b). Both SEM images exhibit parallel abrasive grooves, indicating mild abrasive wear as the dominant mechanism; however, the grooves in Figure 10(b) appear deeper and more defined, suggesting increased material removal at the higher load. Additionally, the presence of wear debris and micro-pits in Figure 10(b) implies localized breakdown of the lubricant film under greater stress. Despite this, the overall wear remains moderate, demonstrating that SPL+BHT formulation offers considerable protection even at elevated loads, likely due to BHT's role in enhancing oxidative stability and supporting boundary film formation to mitigate severe surface degradation.

Figures 11(a) and 11(b) depict the pin surfaces lubricated with super olein (SPL) combined with antioxidant BHA. In both SEM images, the wear mechanism is predominantly abrasive, as evidenced by the presence of parallel grooves; however, Figure 11(b) shows more severe damage with a pronounced central groove and signs of material pull-out or delamination, likely due to lubricant film breakdown at higher contact stress. Additionally, both images reveal wear debris, but their size and frequency increase in Figure 11(b), indicating elevated surface distress. This suggests that while BHA offers oxidative stability and some anti-wear benefits, its performance under higher load is less robust than at lower load, possibly due to limited boundary film reinforcement or thermal degradation under stress. In contrast, the pin lubricated with SPL + BHT exhibited relatively minor wear, with only a few deep furrows and a smoother wear track. This indicates the occurrence of slight adhesive wear. Although some adhesion between the surfaces was observed, it was less severe compared to SPL + BHA. According to Joshy and Manipal, 2021, the increase in surface temperature and shear forces generated by asperity contact leads to the desorption of the physisorbed layer. As the applied load increases, the wear characteristics of the pin surfaces evolve, demonstrating more pronounced wear features (Mussa et al., 2022). Over prolonged sliding motion, material transfer across the contact area becomes evident (Li et al., 2022). Under higher load conditions, the wear patterns on the pin surfaces intensify due to increased contact pressures, which contribute to greater material deformation, adhesion, and wear.

When comparing the tribological performances of the three lubricants – industrial oil, SPL + BHT, and SPL + BHA – it is evident that the industrial oil offers the most stable wear surface under both load conditions, attributed to its well-formulated additive system that maintains effective lubrication and wear resistance. Among the two bio-based lubricants, SPL + BHT demonstrates superior performance over SPL + BHA, particularly under the higher load (1.5 kg), as seen in the SEM images where SPL + BHT maintains smoother wear tracks with less severe surface damage. This difference in performance can be attributed to the molecular structure of the antioxidants themselves. While both BHA and BHT possess a single hydroxyl group responsible for scavenging free radicals, BHT contains two bulky tert-butyl groups in ortho positions, which provide steric hindrance that stabilizes the antioxidant and enhances its thermal and oxidative resistance. This structural advantage allows BHT to better preserve the lubricant film under high stress, thereby reducing abrasive wear. In contrast, BHA has a less hindered structure with lower thermal stability, making it less effective in protecting the surface under increased load, as reflected by the deeper grooves and signs of delamination observed in the SPL + BHA sample.

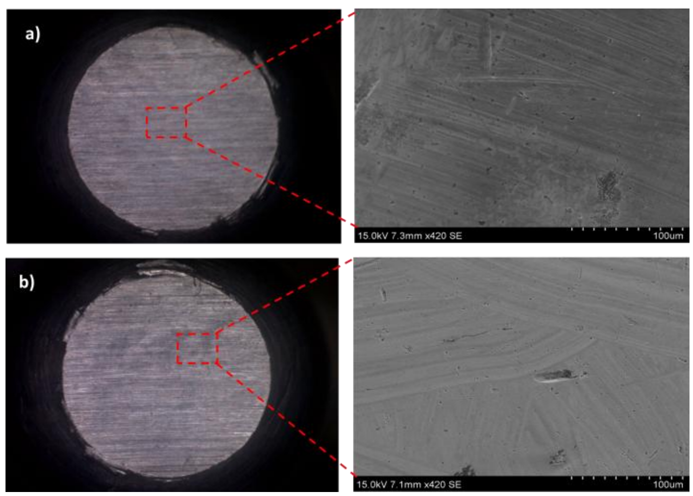

Figure 9: Topography of the pin lubricated by industrial oil with (a) 0.5 kg load (b) 1.5 kg load.

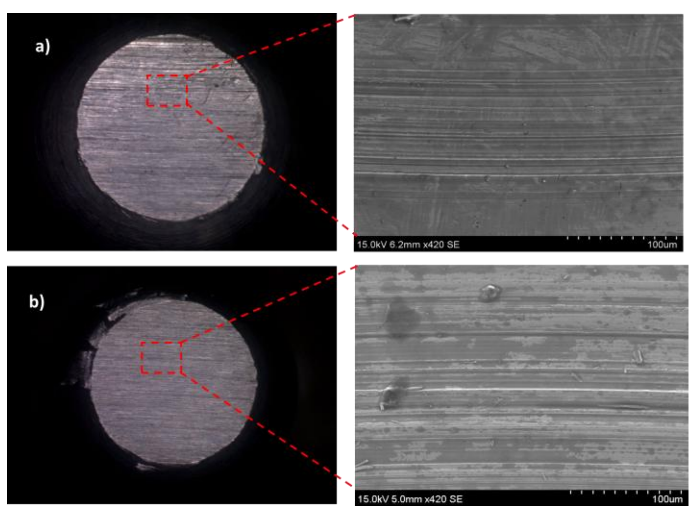

Figure 10: Topography of the pin lubricated by SPL + BHT with (a) 0.5 kg load (b) 1.5 kg load.

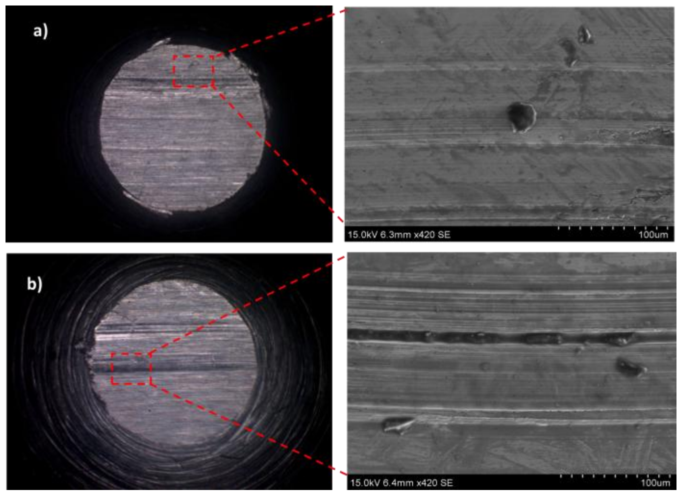

Figure 11: Topography of the pin lubricated by SPL + BHA with (a) 0.5 kg load (b) 1.5 kg load.

4.0 CONCLUSION

In this study, the additives which were BHT and BHA have been added to the bio-based lubricant, super olein, to enhance their properties. The tribological performance of this oil were evaluated and compared to the industrial oil mutually. It can be concluded that:

(1) The coefficient of friction for SPL added with BHT is lower compared to industrial oil by 6.23 % and 18.74 % for SPL added with BHA. This means that the presence of BHT in the oil formulation reduces the resistance to motion between surface in contact.
(2) For wear scar diameter, industrial oil shows a better result with average diameter 867 μm that 30.01 % better than SPL added with BHT and 44.93 % for SPL added with BHA. A smaller wear scar diameter is generally desired as it indicates less wear and damage on the surfaces in contact. The higher wear scar diameters for the SPL oils with additives (BHT and BHA) may suggest that these formulations might not provide as effective lubrication and protection against wear as the industrial oil.
(3) The surface roughness of industrial oil is lower compared to SPL added BHT by 27.19 % and 28.68 % for SPL added with BHA. A higher surface roughness value indicates more irregularities and variations in the texture of the surface.
(4) The SPL added BHT shows a better topography of the pin compared to SPL added with BHA. A better topography suggests that the surface of the pin in contact with the oil is smoother, more uniform, and potentially less prone to wear or damage.

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