

The Thermo-physical and Tribology Characteristics of Green Hybrid TiO_2 : SiO_2 Nanolubricants

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ABSTRACT

Minimum Quantity Lubrication (MQL) is one of the emerging sustainable techniques in the machining process nowadays. MQL reduces heat at the cutting zone through a small quantity of lubrication supplied in the form of mist. However, conventional MQL has limitations in hard-to-cut materials such as Inconel. Hence, nanolubricant minimum quantity lubrication (NMQL) is explored in due to enhancement in the thermal conductivity and viscosity properties. This paper reviews the thermos-physical and tribology properties of the hybrid nanolubricants in green palm oil with volume concentrations of 0.01%, 0.03%, 0.05%, 0.07%, and 0.1% of TiO_2 : SiO_2 (60:40). There was stability assessments made which were visual sedimentation inspection, absorbance value from Uv-Vis spectrophotometry and the Zeta test. Meanwhile, the thermos-physical properties of thermal conductivity and dynamic viscosity were also evaluated. Finally, the performance in tribology properties was gauged using Koehler four-ball tribology tester to analyse coefficient of friction (COF), and wear scar diameter (WSD). The lowest COF and WSD were obtained at a volume concentration of 0.03%. In conclusion, it is feasible to adopt TiO_2 : SiO_2 (60:40) in palm oil as an alternative green nanolubricant MQL since it has demonstrated better tribology performance as compared to base fluid of palm oil.

Keywords: Green nanolubricant; TiO_2 : SiO_2 ; palm oil; thermo-physical; tribology

INTRODUCTION

Implementing environmentally friendly machining is crucial for accomplishing sustainable development. The drastic growth in machining production nowadays has required a more robust metal working fluid (MWF) standard. The reason MWF is used is to remove heat, lubricate, prevent corrosion, and wash off metal chips from the working area. The limitation of conventional, mineral oil-based cutting fluids is that they can pollute water and soil when disposed into the environment. Furthermore, there is also health risks for workers, especially for operators that are involved directly with the machining process using conventional lubricants for long working hours (Fernando et al. 2019). Thus, the sustainable goal of

the machining process is to use less cutting fluid while maintaining or improving the cutting performance.

In comparison to traditional flood cooling systems, MQL is more effective in significantly reducing grinding forces, wear, and surface roughness of workpiece materials (Dambatta et al. 2018). It has also outperformed conventional flood cooling systems in terms of performance (Zulkifli et al. 2023). The conventional MWF supply flood, it is hard to reach the tool-workpiece, hence Minimum Quantity Lubricant (MQL) supplying in the form of fine mist can reach the area and reduce the heat removal process. Additionally, the MQL technique was shown to have better tribological qualities, safer, and more environmentally friendly (Dambatta et al. 2019).

Lubricants are essential in reducing friction and wear in mechanical systems, allowing these systems to operate

for longer periods while also promoting environmental conservation (Hamisa et al. 2023). Moreover, lubricants protect machinery by minimizing wear and friction on moving parts, preventing corrosion, dissipating heat, and facilitating power transfer (Pandey & Sharma, 2018). As outlined by Yeoh Jun et al. (Jason et al. 2020), lubricants can exist in three physical states which are solid, semisolid, and liquid. Commercially available lubricants are formulated by blending various base oils and additives. The main types of base oils are vegetable, synthetic, and mineral oils (Kotia et al. 2018). Vegetable oils-based cutting fluids commonly include oils such as palm, soybean, castor, sesame, olive, coconut, and other similar vegetable oils (Kazeem et al. 2022). Furthermore, a study on the use of bio-metalworking fluid (bio-MWF) from treated cooking oil (palm oil) (TRCO) in machining AISI 4340 alloy steel, it is chosen for its availability and non-edibility resulted in improvement in cutting force and surface roughness compared to dry cutting, with lower cutting forces and enhanced surface finish achieved (Ahmad et al. 2022).

Research on the improvement of MQL has now been aggressively done through the addition of nano-sized particles into the cutting fluid. This will enhance the cooling and lubricating properties of the base fluid in terms of wear resistance, permeability, and thermal conductivity which can be enhanced by using nano MQL (NMQL) (He et al. 2023). The technique of NMQL with vegetable cutting fluid can increase the surface quality of a product while reducing power consumption and approaching sustainable manufacturing (Abbas et al. 2019).

The efficiency of oil as a lubricant is greatly influenced by characteristics such as the rate of cooling that increases as thermal conductivity is increased. The factor of volume concentration of nanoparticles in a biodegradable base lubricant has to be optimum, as the higher concentration of nanoparticles may result in agglomeration, which is defined as the particles clumping together, preventing nanoparticles from depositing surface irregularities. Every variable has effects on the tribological performance of nanoparticles combined with lubricants (Panda et al. 2022). Lubricant parameters including viscosity, pressure properties, wear scar diameter (WSD), coefficient of friction (COF), and load-bearing capacity have all shown notable improvements with the addition of nanoparticles that can enhance the performance of the lubricant (Singh et al. 2019).

The current machining industry is pushing towards green manufacturing using nano lubricants in biodegradable palm oil (Ibrahim et al. 2020). The additive of nanoparticles can increase the heat transfer when used for the machining process as it is high in thermal conductivity, high contact surface as well as improved Brownian motion dispersion.

Hence, the cutting fluid's lubrication and thermal properties are enhanced by the small size of the nanoparticles (Chinchani et al. 2021). Furthermore, a study by Das et al. on high strength and durability metal on AISI 4340 steel under turning machining process using nanolubricant Al_2O_3 , Fe_2O_3 , and CuO dispersed in rice bran oil has shown improvement in terms of surface tension, contact angle, thermal conductivity, and viscosity as compared to traditional cutting fluid (Das et al. 2019). The usage of nanolubricants in machining operations has resulted in positive effects on resolving the heat dissipation issue while working with difficult-to-cut materials. This is due to the lower thermal conductivity in base fluids as compared to nano-cutting fluids (Said et al. 2019).

The thermo-physical properties of nanofluids are further improved with the introduction of the hybrid nanolubricant. It is reported that the 0.01% TiO_2/PVE , 1.00% SiO_2/PVE , and 0.01% $\text{TiO}_2\text{-SiO}_2$ nanolubricants have proven to aid heat transfer with the increment in the thermal conductivity and dynamic viscosity (Ismail et al. 2023). Another finding by Jason et al. showed that at a volume concentration of 0.03%, the $\text{TiO}_2\text{-SiO}_2/\text{POE}$ hybrid nanolubricant demonstrated the greatest reduction in WSD, ultimately reaching 12.4% (Hamisa et al. 2023). The hybrid nanolubricant of $\text{SiO}_2\text{-TiO}_2/\text{PAO}$, in a volume concentration of 0.01%, has demonstrated the maximum decrease in COF, measuring 2.53% or 0.97 (Ismail et al. 2024).

In comparison to dry and flood machining, the nano MQL was not only observed to have a better surface finish, and lower cutting forces, but also save power consumption and higher tool life (Shafi et al. 2018). A study on the NMQL of 0.5 vol% hBN with Ester-based cutting oil stated that the additive of nanoparticles in MQL has resulted in better tool life and surface roughness when compared to dry machining (Yıldırım et al. 2019). The improved thermal conductivity in NMQL has enabled better heat transfer in of tool-workpiece interface (Balasudhakar et al. 2023). In addition, NMQL is a better option when it comes to handling outstanding qualities at high temperatures such as Inconel, a nickel-based super alloy because it is difficult to retain its qualities at high temperatures for extended periods without changing the Inconel metal properties.

Studies by Naresh Babu et al. (Naresh Babu & Muthukrishnan, 2020), stated that there is an improvement using copper nanofluid under MQL in comparison to dry machining and oil machining which has resulted in reduced tool wear of 36%, and a 24% improvement in surface roughness. In another study, the NMQL with vegetable cutting fluid showed a decrease in cutting force of 27.4%, and an improved of surface roughness of 33.8% (Pal et al. 2020).

This study aims to evaluate the effectiveness of 0.01%, 0.03%, 0.05%, 0.07%, and 0.1% of $\text{TiO}_2\text{:SiO}_2$ (60:40)

nanoparticles green lubricant of palm oil. The green nanolubricant is assessed for its stability, thermo-physical characteristics, and tribological behaviors. At the end of the study, the most significant improvement in the four-ball test in terms of coefficient of friction (COF), and wear scar diameter (WSD) was recommended as the most feasible green nanolubricants of $\text{TiO}_2\text{:SiO}_2$ (60:40) for NMQL.

METHODOLOGY

THE PREPARATION OF NANOLUBRICANT

The experimental study utilised hybrid nanoparticles of TiO_2 and SiO_2 in a 60:40 ratio, with average dimension of 50nm and 30nm respectively. The TiO_2 of 99.9% high purity level was sourced from HWANO, while the SiO_2 with 99% purity, was obtained from Guangzhou Jiechuang Trading Co., Ltd. The physical properties of TiO_2 and SiO_2 are presented in Table 1. The base fluid for the green nanolubricant was palm oil, supplied by Delima Oil Products. The specifications of the palm oil lubricant in Table 2.

The nanolubricants were prepared using a two-step method, selected based on its ability to enhance the stability of the resulting nanolubricants as demonstrated in previous studies by (Idris et al. 2021). The volume concentration of 0.01%, 0.03%, 0.05%, 0.07%, and 0.1% of $\text{TiO}_2\text{:SiO}_2$ were then prepared in 60:40 ratio. The weight of the nanoparticles for a given volume concentration of nanolubricants was determined based on Equation (1). A similar equation has been used in other studies to produce nanolubricants (Ismail et al. 2024).

$$\phi = \frac{\frac{m_n}{\rho_n}}{\frac{m_n}{\rho_n} + \frac{m_{base}}{\rho_{base}}} \times 100\% \quad (1)$$

Where ϕ (%) refers to the volume concentration of nanolubricant, m_n (kg) is the mass of the nanoparticle, ρ_n (kg/m^3) is the density of nanoparticles, m_{base} is the mass of base palm oil and ρ_{base} is the density of base palm oil. The required nanoparticle was measured using a high-precision analytical balance. A surfactant, 0.5% volume of Triton X - 114 was added to the prepared nanolubricants to enhance stability. The surfactant reduces surface tension and improves the dispersion of solid particles within the liquid medium (Sezer et al. 2019). Subsequently, each sample was stirred using a magnetic stirrer for 30 minutes,

followed by sonicate for 2 hours. The sonication process employs high-frequency vibrations was utilised to achieve uniform dispersion of nanoparticles within the palm oil-based lubricant (Hisham et al. 2024). The preparation apparatus is depicted as in Figure 1.

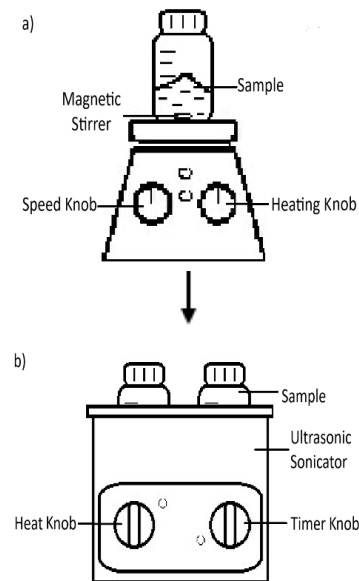


FIGURE 1. The preparation of nanolubricants; (a) magnetic stir (b) ultrasonic sonicator

STABILITY OF $\text{TiO}_2\text{:SiO}_2$ (60:40) IN PALM OIL

The stability of nanolubricants was assessed using three methods to prevent nanoparticles sedimentation and aggregation at the bottom of the test tube, which would indicate instability (Ismail et al. 2023). Initially, a qualitative approach was employed called visual sedimentation observation. Nanolubricants samples were observed after the preparation day and were continuously observed over a period of one month.

TABLE 1. Properties of $\text{TiO}_2\text{:SiO}_2$ (Ismail et al. 2023)

Property (s)	Unit	TiO_2	SiO_2
Density	kg/m^3	4230	2220
Molecular mass	g/mol	79.87	60.08
Average particle diameter	nm	50	30
Specific heat	$\text{J}/(\text{kg}\cdot\text{K})$	692	745
Thermal conductivity	$\text{W}/(\text{m}\cdot\text{K})$	8.4	1.4

TABLE 2. Properties of palm oil (Karmakar et al. 2017)

Vegetable Oils	Iodine value	Pour Point (°C)	Cloud Point (°C)	Kinematic Viscosity at 40 °C (mm^2/s)	Flash Point (°C)	Density at 15 °C (g/cm^3)
Palm oil	48-58	23.6	25.2	39.4	252	0.919

The second method of inspection was UV-Vis spectrophotometry as depicted in Figure 2. The instrument used was Jasco/V 670-EX UV-Vis, which operates within a measurement range of 190 to 3200 nm and has an accuracy of ± 0.3 nm. The UV-Vis measures absorbance, representing the amount of light absorbed by nanolubricant, and transmittance, which indicates the amount of light passing through the sample. Five different sonication durations were analysed, including samples of 0 hours,

without any ultrasonication while other nanolubricants were sonicated for 30 minutes, 1 hour, 1.5 hours, and 2 hours. The final method used to evaluate stability was zeta potential analysis, conducted with a nanolubricant concentration of 0.01%. The zeta potential measurements were performed using the Malvern Zetasizer, as shown in Figure 3. Absolute value readings of more than 60 mV are said to be in excellent stability (Khalid et al. 2021).

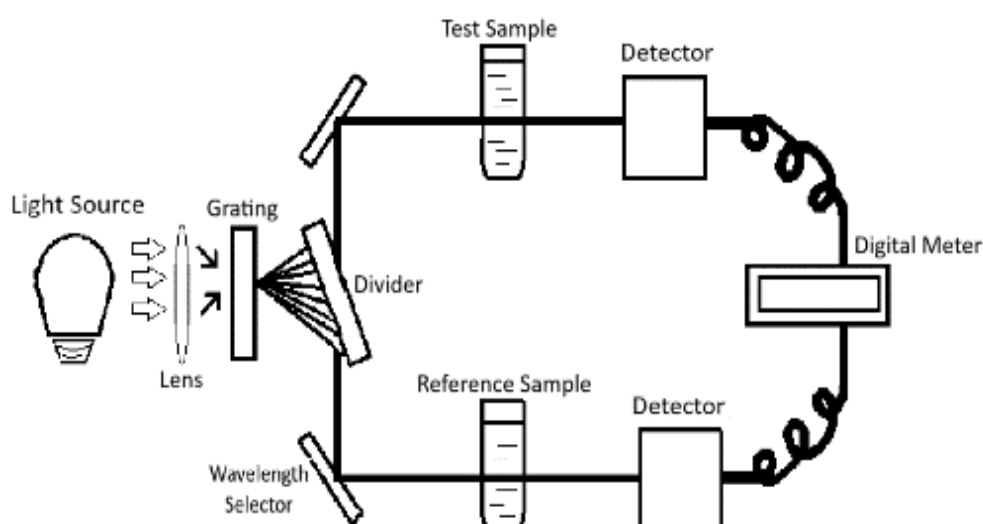


FIGURE 2. UV-Vis spectrophotometry

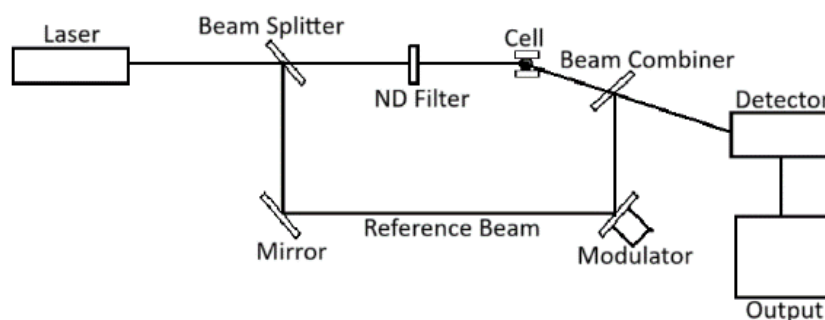


FIGURE 3. Malvern Zetasizer machine

THERMOPHYSICAL PROPERTIES MEASUREMENT

The thermo-physical properties evaluated in the study included dynamic viscosity and thermal conductivity. For the dynamic viscosity measurements, 15 ml of nanolubricant with concentrations of 0.01, 0.03, 0.05, 0.07, and 0.1 TiO₂: SiO₂ (60:40)/Palm oil were prepared and measured using the Digital Rheometer Electronic 301 as shown in Figure 4. The temperature was varied between 28°C to 90 °C to analyse the viscosity behaviour.

The thermal conductivity was evaluated based on the established Maxwell model as represented in Equation (2) (Bellos & Tzivanidis, 2018).

$$\phi = \frac{\frac{m_n}{\rho_n}}{\frac{m_n}{\rho_n} + \frac{m_{base}}{\rho_{base}}} \times 100\% \quad (2)$$

Where k_{nl} is the thermal conductivity of nanolubricant, k_n is the thermal conductivity of nanoparticles, TiO₂: SiO₂ (60:40), and k_{base} is the thermal conductivity of base palm oil and ϕ is the volume concentration of nanolubricant.

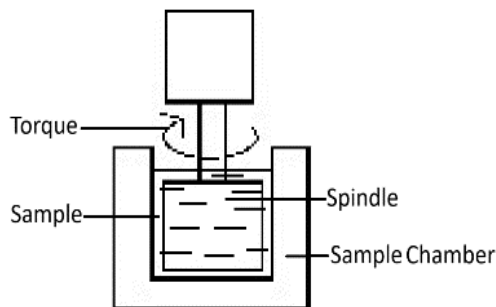


FIGURE 4. Digital Rheometer Electronic 301

TRIBOLOGY PROPERTIES MEASUREMENT

For the tribological testing, a Koehler Four-Ball Tester was utilised, as shown in Figure 5. The test was performed in accordance with ASTM D4172 – 18 (Hamisa et al. 2023) to measure the coefficient of friction and the wear scar diameter. Each test utilised four steel balls with diameter of 12.7 mm, hardness of 60 (±0.2) HRC, chromium steel grade G20, ISO 3290 specifications.

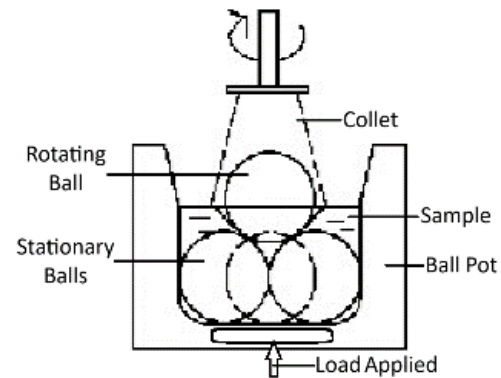


FIGURE 5. Koehler four-ball test machine

The experiment was conducted at 75°C, each test was conducted for 60 minutes. The consistency of temperature throughout the experiment was ensured by a preprogrammed temperature controller. The rotation speed was set at 1200 RPM with load of 40 kg at the lever arm. The four-ball test was repeated three times to ensure the reliability. Afterward, the dimensions of the wear scar were measured using Optical Microscope (Light Compound Microscope).

RESULTS AND DISCUSSION

EVALUATION ON THE STABILITY OF NANOLUBRICANT

SEDIMENTATION OBSERVATION

The stability of the nanolubricants was monitored from the day after preparation until the 30th day of preparation. This practice is aligned with other researcher's practice such as Kamarulzaman et al. who similarly observed the stability of CNC-CuO nanoparticles in engine oil for 30 days, noting that the nanolubricant remained well-mixed without agglomeration at the base of the test tube in the first week. However, a clear layer began to form at the top of the nanolubricant thereafter (Kamal Kamarulzaman et al. 2023). In the present study, comparison was made every 5 days using a single concentration of 0.03% TiO₂: SiO₂ (60:40)/Palm oil, and the effect of sonication duration was observed. Five sonication hours which are 0 hours (no

sonication), 30 minutes, 1 hour, 1.5 hours, and 2 hours. The result of the visual observation can be seen in Figure 6. All samples appeared muddy and yellowish on the first day of observation, with no visible nanoparticles clumps at the test tube base, indicating the stability of the prepared samples as shown in Figure 6 (a). Over time, the samples' yellowish colour intensities gradually decreased. By the 20th day, a faint sedimentation line became visible as shown in Figure 6 (d), with minor sediment accumulate at the bottom of the test tube. By the 30th day as shown in Figure 6 (f). The separation between layers became more obvious. Comparatively, it also highlighted that samples with 2 hours sonication had the highest stability samples, while samples without sonication (0 hours) have the least stability. Based on these observations, 2 hours sonication time was selected for the preparation of samples used in the thermo-physical properties' assessments.

UV-VIS ANALYSIS

The stability of the nanolubricants with a concentration of 0.003% TiO_2 : SiO_2 (60:40)/Palm oil, subjected to varying sonication hours of 0, 0.5, 1, 1.5 and 2 hours, was assessed at a wavelength of 364 nm. This wavelength was selected based on the peak wavelength detected for the 0.003% TiO_2 : SiO_2 (60:40)/Palm oil, as shown in Figure 7. The influence of sonication time on nanolubricant stability is illustrated in Figure 8, where the lowest stability was observed for the sample with 0 hours sonication, as expected. Conversely, the 2 hours sonicated sample exhibited the highest stability. These results align with the findings of Zawawi et al. (Zawawi et al. 2019) who also identified 2 hours sonication the optimum for excellent stability. Initially, the nanolubricants had the murkiest colour, resulting in the highest absorbance, as less light passed through the samples. After the 19th day, sedimentations began, allowing more light to pass through and causing significant reduction in absorbance. In comparison to other samples, the 2 hours sample remained the most stable throughout the observation period.

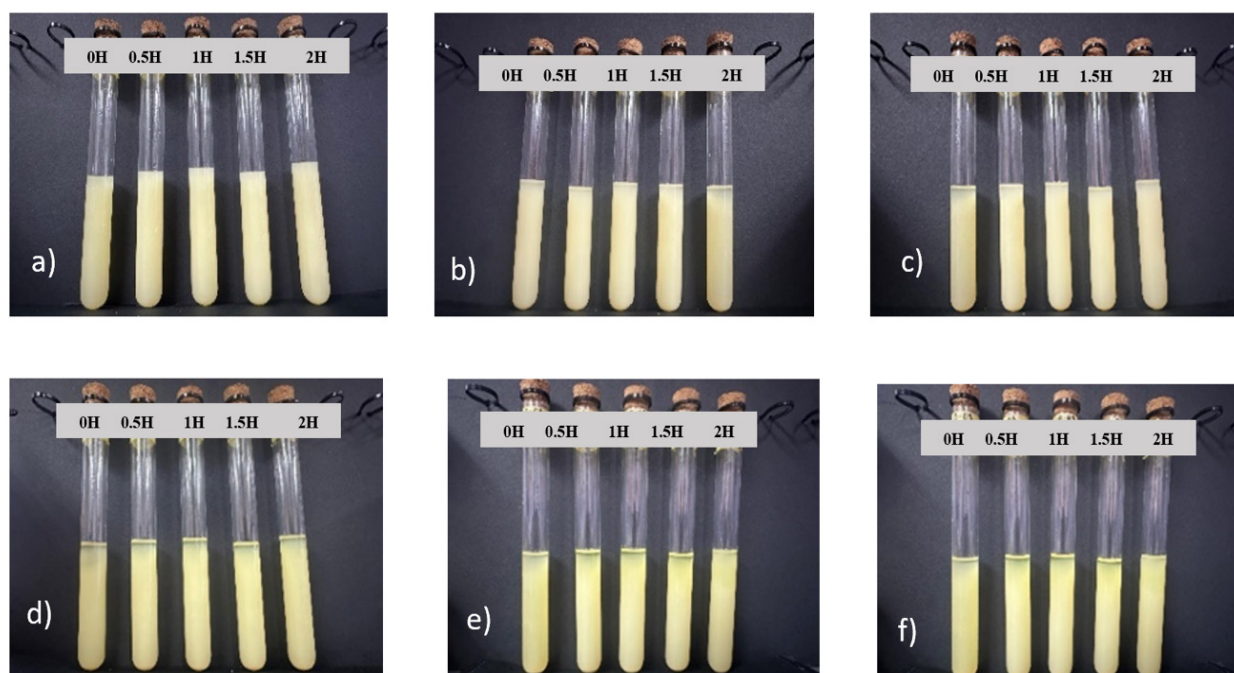


FIGURE 6. Sedimentation observation for 0.03% TiO_2 : SiO_2 (60:40)/Palm oil (a) After Preparation; (b) 5th day; (c) 10th day, (d) 20th day; (e) 25th day and; (f) 30th day

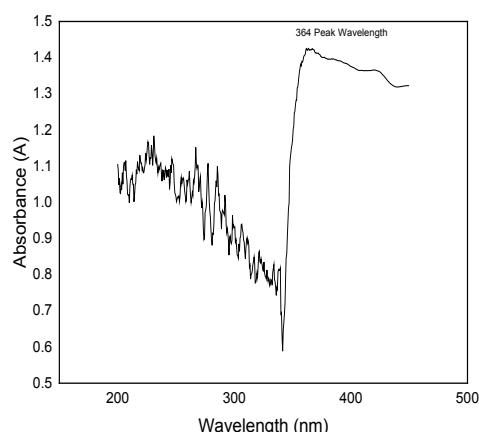


FIGURE 7. Highest wavelength for volume concentration 0.003% TiO_2 : SiO_2 (60:40)/Palm oil nanolubricant

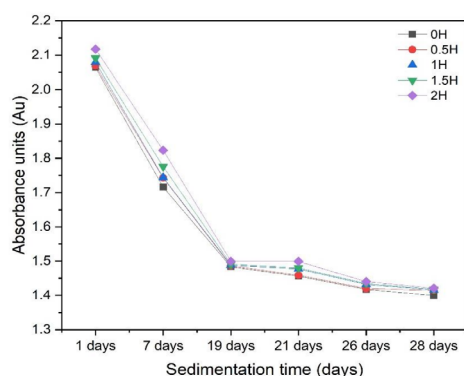


FIGURE 8. Effect of sonication duration towards absorbance unit of 0.003% TiO_2 : SiO_2 (60:40)/Palm oil nanolubricant

The relationship between volume concentration and absorbance was also examined, as depicted in Figure 9. The absorbance was linearly increased as the volume concentration was varied from 0.0001 to 0.003 %. This observation aligns with the Beer-Lambert law, which states that absorbance (A) increases proportionally with volume concentration (ϕ) (Zawawi et al. 2019).

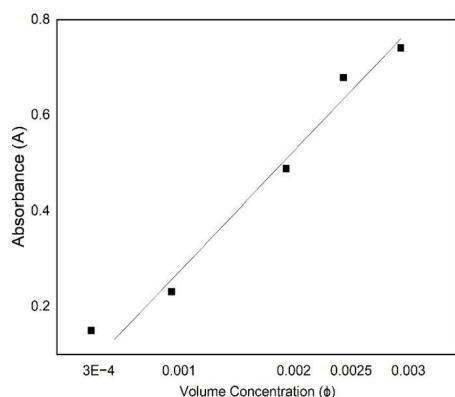


FIGURE 9. Beer-Lambert correlation

ZETA POTENTIAL

Finally, the stability of the nanolubricants was evaluated using Zeta Potential analysis. According to Hamisa et al (Hamisa et al. 2023), the optimum stability of a nanolubricant should be 60mV or higher. As shown in Figure 10, the zeta potential of the prepared sample with a 0.01% volume concentration of TiO_2 : SiO_2 (60:40)/Palm oil was measured at 266mV, indicating that the sample exhibits excellent stability.

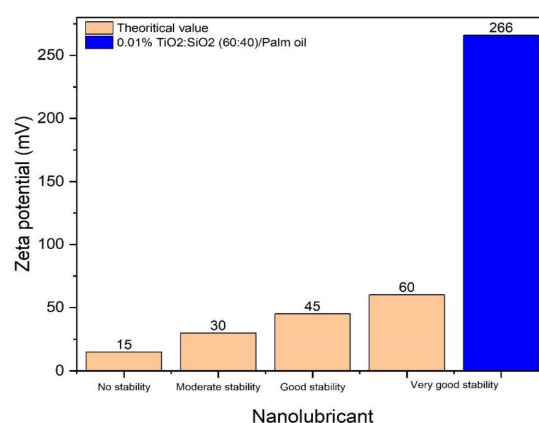


FIGURE 10. 0.01% TiO_2 : SiO_2 (60:40)/Palm oil zeta potential

PROPERTIES OF THERMO-PHYSICAL

DYNAMIC VISCOSITY OF NANOLUBRICANTS

In terms of thermo-physical properties, dynamic viscosity is a crucial factor due to its direct influence

on tribological performance. The higher dynamic viscosity is preferred, as it will result in better tribology properties. The effect of temperature on the dynamic viscosity is illustrated in Figure 11, where it was observed that the dynamic viscosity decreased as temperature increased. This reduction is due to an increase in the kinetic energy of the molecules at higher temperatures, which weakens intermolecular forces and thus lowers viscosity (Mande et al. 2024). In general, 0.1% volume concentration consistently exhibited the highest dynamic viscosity across all temperature ranges. In contrast, the base oil showed the lowest dynamic viscosity throughout the experiment.

The detailed view of the measured dynamic viscosity is presented in Figure 12, where it was observed that the viscosity increased as the nanoparticle concentrations were increased. The highest dynamic viscosity was recorded for the 0.1% volume concentration, showing a 6.57% increase compared to base fluid at 57°C. Higher concentrations of nanolubricants resulted in more friction between the

particles due to additional nanoparticles as compared to lower concentration quantities (Idris et al. 2024).

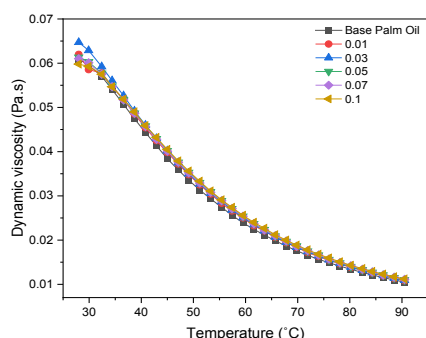


FIGURE 11. Dynamic viscosity effect against temperature variation

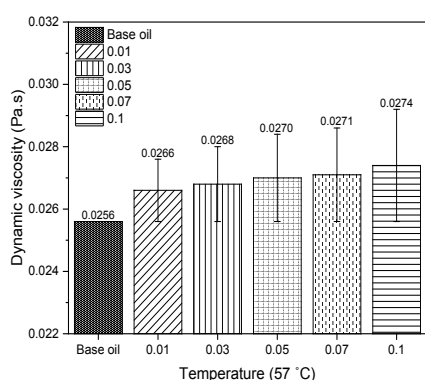


FIGURE 12. Detailed view on volume concentration effect to the dynamic viscosity at temperature of 57°C

THERMAL CONDUCTIVITY OF NANOLUBRICANTS

In terms of thermal conductivity, the nanolubricant with a 0.1% volume concentration of $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil demonstrated the highest thermal conductivity, with a 33% improvement over the base palm oil. Conversely, the base palm oil exhibited the lowest thermal conductivity. This trend is similar to the research on green Bio-glycol-based $\text{TiO}_2\text{-SiO}_2$ nanofluids exhibited a thermal conductivity enhancement of up to 12.52% as compared to the base fluids of the W/BG mixture (Zainon & Azmi, 2021).

The relationship between thermal conductivity and volume concentration in this study is shown in Figure 13. The nanolubricant with 0.1% $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil achieved the highest thermal conductivity of 33% improvement over the base lubricant, which had a thermal conductivity of 0.167W/m.K. This was followed by 0.07% and 0.05% $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil nanolubricant with 0.22% and 0.15% improvement as compared to base palm

oil. The enhanced thermal conductivity in the nanolubricants can be attributed to the increased Brownian motion of the nanoparticles. The random motion of particles within the fluid enhances thermal dispersion by allowing more effective heat transfer between the active particles and the palm oil base molecules (Zailan et al. 2024).

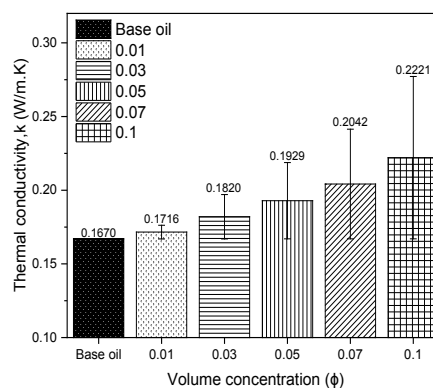


FIGURE 13. Thermal conductivity against volume concentration of nanolubricants

TRIBOLOGY PROPERTIES

COEFFICIENT OF FRICTION OF NANOLUBRICANTS

The coefficient of friction for $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil at various concentrations is shown in Figure14. Research by Al-Janabi et al. (2024)

reported that high value of coefficient of friction for the nanolubricants sample due to the boundary lubrication regime, where the two surfaces in direct contact without lubricant separating the surfaces (Al-Janabi et al. 2024). The highest improvement in COF was observed with the 0.03% concentration, followed by 0.05%, 0.07%, 0.01%, base oil, and finally 0.1% concentration. The COF values exhibited fluctuations over time, with a relatively stable pattern observed between 20 to 40 minutes. A higher volume concentration of nanoparticles as an additive to the base oil does not necessarily show a better COF as the optimal volume concentration is 0.03%.

The highest volume concentration of nanoparticles studied, which is 0.1% did not achieve the expected improvement in COF. Instead, 0.03% $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil is the threshold value in this hybrid combination. The COF of 0.1% is moreless similar to base palm oil COF which is less significant in terms of beneficial in tribology improvement. This improvement can be attributed to the formation of a tribo-film on the worn surfaces, which acts as a solid lubricant filling surface gap, or the presence of

an exceedingly thin lubricating layer that minimizes shear stress.

Additionally, the mobility of nanoparticles between the contact surfaces plays a crucial role, as it transforms pure sliding friction into rolling friction, thereby reducing interfacial frictional surface action (Ismail et al. 2024). A study conducted by Htwe et al. states that nanoparticles were found to tend to aggregate into large, micro-scale clusters hindering further friction and wear. Therefore, an optimal concentration of nanoparticles is crucial to effectively reduce coefficients of friction and wear (Htwe et al. 2024).

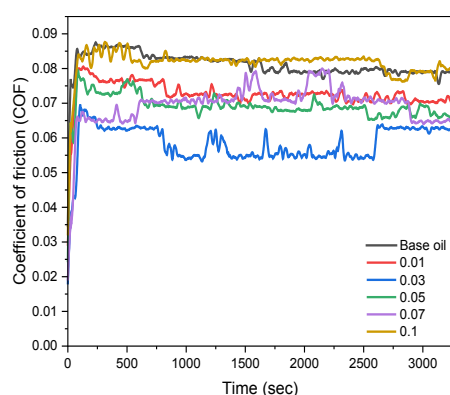


FIGURE 14. Coefficient of friction against time

The findings are well supported by a similar trending of the Al_2O_3 -PAG (polyalkylene glycol) nanolubricants of studied at volume concentrations of 0.01%, 0.03%, and 0.05%. It was conducted at 1200 rpm and a load of 40 kg. The results indicated that a concentration of 0.03% produced the greatest reduction in COF by 0.0078% as compared to the base fluid (Safil et al. 2024).

WEAR SCAR DIAMETER (WSD)

Another tribology characteristic examined was the wear scar diameter (WSD) for various concentrations of $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil nanolubricants. As shown in Figure 15, the base palm oil exhibited the largest WSD at 0.5902mm. The volume concentration of 0.03% of $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil resulted in a notable 19.5% reduction in WSD. This was followed by 0.05% and 0.07% concentrations, which reduced WSD by 7.2% and 6.5%, respectively. The addition of nanoparticles to the base lubricant has enhanced the lubricant's load-carrying and prevented wear properties.

The same pattern of findings is also reported by Kulkarni et al. (Kulkarni et al. 2024) who studied the effect of hardness in Al_2O_3 and TiO_2 nanoparticles in 0.4 vol%,

0.25 vol% and 0.1vol% effect towards wear diameter improvement. The study highlighted that the average concentration of 0.25 volume % has resulted in the lowest wear scar diameter also due to the effect of a moderately harder material (TiO_2) as compared to 0.4 vol% of a harder material (Al_2O_3) which has resulted in bigger wear scar diameter.

The nanoparticles' ability as an effective anti-wear in lube is influenced by the relationship between the concentration and material hardness which the study emphasizes, highlighting the necessity of increasing the two components for improved non-wear characteristics for samples.

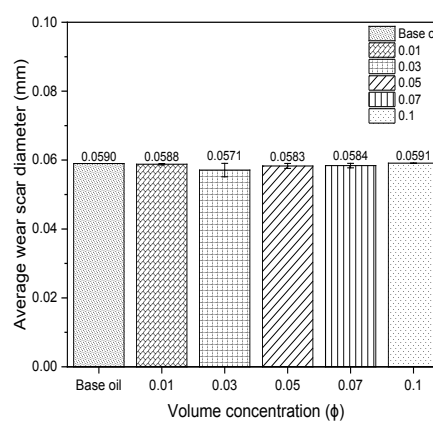


FIGURE 15. Average wear scar diameter against volume concentration of nanolubricant

Figure 16 illustrates the wear scar diameter as observed under an optical microscope, which was used to measure the length of the scar on the steel ball.

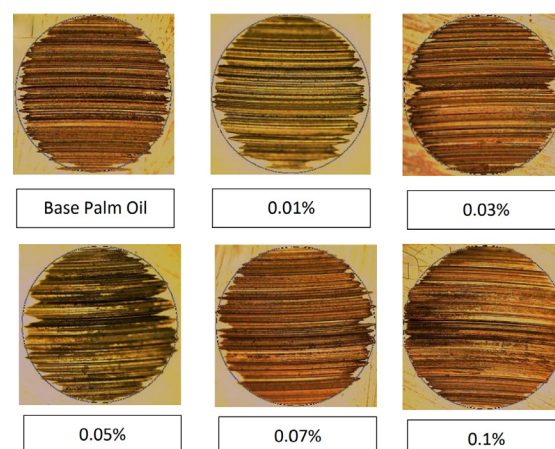


FIGURE 16. Average wear scar diameter against volume concentration of nanolubricant

CONCLUSION

In conclusion, the $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil nanolubricants were comprehensively investigated in this study which covered the stability of the preparation, the thermo-physical properties measurement, and the tribological characteristics. The stability of the samples prepared was confirmed based on visual inspection, UV vis spectral measurement, and also zeta potential measurement. It was confirmed that the samples prepared were in an excellent stability region and the preferred sonication duration is 2 hours to ensure maximum stability.

Meanwhile, the thermo-physical nanolubricants characteristics show that the dynamic viscosity and thermal conductivity of the $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil nanolubricants was improved by 6.34% at 90°C and 33% respectively as compared to the base lubricant of palm oil with the 0.1 vol %. concentration. Finally, on the tribological characteristics, the $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil has shown improvement in COF and WSD as compared to the base palm oil. It was also highlighted that the threshold value for both COF and WSD was given by 0.03% volume concentration of $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil nanolubricants. Any further addition of nanoparticles to this hybrid combination exceeding 0.03% volume concentration of $\text{TiO}_2\text{:SiO}_2$ (60:40)/Palm oil nanolubricants may not be beneficial to the tribological characteristics. However, further experimental work in actual application should be performed to validate such findings.

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DECLARATION OF COMPETING INTEREST

None.

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