

Tribological Analysis of Treated Recycled Vegetable Oil-Based Lubricants for MQL Machining



Zulaika Zulkifli, Nurul Hayati Abdul Halim*, Ahsana Aqilah Ahmad, Zainoor Hailmee Solihin

School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia.

*Corresponding Author:



ABSTRACT: Machinability in metal cutting is heavily reliant on the cutting fluids to lubricate and reduce friction and wear between surfaces. Thus, this study investigates the tribological performance of treated recycled vegetable oil (TRVO) as a sustainable biodegradable lubricant in minimum quantity lubrication (MQL) machining. The used palm-based cooking oil was recycled and treated through a series of filtering processes, which was then characterized for its viscosity. Its tribological performance was analysed through pin-on-disc tests using a tribometer with uncoated tungsten carbide pins and mild steel discs. The study mimicked the milling cutting condition by employing tool material for the pin and replicating the wear, frictional force, coefficient of friction, and pin temperature that are typically observed in milling processes. The sliding tests showed TRVO, with a viscosity of 41.05 cSt, led to an average wear, frictional force, coefficient of friction, and pin temperature of 16.219 μm , 0.1494 N, 0.0013, and 23.80 $^{\circ}\text{C}$, respectively after 1 hour of running. The continuous rubbing action also affected heat-dependent variables such as surface roughness and microhardness which correlated strongly with the tribological properties of TRVO. The findings demonstrate the potential of TRVO as an effective for conventional cutting fluids, promoting sustainability in the machining processes.

KEYWORDS: Treated Recycled Vegetable Oil, Minimum Quantity Lubrication, Sustainable Machining; Pin-on-disk Test, Tribology.

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I. INTRODUCTION

Minimum Quantity Lubricant (MQL) is one of the sustainable machining approaches with the main aim of reducing the consumption of cutting fluid in metal cutting without compromising its function as a surface lubricator. In metal cutting, the lubrication effect supplied by the Metal Working Fluid (MWF) is crucial to reduce the sliding friction between the tool-workpiece and tool-chips interface in order to reduce the heat that is inherently generated (Yan et al., 2016). As highlighted by Nallasamy et al. (2018), almost 50% of the lubricants used during cutting end up in the environment. Thus, the MQL approach is introduced where the consumption of MWF is in the form of mist flow at almost 100 times lower than those used in conventional flood cutting (Halim et al., 2020). According to Roy et al. (2019), the cutting fluid consumption in MQL is very little; thus, further disposal processes of the fluid are not necessary as it gets vapourized during machining. This action maximizes its effectiveness in meeting the objectives of sustainable machining which includes reducing energy consumption, waste, and cost, as well as for better operational safety and personal health (Dawood et al., 2015). Despite its proven effectiveness in enhancing machining performances and sustainability, research on MQL keeps growing with the current interest in developing

alternatives for the MWF that are greener, cost-effective, safe, as well as offer biodegradability aspect (Pereira et al., 2016; Faga et al., 2017; Halim et al., 2020). This also aligned with global eco-awareness on the rise and strict regulations of MWF, particularly on its effect on humans as well as the environment, associated with petroleum and mineral oils of MWFs.

As of today, about 95% of the MWF's used by industries are mineral and synthetic-based. These types of oils potentially improve machining performances. However, the majority of them are not biodegradable, and their low viscosity index may cause insufficient lubrication film that leads to higher friction and significant heat generation at tool chip contact surfaces (Talib et al., 2019). For the safety aspects, the MQL mist that is produced using mineral-based cutting oil exposes the workers to health risks such as skin and eye irritation, respiratory problems, and cancers (Musavi & Davoodi, 2020). For instance, Raynor et al. (2005) discovered that using commercial oil produces aerosol or mist that is 30% to 90% higher than vegetable oil. To address these concerns, bio-based lubricants such as vegetable oils and neem oil emerge as an excellent alternative to traditional MWF due to their eco-friendliness, lower toxicity, affordability, and renewability (Padmini et al., 2015; Panneer & Panneerselvam, 2020). These bio-lubricants exhibit exceptional lubricating properties, such

as high lubricity, high viscosity index, high flash point, and low volatility. However, different sources of lubricants offer different characteristics that also influence the machining performance differently. As stressed by Dawood *et al.* (2015), careful consideration must be taken when choosing the right lubricant for the MQL cutting as most machining performances, such as tool wear rate and surface roughness, highly depend on its capability to lubricate the contacts and dissipate heat during cutting.

According to Khot and Borah (2015), tribology is the study of surfaces in motion relative to each other which includes the principles of friction, lubrication, and wear, along with their practical applications. In machining, tribological performances refer to the effectiveness of a lubricant in managing friction, wear, and heat generation at the interface between the cutting tool and the workpiece. The viscosity of the lubricant also plays a key role during the cutting process as it forms a thin sacrificial layer that acts as a friction and wear reducer at the contact point (Sahab *et al.*, 2017). This layer is essential in tribology as it functions to minimize direct contact between the tool and workpiece, thus reducing wear and friction. Furthermore, lubricants with higher viscosity provide a higher load-carrying capacity that is significant in reducing friction, as well as the wear rate of the interacting surfaces. The tribological performance of the lubricant is further enhanced by its ability to maintain this stable lubrication film, even at extreme cutting temperatures, with minimal loss of oil volume due to vaporization, as reported by Talib *et al.* (2019). This stable film ensures continuous protection against wear, extending the tool's lifespan and improving the overall efficiency of the cutting process.

The potential of vegetable oils such as coconut oil, sunflower oil, canola oil, and sesame oil to replace the MWF as cutting fluids in machining applications has been continuously investigated. Most researchers have observed the superiority of vegetable oil-based cutting fluids over traditional mineral oil-based in terms of reduced surface roughness and tool wear, lower cutting forces, and increased tool life (Padmini *et al.*, 2015; Pereira *et al.*, 2016). Recently, investigations have been directed toward the suitability of recycling used vegetable oils in various machining applications (Ahmad *et al.*, 2022; Azhar *et al.*, 2022). However, understanding its characteristics, particularly its tribological performances, is still vague. This knowledge gap presents a critical challenge that needs to be addressed owing to its potential as an environmentally friendly and sustainable lubricant in the machining industry. Besides, the type of used vegetable oil to be recycled and the way of recycling and treatment processes may influence the results. The main motivation is to develop a sustainable biodegradable lubricant that is also capable of maintaining high machining performances.

Hence, this study focuses on the characterization of the treated recycled vegetable oil (TRVO). Its performances were analysed tribologically through sliding tests using uncoated tungsten pins, mild steel discs, and a tribometer. The main aim is to mimic the milling cutting operations in a more tribologically accurate manner where it exposes the new disc surface at the point of contact with the pin while operating at

fast sliding speeds and strong cutting forces. Mild steel is widely applied in pipelines, buildings, and bridge industries due to its excellent mechanical and chemical properties. The growth of environmental concerns among industry players particularly relating to the usage of conventional cutting fluids necessitates the development of sustainable alternatives. The outcomes of this study are expected to contribute to sustainable machining practices, aligning with global efforts to minimize environmental impact and improve industrial efficiency.

II. METHODOLOGY

The methodology employed in this study is designed to achieve the research objectives. This research applied an experimental-based approach, focusing on the preparation and characterization of treated recycled vegetable oil (TRVO) and its tribological performance evaluation.

A. Preparation of Treated Recycled Vegetable Oil (TRVO)

In this study, palm-based cooking oil from the deep-frying process was collected as the base material for developing the green metal cutting lubricant. The cooking oil is a local brand and is sourced from a commercial market. This oil was selected as it is widely available and economically viable in Malaysia. The choice is also driven to maximize the sustainability aspects of MQL machining by promoting the reuse of materials that would otherwise be discarded.

The treatment process for the used cooking oil was carefully conducted to ensure the removal of impurities and the improvement of the oil's properties for use as a metal-cutting lubricant. Initially, the cooking oil was filtered using filter papers. This step is crucial as it effectively removes large and noticeable particles, which could otherwise interfere with subsequent treatment stages. Then, 10 wt.% of Palm Kernel Activated Carbon (PKAC) was added to every 50 g of the filtered oil. This proportion was chosen to ensure effective adsorption of impurities and unwanted compounds, such as excess fats, chemicals, residual odors, and pigments within the used palm oil. Before that, the PKAC was sieved to obtain a particle size range between 250–297 microns. This specific size range is selected to maximize the surface area for adsorption, which is essential for the effective removal of the impurities. The PKAC has been widely recognized for its superior adsorption capacity, particularly in oil treatment applications, where it helps to enhance the oil's quality and extend its usability (Ahmad *et al.*, 2022). As mentioned by Shahdan *et al.* (2021), the adsorption of used cooking oil with PKAC is important to effectively reduce the value of acid in the oil.

The mixture was then heated at 100 °C for 80 minutes using a magnetic stirrer hot plate. The heating process serves multiple purposes including activating the PKAC, accelerating the adsorption process, and ensuring the proper mixing between the carbon with the oil. This step is critical for achieving a homogenous treatment, as recommended by a previous study on the adsorption test of activated carbon from palm shells (Faisal *et al.*, 2021). After the heating process, the mixture was allowed to cool at room temperature which then went through a multi-stage filtration process using filter papers

with pore sizes of 2.5, 6, and 11 μm . This systematic filtration is designed to remove any remaining fine particles, resulting in a highly purified oil. Figure 1 shows the filtering process using the filter paper to collect the treated recycled vegetable oil (TRVO).

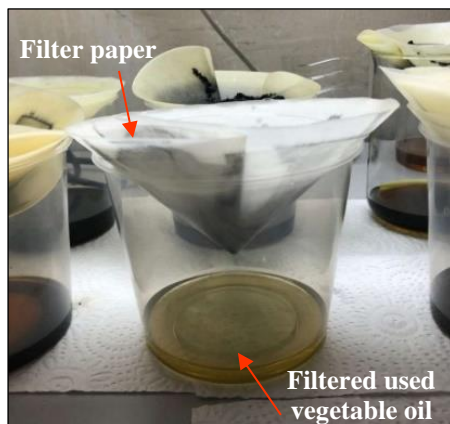


Figure 1: The filtering process using the filter paper

B. Characterization of TRVO – Kinematic Viscosity

A Cannon-Fenske Routine Viscometer system was used to measure the kinematic viscosity value of the TRVO. A U-shaped glass tube with a U156 serial number was filled with 25 ml of TRVO at a constant temperature of 40 °C. The accurate time for the liquid to flow between two marked points on the tube was measured using a stopwatch, and the process was repeated three times in order to get an average value for the TRVO. To measure the viscosity, Eqn. 1 is applied (Zulhilmi et al., 2024). The viscosity value of used cooking oil before treatment was also measured for comparison purposes. The ambient conditions, including room temperature and humidity, were monitored to minimize variations that could affect the results.

$$v = T_{const} t \quad (1)$$

where v = absolute kinematic viscosity, T_{const} = temperature constant, and t = time taken.

C. Samples Preparation for Tribology Testing

This experiment used mild steel as the disc plate, while uncoated tungsten carbide was used as the pin gauge. Mild steel was chosen because understanding its tribological performance is important to industrial components and systems optimization where it is employed, such as bearings, gears, and machine parts. Its mechanical properties, including strength, ductility, and toughness, make it an ideal material for various engineering applications (Sultana et al., 2014). While for the pin, it is made of tungsten carbide which is a widely used material for cutting tools in metal cutting and machining operations due to its exceptional hardness, wear resistance, and thermal stability (Morozow et al., 2021).

In this study, the mild steel discs and uncoated tungsten carbide pins were prepared to dimensions illustrated in Figure 2a. To allow for precise and reliable measurements on pin and disc surfaces throughout the test, a series of grinding processes were performed on the discs and pins. The process is essential to remove any burr, obvious marks, and rustiness on any

surfaces as per ASTM E3-80/95 (Talib et al., 2019). The process was conducted using a surface grinding machine and Silicon Carbide (SiC) abrasive papers of 400 and 600-grid grade, to get perfect flat round discs and pins.

After that, all samples were subjected to a polishing process to remove any scratches and obtain a mirror surface. This process was conducted using the grinding machine with silicon carbide (SiC) paper ranging from 600 to 800-grid grade, followed by a polishing pad with diamond paste at 3 μm . A total of 3 sets of discs and pins were prepared. Figures 2b and 2c show samples of the disc and pin for pin-on-disc test. Table 1 shows the specification of the mild steel disc.

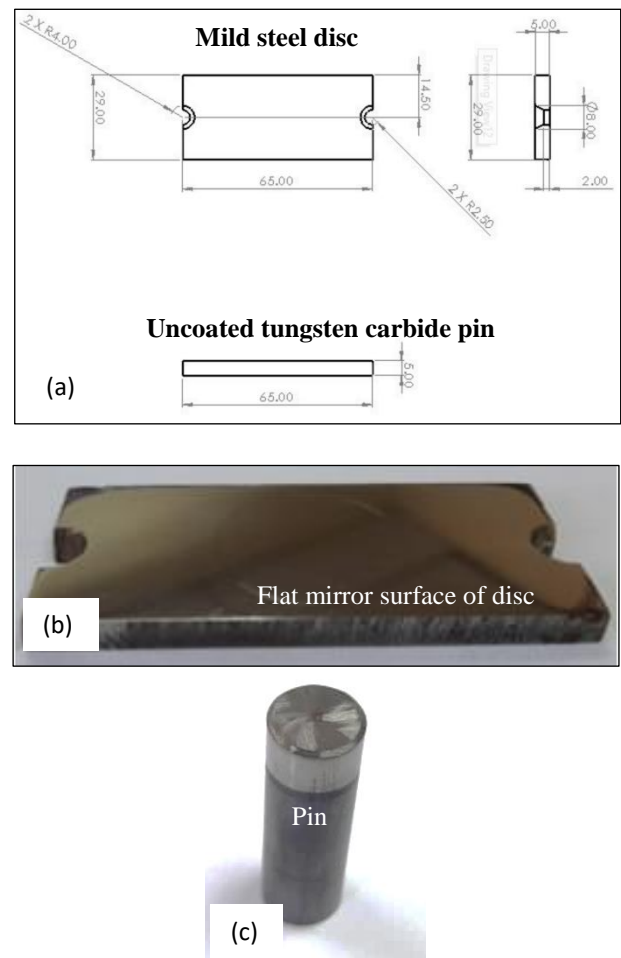


Figure 2: a) Dimensions, (b) sample of mild steel disc and (c) uncoated tungsten carbide pin

D. Tribology through Pin-on-Disc Tests

The tribology testing was conducted through sliding pin-on-disc tests using a tribometer machine as shown in Figure 3. The test was selected as it is known to be one of the standardized methods for assessing the tribological properties of materials. It allows for the investigation of wear rates, friction coefficients, temperatures, and material transfer between surfaces, which are important aspects for understanding machining performances and wear mechanisms that occur in practical applications (Li et al., 2016). The test was carried out continuously for 1 hour during which the vertical stationary cylindrical pin gauge was pressed against

the rotating mild steel disc plate under 20 N load, and the lubricant was applied to the interface between the pin and the disc. For consistency and reproducibility, the sliding test was repeated three times with different sets of pins and discs and then the average values of wear rate, frictional force, coefficient of friction, and pin temperatures were measured. This practice is consistent with Sharma et al. (2013) who also conducted the pin-on-disc test. This test replicates the real-life event of a milling process using the TRVO as the lubricant. Table 2 shows the parameters setting to run the tests.

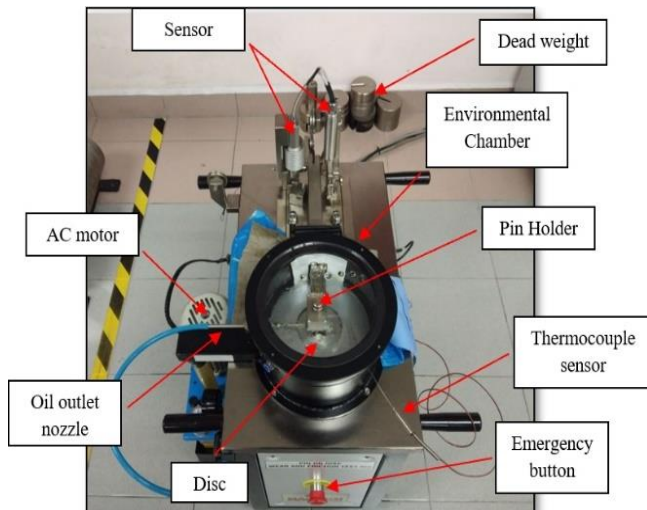


Figure 3: Tribometer machine and setup

Table 1: Mild steel disc specification

| Specification | Value |
|-----------------------------|---|
| Material | S275 Mild steel |
| Chemical Composition | Manganese (Mn): 1.6 %, Silicon (Si) 0.50%, Carbon (C): 0.25%, Sulphur (S): 0.05%, and Phosphorus (P): 0.04% |
| Thickness (mm) | 5 |

Table 2: Parameters setting for pin-on-disc test

| Parameter | Value |
|--------------------------|-------|
| Speed (rpm) | 1000 |
| Time (mins) | 60 |
| Load (N) | 20 |
| Pin diameter (mm) | 8 |
| Track radius (mm) | 10 |

E. Microhardness and Surface Roughness Measurement

It was reported that the heat generated along the pin-on-disc test tends to work-harden the disc (Sultana et al., 2014). According to Haron et al. (2021), this is due to the exposure of the surface to higher temperatures and pressures during the friction test. Thus, in this study, each disc's microhardness was measured using a Vickers microhardness tester at a load of 1000 N and 15 seconds dwell time, before and after each test. Three readings were taken from three random spots to get the average microhardness values for that contact surface. At the same time, the heat-dependent sliding output of surface roughness was also measured and analysed using a Surf Test machine. The arithmetic averaged surface roughness (Ra) of

the disc surface was measured using a contact technique where the stylus traversing length was set to the cut-off length, λ_c , of 0.8 mm, following ISO 4288:1996. Three measurements were taken at random locations along the sliding path to accurately characterize the Ra.

III. RESULTS AND DISCUSSION

A. Viscosity Analysis of TRVO

Figure 4 shows that the treatment process on the used cooking oil reduced its viscosity from 51.78 to 41.05 cSt. The reduction happened due to the effect of cleaning and heating processes during treatment (Yin et al., 2021). However, the value of the viscosity obtained is relatively higher when compared to Ahmad et al. (2022) who also used TRVO at 31.9 cSt in MQL machining. Oils with lower viscosities typically have greater consumption and better dispersion since the size of oil particles increases with the reduction of viscosity (Pereira et al., 2017). In the case of canola oil as the based-oil-lubricant, the frictional force generated is slightly lower than TRVO due to its lower viscosity value at 39 cSt (Shalwan et al., 2020). Nonetheless, Pervaiz et al. (2019) highlighted the advantage of oils with higher viscosity which increases the lubrication capacity, but at the same time, reduces the penetration ability during metal cutting. This aligns with Teng Gao et al. (2018) finding that the lubricating effect of the cutting fluid increases with an increase in viscosity, but falls off after the viscosity reaches a certain value. Thus, it can be said that in MQL machining, oils with lower viscosity are recommended as they offer better dispersion and penetration for an efficient lubrication effect particularly at contact zones between the workpiece and cutting tool. However, identifying an optimum condition for the MQL oil is important to maximize its lubrication effectiveness.

B. Tribological Behaviours

Table 3 shows the pin-on-disc test results. From three specimens, it was found that the average wear is 16.219 μm , and the average frictional force is 0.1494 N. For the coefficient of friction and pin temperature, their average values are 0.0013, and 23.80 $^{\circ}\text{C}$, respectively.

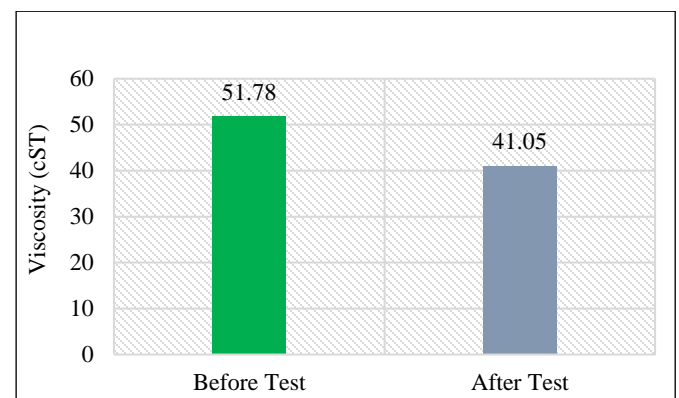


Figure 4: Viscosity of TRVO (Comparison at 40 $^{\circ}\text{C}$ (cSt)) before and after oil treatment

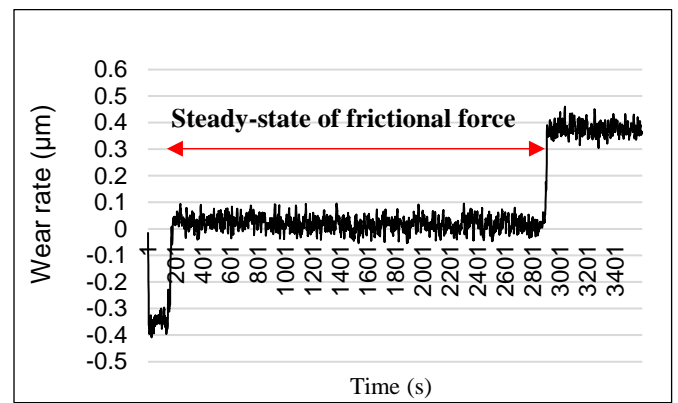
Table 3: Pin-on-disc test results

| Specimen | Wear (μm) | Frictional force (N) | Coefficient of friction | Pin temperature ($^{\circ}\text{C}$) |
|----------------|---------------------------|----------------------------|-------------------------------|--|
| Test 1 | 17.16 | 0.1689 | 0.00084 | 24.87 |
| Test 2 | 16.11 | 0.1306 | 0.00103 | 23.81 |
| Test 3 | 15.38 | 0.1488 | 0.00204 | 22.71 |
| Average | 16.21 | 0.1494 | 0.0013 | 23.80 |

Figure 5 shows the graph of wear rate against time in which the wear slowly developed with the sliding time. The wear rate begins at a high level which then subsequently declines. As the sliding time increases, the reduction in the wear rate is not so marked. The same phenomenon was observed by Shalwan et al. (2021) who evaluated the tribological performances of canola-oil-based lubricants. According to them, this phenomenon is known as a steady state of the rubbing procedure where the wear rate remains constant to sliding time. This trend frequently happens in metals and polymers as the rubbed surface is not very much altered during the sliding test (Shalwan et al., 2021). According to Sahab et al. (2017) and Maarof et al. (2019), the thicker lubricant from higher viscosity develops a thin separator film between the contact surfaces which serves as a cushion that provides the load-carrying capacity and is efficient in reducing the shear stress as it subsequently reduces the frictional force between the pin and disc. In this test, the lubricant cushion is believed to reduce the direct metal-to-metal contact that immediately controls and reduces the wear rate.

Before the end of the test, a gradual increase in wear rate can be observed, which showed a partial degradation of the lubricant cushion due to continuous friction between surfaces. When compared with dry conditions, Grzesik et al. (2006) reported severe wear progression with sliding distance, caused by direct metal-to-metal contact under the absence of lubricant between the contact surfaces.

For the frictional force, Figure 6 shows that the values are negatively low at the beginning of sliding, then remain stable and reach a steady state. This finding is parallel with Shalwan et al. (2020) under canola bio-lubricant. When referring to Cho et al. (2016), they mentioned that negative frictional force at the beginning of the sliding test is normal, as the initial movement is usually hindered by contact between surface asperities and the phenomenon of static friction. These asperities resist motion and cause an increase in static friction, which is the force required to overcome this initial resistance. With continuous sliding, these forces become positive, stabilize and transit to the steady-state stage as asperities undergo plastic deformation and wear, leading to a smoother interface.

Figure 5: Wear rate (μm) vs. time (s)

Also shown in Figure 6, the steady-state continued in the long run under the constant supply of lubricant throughout the test. It is believed that this condition forms a boundary lubrication film between the contact surfaces, which effectively minimizes direct asperity contact, stabilizes the frictional force at near-zero levels, and results in consistent sliding conditions. This finding is desirable for metal-cutting applications, as the lubricant effectively maintains low friction and temperature, which are crucial for tool life and machining efficiency.

The same progress pattern can be observed for the coefficient of friction as illustrated in Figure 7. According to Yin et al. (2021), the values of frictional force and coefficient of friction are dependent as both reflect the lubrication performance at the contact interfaces. A reduction in the coefficient of friction provides evidence of an efficient lubrication effect. However, it can also be seen from Figures 6 and 7 that both frictional force and coefficient of friction rose sharply after about 45 minutes of running which is believed to happen as a result of frictional interaction between the continuously sliding bodies. Courbon et al. (2020) mentioned in their study that the friction coefficient may also change due to different mechanical properties at the pin and disc interface. In addition, the study conducted by Shalwan et al. (2020) emphasized that the frictional behaviour of mild steel is influenced more by the applied load and velocity than the sliding distance and time. Based on their observation, a low applied load generates high frictional force compared to a high applied load.

It is known that the continuous generation of frictional heat at the sliding interfaces increases the temperature of the contacting surfaces. Figure 8 shows the correlation between pin temperatures and sliding time. As can be seen, the pin temperature gradually reduces with time. This finding proves the ability of the TRVO lubricant to slip into the sliding zone between the pin and disc surfaces, and lubricate the contact area, hence reducing friction as well as temperatures. According to Talib et al. (2019), sufficient lubricant effect also possibly alters the sliding friction into rolling friction that further reduces the heat that is inherently generated during cutting. In MQL machining practices, the lubricant is supplied in the form of oil mist through a high-pressure jet direct to the chip-tool interface (Borkar et al., 2011). Thus, more heat is

expected to be dissipated where lower cutting temperatures with longer tool life could be achieved.

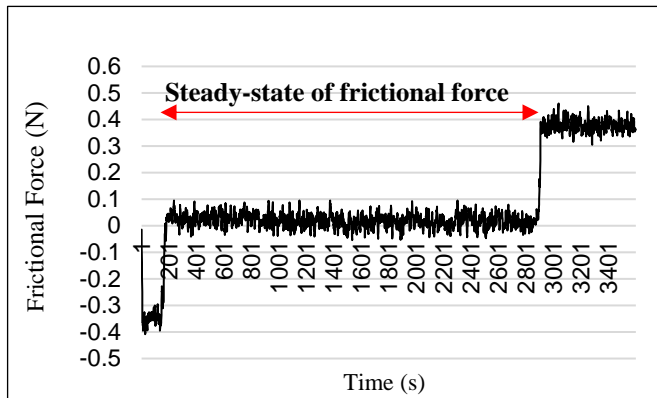


Figure 6: Frictional force (N) vs. time (s)

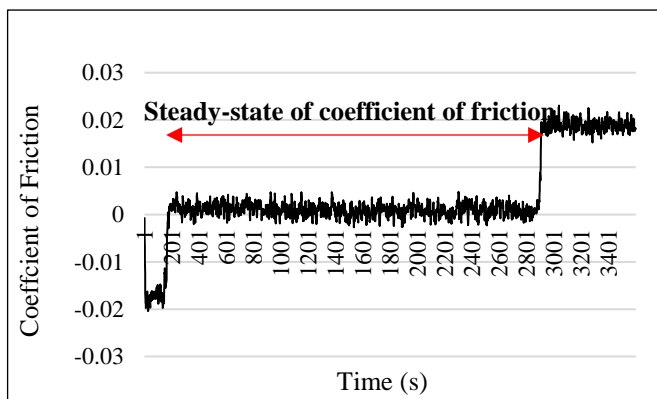


Figure 7: Coefficient of friction vs. time (s)

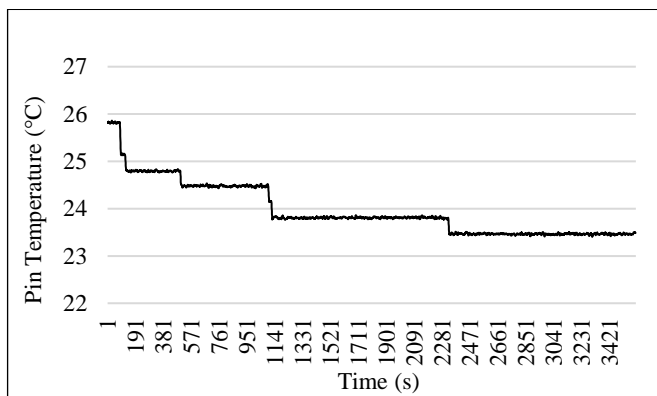


Figure 8: Pin temperature (°C) vs. sliding time (s)

C. Microhardness and Surface Roughness Analysis

Grzesik et al. (2006) mentioned that one of the factors that influence a workpiece's surface integrity is the absence or presence of coolant or lubricant during cutting. Thus, in this study, the microhardness of the discs after the tests were compared and analysed. As shown in Figure 9, the average microhardness was found to increase by 3.8%, from 125.08 to 130.03 HV.

The increase in the hardness of the machined surface can be attributed to a phenomenon called work hardening which normally occurs during the sliding contact such as in metal

cutting operations like milling and turning. For the case of the pin-on-disc test, the pin slides against the disc, where the material near the surface experiences severe plastic deformation due to the high contact pressure and frictional forces. This deformation leads to an increase in dislocation density within the material's microstructure, making the surface harder than its origin (Che Haron et al., 2021). Additionally, the application of lubricants in the test could have played a role in moderating temperature rises while still allowing localized stresses to induce work hardening. The combination of controlled thermal conditions and mechanical stress promotes the formation of a harder surface layer, which is beneficial for enhancing wear resistance.

For the mild steel disc, it is known that this low-carbon steel is highly ductile, malleable, and not as strong as high-carbon steels or other alloys. Its wide application in construction and automobile industries for beams, frames, reinforcing bars, as well as car chassis and panels, requires some level of ductility, weldability, strength, and formability (Nader & Shather, 2022). Thus, an increase in microhardness may change and improve the mild steel properties and application and correspondingly, an increase in strength. This is related to the material's ability to withstand deformation, including higher loads and stresses, making it suitable for applications where higher strength is required.

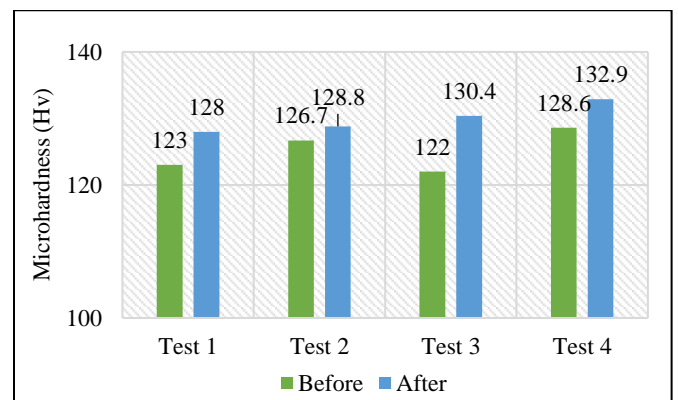


Figure 9: The hardness of the disc before and after the pin-on-disc test

Through surface roughness analysis, it was found that the surface roughness of the disc increased by 30.2% as compared to before test condition, which was from 0.03 to 0.043 μm as shown in Figure 10. At the same time, the surface roughness of the pin also increased from 2.19 to 2.222 μm , or equal to 1.44%, as shown in Figure 11. The increase in the surface roughness of the disc and the relatively smaller increase in the surface roughness of the pin can be attributed to the higher hardness and superior wear resistance of the tungsten carbide material of the pin. Its chemical composition makes it a dense, hard structure capable of withstanding abrasive forces during sliding, thereby protecting the pin from substantial surface damage.

A tribological analysis under cryogenic conditions conducted by Yousfi et al. (2017) reported a significant correlation between surface roughness and the coefficient of friction which is similar to the finding in this study. The

continuous rubbing action between surfaces generates higher heat at the contact area that also increases heat and friction-dependent variables such as wear rate and surface roughness. The rougher surface requires more cutting forces which in turn increases the friction coefficient as can be seen in Figure 7.

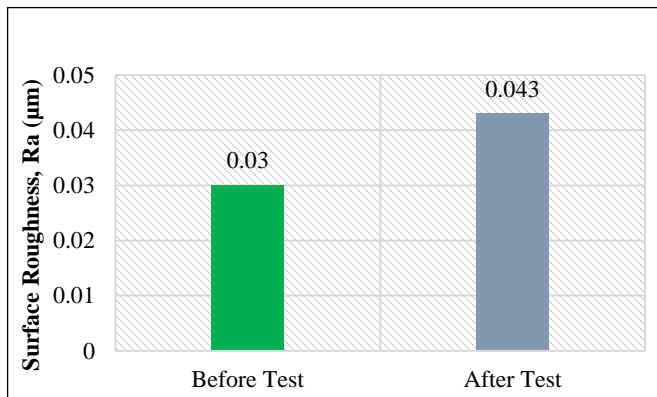


Figure 10: Average surface roughness of disk

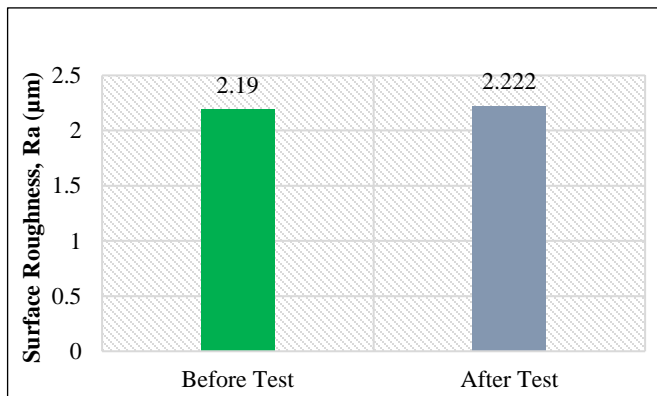


Figure 11: Average surface roughness of uncoated carbide pin

IV. CONCLUSION

This study discusses the treatment, characterization, and performance of treated recycled vegetable oil (TRVO) through pin-on-disc tests in terms of its tribological aspects, and its correlation with surface roughness and microhardness of the sliding surfaces between uncoated tungsten carbide pin and mild steel disc. At a viscosity of 41.05 cSt, the TRVO results in an average wear of 16.219 µm after 1 hour of running, while the frictional force and coefficient of friction on average were 0.1494 N and 0.00143, respectively. The pin temperatures were found to reduce with the operating time at an average of 23.80 °C. Analysis of the surface roughness showed both pin and disc resulted in rougher surfaces at 2.222 µm and 0.043 µm, respectively after the tests. These conditions align with the increase of frictional force and coefficient of friction before the end of the tests, and consequently increased heat, resulting from the continuous sliding actions of the two surfaces. The mild steel's microhardness is also found to increase from 125.08 to 130.03 HV as a response to the work hardening that occurred from sliding friction that continuously happened along the tests. To confirm the findings and assess whether the developed TRVO is able to function well as a MWF under

more realistic settings, actual machining tests under MQL conditions with this fluid are highly suggested.

AUTHOR CONTRIBUTIONS

All authors play a vital role in the completion of this study including designing and conducting the experimental works. For the writing part, the main author is **Nurul Hayati Abdul Halim**, while the others are also involved in the writing process for drafting and revising content, analysing data, providing critical discussion, as well as approving the final version.

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