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Evaluation of various loads on the tribological performance of palm oil biodiesel-based lubricant using the ball-on-disc tribometer

Favian Jikol [1], Mohd Zaid Akop [1*], Yusmady Mohamed Arifin [1], Mohd Azli Salim [1], Safarudin Gazali Herawan [2]

[1] Faculty of Mechanical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, MALAYSIA.
[2] Industrial Engineering Department, Faculty of Engineering, Bina Nusantara University, INDONESIA.
*Corresponding author: zaid@utem.edu.my

KEYWORDS

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Friction
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Viscosity
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ABSTRACT

Due to the depletion of petroleum resource and environmental concern, there is demand for the development of biodiesel-based lubricant which will be more environmental-friendly, biodegradable, and less toxic. By employing the ball-on-disc tribometer, this study aims to examine the tribological properties of palm oil biodiesel considering their interaction with automotive parts under lubricated conditions in an internal combustion engine. The biodiesel-based lubricants were blended at the ratio of 10%, 20%, 30%, 40%, and 50% with base diesel fuel. The friction and wear characteristics of these blends were caried out at 150rpm for 1000m sliding distance with dissimilar loads of 30N, 60N, and 90N. Experimental results showed that the coefficient of friction was the highest for B10 at 30N load, B20 at 60N load, and B40 at 90N load, respectively. The wear rates for B20, B30, B40, and B50 lubricant were higher under 60N load than under 30N load. All lubricant wear rates dropped at 90N load except for the B20 lubricant. Grooves with varying condition were forming parallel to the sliding direction. As a result of sliding effect and material removal, abrasive wear of different degrees of severity and pits had developed on the surface of the aluminum wear disc.

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1.0 INTRODUCTION

In industrial applications, wear and friction between sliding surfaces can result in a number of problems, including higher expenses, shorter machine lifespans, malfunctions, energy loss, and decreased system efficiency (Ideris et al., 2023). The global requirement to save energy by minimising friction and wear of components or parts has led to the introduction of several alternative technologies for sustainability, such as thin film coatings, green lubricants, and bio/eco-materials (Mahmud et al., 2019). Wear refers to the undesirable alteration in the separation of small particles due to mechanical actions on a material's surface. On contact surfaces, friction forces reduce strength, while wear deteriorates operating tolerances and preventing the optimum functionality of machine parts (Cetin et al., 2022). Additionally, continuous friction also raises the wear rate, causing metal deformation (Babu et al., 2022). In industrial machines, friction and wear lead to energy loss and material waste, thus, necessitating proper control. When mechanical components in relative motion come into contact, friction arises, dissipating energy and reducing the efficiency of mechanical devices (Woma et al., 2023). As being mentioned by Humelnicu et al. (Humelnicu et al., 2019), approximately 50% of fuel energy is lost to friction in internal combustion engines. Diesel and vegetable oil fuel mixtures improve lubrication, considering that around 40-50% of all energy lost through internal engine friction is due to piston ring-cylinder friction. This is in agreement with Gil et al. (Gil et al., 2019) who stated that engine fuels also lubricate engine injection equipment components. Biofuels used in internal combustion engines can increase wear on these components due to a higher coefficient of friction between mating surfaces. However, incorporating biofuels as diesel additives reduce the wear of cooperating elements, likely due to improved lubrication film durability. Moreover, lubrication reduces friction in engine components, lowering wear, and extending engine lifespan.

One of the most applied methods to mitigate friction and wear in moving components is the use of lubricant. Due to strict pollution norms and regulations, oil refineries are now required to manufacture diesel with a low sulphur level, which ultimately affects the fuel's lubricating characteristics. Engines using low sulphur fuel are known to have issues with excessive wear and corrosion, erosion of the fuel injector nozzle, difficulties starting the engine, high emissions, and reduced power (Chourasia et al., 2021). Lubricity is also vital for the integrity of the injection system, with sulfur compounds primarily responsible for injector nozzle lubrication. Hence, adding biodiesel to diesel enhances the fuel's tribological performance (De Farias et al., 2014). To mitigate these issues, bio-lubricants were introduced. The application of bio-lubricants such as that made of vegetable oils has gain popularity in various sectors due to the material's availability and sustainability. Despite their potential, vegetable oils are generally unsuitable for direct use as lubricants because they exhibit poor thermo-oxidative stability and inadequate performance at low temperatures (Audu et al., 2023). To address these limitations, researchers have extensively explored chemical modification techniques. These methods often involve enhancing the oil's properties with chemical additives like antioxidants, pour point depressants, and viscosity modifiers to improve its functionality as a lubricant. Besides, additives and palm biodiesel blends such as B10 and B20 exhibit lower frictional force than conventional diesel (Raja et al., 2023). Another crucial characteristic of bio-lubricants is their longevity compared to other petroleum derivatives. However, disposing of lubricant residues demands responsibility due to their resistance to biodegradation, especially for fossil-based oil lubricants (Ojaomo, Samion, Yusop, et al., 2023; Shahabuddin et al., 2022).

Transesterification and esterification, hydrogenation, epoxidation, and estolides formation are the main chemical procedures for bio-lubricant production (Nogales-Delgado et al., 2023). According to Kurre and Yadav (Kurre & Yadav, 2023), viscosity is the key characteristic of bio-lubricants. It refers to the degree of resistance a fluid exhibits between its layers. When sample lubricant has higher viscosity, it minimizes metal-to-metal contact during testing. Furthermore, Babu et al. (Babu et al., 2022) also mentioned that bio-lubricants exhibit excellent lubricating properties due to their high viscosity. However, it has been observed that increasing the proportion of biodiesel in petroleum diesel fuel for compression ignition engines significantly dilutes the engine lubricants (Hamdan et al., 2018). Additionally, viscosity of biodiesel is also the key factor for evaporation and deposition mechanism as we experimented in our previous work (Jikol et al., 2024b, 2024a). Not only that, Arifin et al. (Arifin et al., 2008) also stated that impingement interval, hot surface temperature, and deposit heat transfer are additional elements that can impact fuel deposition in addition to fuel type. These variables are dependent on adhesion force, which is primarily caused by capillary and Van der Waals forces operating between two contacting surfaces. Adhesion force is also influenced by the fluid affinity and surface reactivity of the interacting surfaces.

In the literature, there are several studies regarding tribological performance of bio-lubricants. One of the early works regarding implementation of palm oil as a bio-lubricant was conducted by Masjuki and Maleque (Masjuki & Maleque, 1996), where they tested the performance of low blending lubricants which less than 10%. They discovered that the sliding contact between two materials with significant different in hardness will result in rough surface layer on the softer material due to material removal, mainly abrasion. Another work by Imran et al. (Imran et al., 2013) investigated the performance of jatropha oil as bio-lubricant. Similar blend proportions were being studied as in our paper which were 10% to 50% instep of 10%. However, their experimental setup was using the pin-on-disc tribometer. Their work revealed that with continuous sliding, the material is eroded and fresh metal surface is exposed. This will influence the friction and wear behavior since exposed fresh metal has lower tendency to react with lubricant additives. Additionally, there is no information regarding the performance of the lubricant without additives. Singh et al. (Singh et al., 2016) carried out a work on friction and wear characteristics of jatropha oil-based biodiesel blended lubricant at different loads. They found that with increased load, contact conditions varied where higher load resulting in higher coefficient of friction and wear rates. Furthermore, lubricant with higher viscosity exhibits lower coefficient of friction and minimum wear rates due to metal-to-metal contact. This indicates that the lubrication between the two sliding surfaces likely fell into the hydrodynamic or mixed lubrication regime. In this state, a lubricant film forms a wedge and creates clearance between the moving surfaces, which significantly reduces the coefficient of friction (Ideris et al., 2023). However, in certain work such as by Iswantoro et al. (Iswantoro et al., 2023), the author found that palm oil-based lubricant with high viscosity (B50) exhibits higher degradation which caused more metal wear in the engine compared to mineral diesel. In another work conducted by Bhan et al. (Bhan et al., 2021) using neem oil as bio-lubricant, they found that maximum wear occurred when higher load was applied. They explained that as load increases, pressure on the lubricant film rises, displacing material from the surface and increasing wear. Surprisingly, they also discovered that 10% blend showed better anti-wear performance under all loads, while the 15% blend resulted in maximum wear due to lubricant film instability. These findings indicate that higher blending ratio of bio-lubricant does not guarantee greater tribological performance and vice versa.

In addition, storage condition is also a main factor that affecting the lubricant's tribological properties. Masudi et al. (Masudi et al., 2023) found out that the acid value of biodiesel increases when stored outdoor and exposed to sunlight, which reduce the effectiveness of any antioxidants mixed in the biodiesel. Higher temperature and humidity in outdoor environment contribute to biodiesel oxidation as being studied by Narasimmanaidu et al. (Narasimmanaidu et al., 2023). They discovered that the kinematic viscosity, density, water content, and acid values of B10 fuel increase when stored in outdoor conditions. On the other hand, the effect of storage duration was minimal when the fuel was placed in an indoor condition. This is supported by the findings form Zakaria et al. (Zakaria et al., 2014) who found that for a storage period of less than 84 days, degradation occurred, although the impact was not significant as the alterations remained within acceptable ranges. Meanwhile, degradation of the biodiesel was delayed in an indoor storage condition. Furthermore, Hawrot-Paw et al. (Hawrot-Paw et al., 2020) mentioned that the alteration of fuel properties may already take place during storage. The author also discovered that the friction moment and linear wear of samples were greater after the storage period. These findings indicate that there are other factors influencing wear characteristics of bio-lubricants apart from the load and blending percentage itself.

Owning to its stability, low cost, and the provision of higher maximum sliding speed, the ball-on-disc is the most commonly employed tribometer configuration in the friction and wear testing (Zhang et al., 2021). Moreover, the ball-on-disc tribometer also used to evaluate tribological performance of lubricants especially in cutting operation (Nassef et al., 2024). Given the observed variations in the coefficient of friction, further investigation is necessary to determine the long-term wear of interacting kinematic pairs and to explore how this wear correlates with the coefficient of friction over extended periods of operation. In addition, there is still insufficient work on lubrication performance of palm oil biodiesel with blend ratio of 10%, 20%, 30%, 40%, and 50% available in the current literature. Moreover, the tribological performance of palm oil biodiesel-diesel blend without the inclusion of any additives is not adequately explored. Thus, the novelty of this study is the implementation of palm oil biodiesel-diesel blend as a stand-alone bio-lubricant. We aim to investigate the friction and wear properties when palm oil biodiesel-based lubricant is applied on the wear disc. This will assist us in gaining information on influence of biodiesel-diesel mixing ratio on moving parts of engine such as the piston.

2.0 EXPERIMENTAL PROCEDURE

In this study, the test lubricants used were the palm oil biodiesel mixed with base diesel fuel at different percentage of mixing by volume. The test lubricants were indicated as B10 (10% palm oil biodiesel + 90% diesel), B20 (20% palm oil biodiesel + 80% diesel), B30 (30% palm oil biodiesel + 70% diesel), B40 (40% palm oil biodiesel + 60% diesel), and B50 (50% palm oil biodiesel + 50% diesel). The physicochemical properties of the test lubricants are shown in Table 1.

The experimental work was performed by implementing the ball-on disc tribometer testing according to the ASTM G99 standard (Voort et al., 2017). Apart from investigating the tribological performance of lubricants, the ball-on-disc tribometer also used to evaluate the tribological behavior in cutting operation as being studied by Nassef et al. (Nassef et al., 2024). The stationary steel ball used was a carbon chromium steel AISI 52100 (density 7.85g/cm^3) with a diameter of 12.7mm and the wear disc was fabricated from aluminum alloy Al 4032 (density 2.71g/cm^3) with a diameter of 74mm and thickness of 4mm. Aluminum alloy was used as it is the common material used to manufacture engine parts such as the pistons (Doetein et al., 2020; Srikanth et al., 2017). Figure 1 shows the schematic drawing of the ball-on-disc tribometer and Table 2 shows the parameters used for the test. The sliding speed and sliding distance were fixed for all test conditions. The surfaces of the steel ball and aluminum wear disc were cleaned ultrasonically with ethyl alcohol before and after each set of experiment. The loads were applied manually, and the test lubricants were impinged on the wear disc at a constant droplet interval of 3 seconds to ensure the contact point between the steel ball and the aluminum wear disc was covered with lubricant. The weight of the aluminum wear disc was measured both before and after the test by using an electronic microbalance. The weight loss of the aluminum wear disc was evaluated based on the varying loads applied and the distances slid. Image processing was carried out by using the 3D profilometer.

Table 1: Physicochemical properties of test lubricants.

Properties	**Lubricant**				
	B10	**B20**	**B30**	**B40**	**B50**
Density (kg/m^3)	850	853	857	860	863
Kinematic viscosity (mm^2/s)	3.86	3.91	3.95	3.97	4.00
Heating value (MJ/kg)	44.23	44.12	43.13	42.95	42.74
Acid value (mg KOH/g)	0.18	0.22	0.26	0.30	0.33

Table 2: Parameters applied on machine.

Parameter	**Value**
Load (N)	30, 60, 90
Sliding speed (rpm)	150
Sliding distance (m)	1000

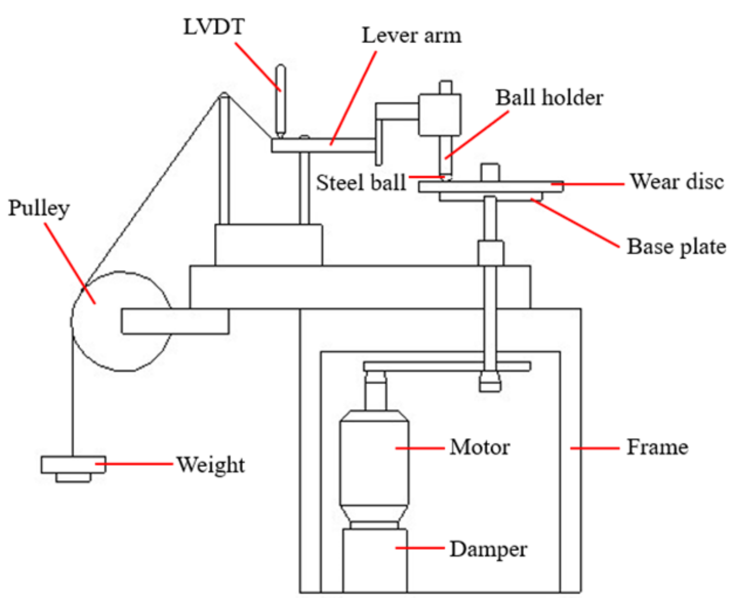


Figure 1: Schematic drawing of the ball-on-disc tribometer.

3.0 RESULTS AND DISCUSSION

Figure 2 shows the friction behavior of the lubricants tested at dissimilar loads. The figure indicates that coefficient of friction increases with respect to load applied on the ball-on-disc tribometer. At 30N load, the highest coefficient of friction was for B10 lubricant followed by B40, B50, B30, and B20. When 60N load was applied, B20 lubricant produced the higher coefficient of friction followed by B10, B40, B50, and B30, respectively. Surprisingly, at 90N load, the highest coefficient of friction was recorded for B40 followed by B50, B20, B30, and B10. For B10 lubricant, the coefficient of friction was lower at 60N and 90N loads compared to that at 30N load. In addition, the coefficient of friction of the B10 lubricant was the lowest at 90N load even it has the lowest viscosity among all test lubricants. This probably caused by auto-oxidation of the lubricant during storage which has caused altercation of the physicochemical properties of the lubricant which resulted in lubricant film instability (Narasimmanaidu et al., 2023; Singh et al., 2017). In addition, the increase in load might have caused viscosity to increase due the oxidation process which results in sludge formation or contamination with insoluble particles. Furthermore, there is still a concern on poor oxidation stability of a palm-oil based lubricant as being mentioned by Ojaomo et al. (Ojaomo, Samion, & Mohd Yusop, 2023). These findings indicate that in some conditions, the coefficient of friction is heavily influenced by the type of surface rather than the load or speed applied (Babu et al., 2022).

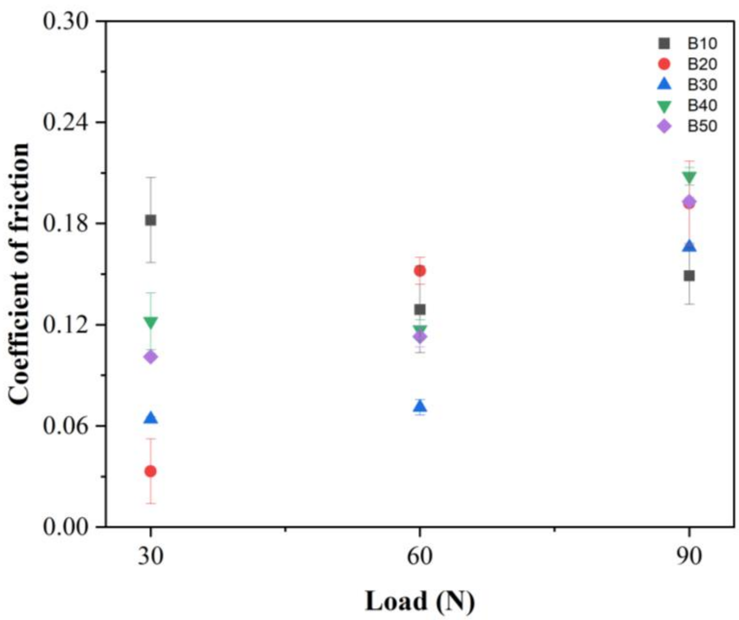


Figure 2: Friction behavior of the lubricants tested at dissimilar loads.

In terms of weight loss of the aluminum wear disc, the application of the B10 lubricant indicates that it has the lowest resistance to material wear as it has the lowest viscosity. As can be seen in Figure 3, the weight loss regarding to B10 lubricant was the highest for every test loads. For B20 lubricant, the weight loss was lowered compared to B30 for 30N and 60N test loads. However, for 90N load, there was a significant difference of weight loss between B20 and B30 usage. For B40 and B50 lubricants, the weight loss of their respective wear disc was identical for the 30N load. For the 60N, the application of B40 lubricant resulted in slightly higher weight loss of wear disc than that of B50, and vice-versa for 90N load. The cumulative weight loss of the aluminum wear disc for all test loads were 36.9mg (B10), 17.5mg (B20), 14.6mg (B30), and 8mg (B40 and B50). In summary, higher viscosity of the lubricant blend minimizes metal-to-metal contact between surfaces, hence reduces material wear.

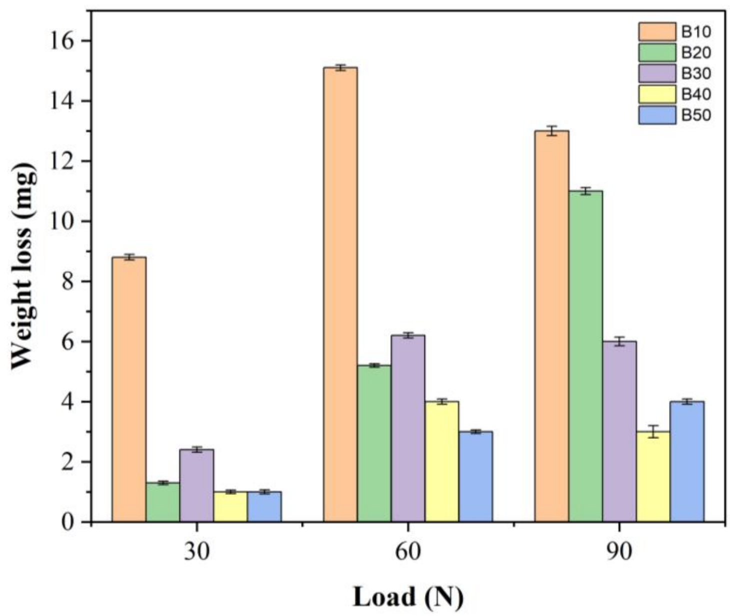


Figure 3: Weight loss regarding to B10 lubricant was the highest for every test loads.

The material wear rate was calculated according to following Equation (2) (Mahmud et al., 2019). With increase of load, wear rate of all the lubricant variants increases as presented in Figure 4. Lubricant with a higher blend ratio showed minimum wear rate as the contact between metal-to metal surfaces was minimum due the higher viscosity in comparison to other lubricant blends. However, for B10 lubricant, the wear rates were significantly lower for higher loads. This might be caused by the lubricant film instability as being stated by Bhan et al. (Bhan et al., 2021). Furthermore, another possible reason for such phenomenon is the alteration of the lubricant's viscosity as the load is increased. Singh et al. (Singh et al., 2017) explained that oxidation process which results in sludge formation or contamination with insoluble particles in a lubricant is more prominent when the load applied is higher. Consequently, viscosity of the lubricant will become higher and affecting the wear rate of material. For B20, B30, B40, and B50 lubricant, the wear rates were higher for 60N load compared to that of 30N load. However, the wear rates for all lubricants decreased for 90N load except for B20 lubricant. Additionally, the increased load might have caused in more sludge formation or contamination, which have caused the viscosity of the lubricants to elevate which resulted in lower wear rate.

The worn surface of the aluminum wear disc after being tested with various loads is shown in Table 3. After each test, the formation of grooves parallel to sliding direction was observed. Moreover, the grooves consist of different sizes and depths. The identified type of wear from the test is mainly abrasive wear with different severity. Some pits which evolved due to material removal were also observed. Further description on the surface condition of the wear disc is presented in the following table.

$V_{loss} = m_{loss}/\rho$ (1)

$k = V_{loss}/WL$ (2)

Where:
V_{loss} = volume loss of specimen (mm^3)
m_{loss} = mass loss of specimen (g)
ρ = density of specimen (g/mm^3)
k = specific wear rate ((mm^3/(N·mm)
W = applied load (N)
L = sliding distance (m)

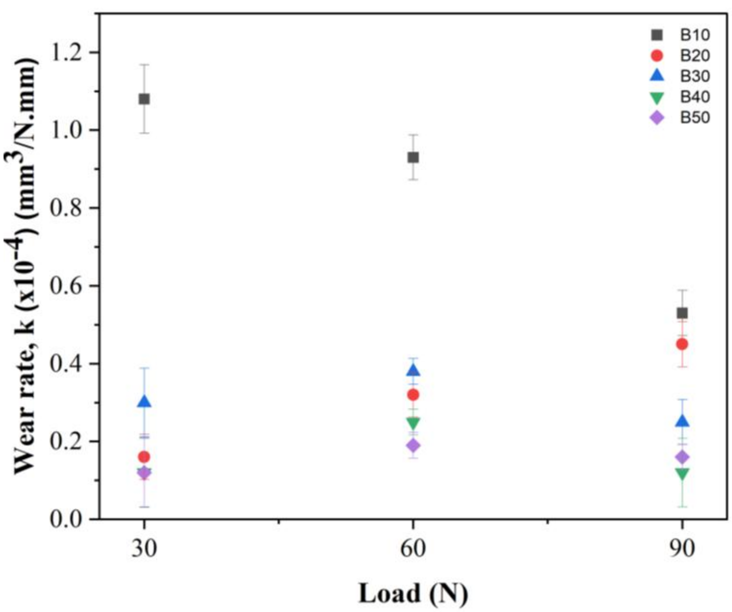
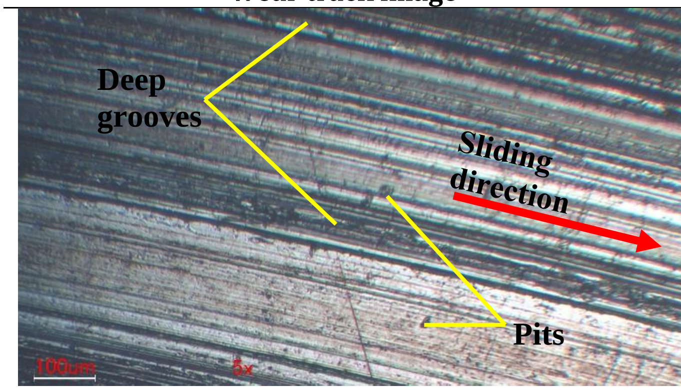
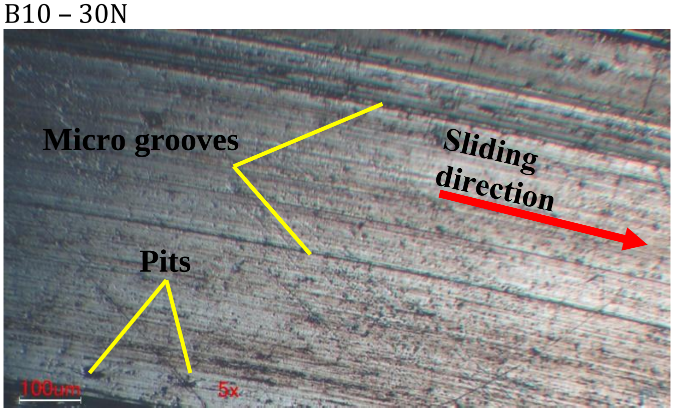
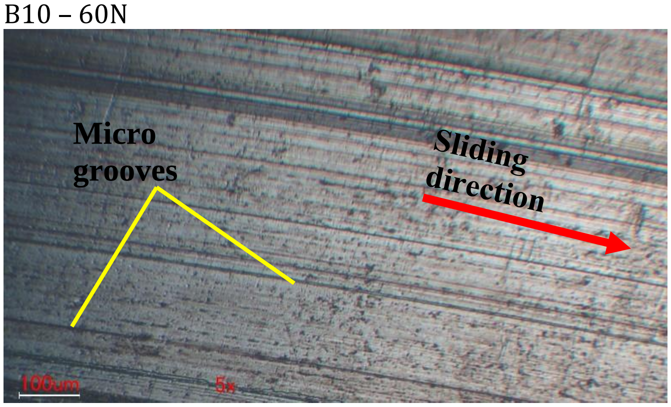
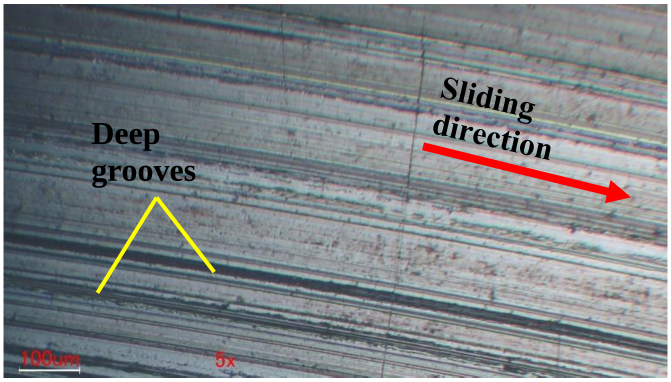


Figure 4: Wear rate of all the lubricant variants.

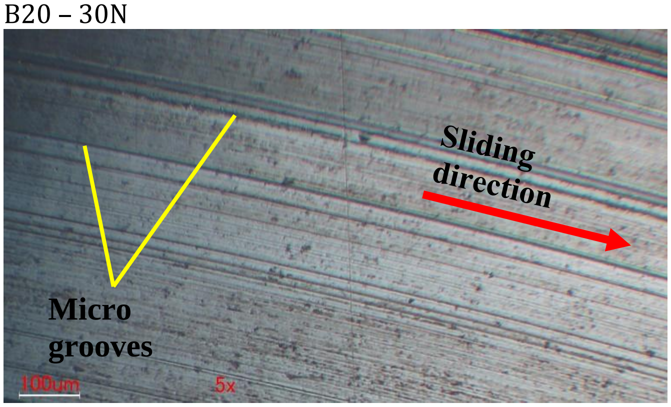
Table 3: Wear track image.

Wear track image	Surface condition
 B10 – 30N	• Severe abrasive wear • The main reason for abrasive wear is because of the significant different on hardness of two surfaces – steel ball and aluminum wear disc • Low viscosity of B10 causing less lubricant film protection between the two surfaces • Grooves parallel to sliding direction • Formation of pits which is material being removed from the surface/minor chipping
 B10 – 60N	• Mild abrasive wear which is smoother compared to adhesive wear • Grooves parallel to sliding direction • Obvious micro grooves compared • Formation of pits which is material being removed from the surface/minor chipping
 B10 – 90N	• Mild abrasive wear • Grooves parallel to sliding direction • Obvious micro grooves



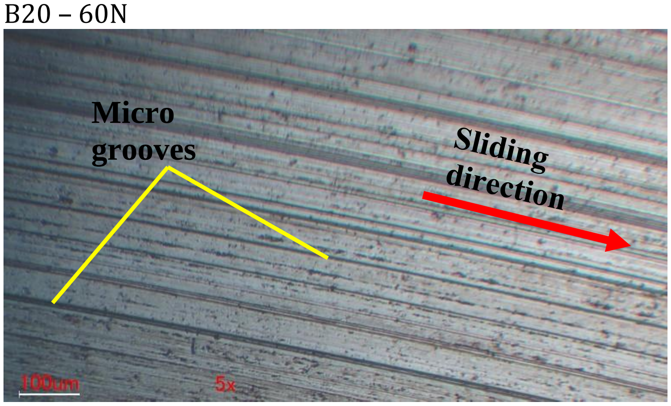
B20 – 30N

- Severe abrasive wear
- Grooves parallel to sliding direction
- Obvious deep grooves



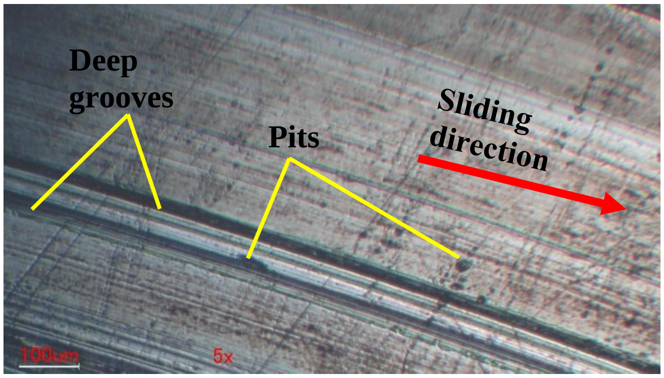
B20 – 60N

- Mild abrasive wear
- Grooves parallel to sliding direction
- Obvious micro grooves



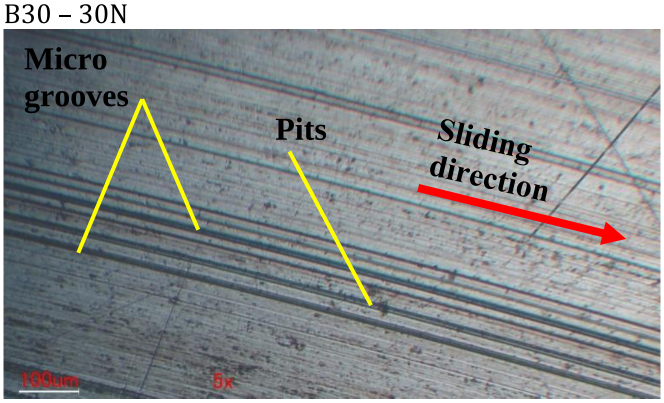
B20 – 90N

- Mild abrasive wear
- Grooves parallel to sliding direction
- Obvious micro grooves



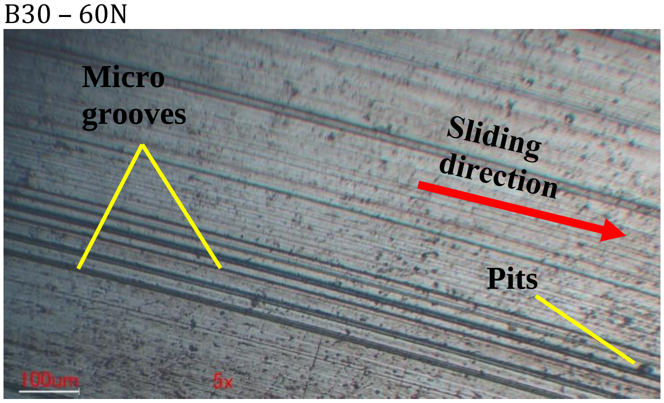
B30 – 30N

- Severe abrasive wear
- Grooves parallel to sliding direction
- Obvious deep grooves



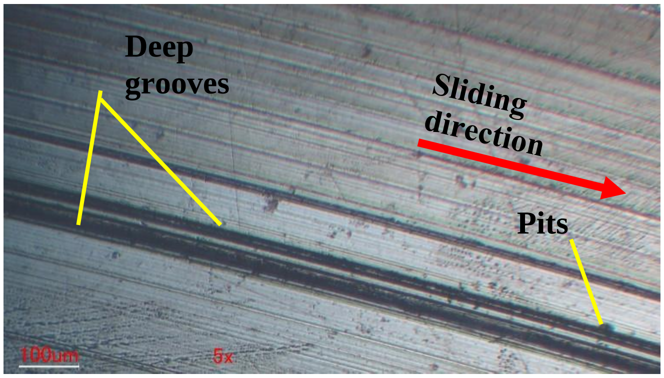
B30 – 60N

- Severe abrasive wear
- Grooves parallel to sliding direction
- Obvious micro grooves



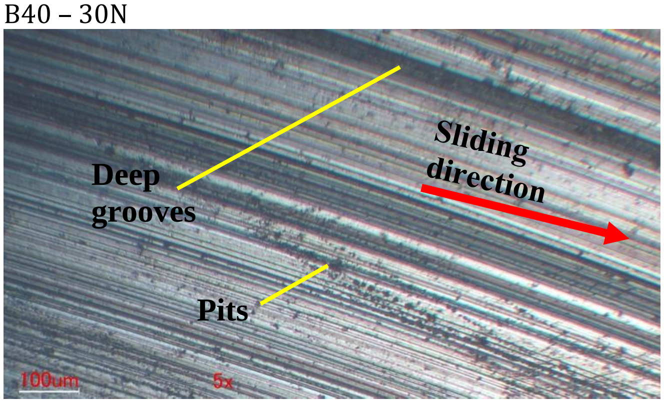
B30 – 90N

- Severe abrasive wear
- Grooves parallel to sliding direction
- Obvious micro grooves



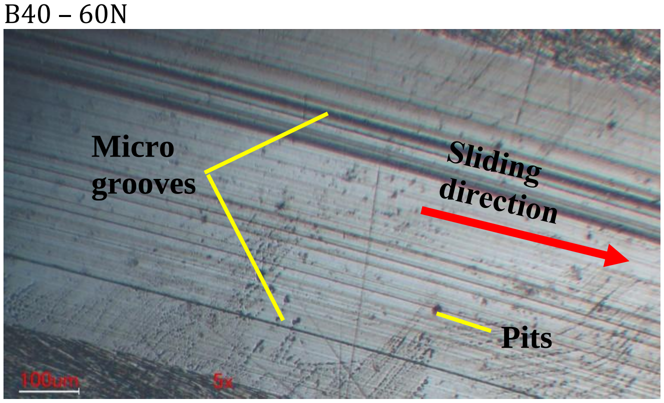
B40 – 30N

- Severe abrasive wear
- Grooves parallel to sliding direction
- Obvious deep grooves



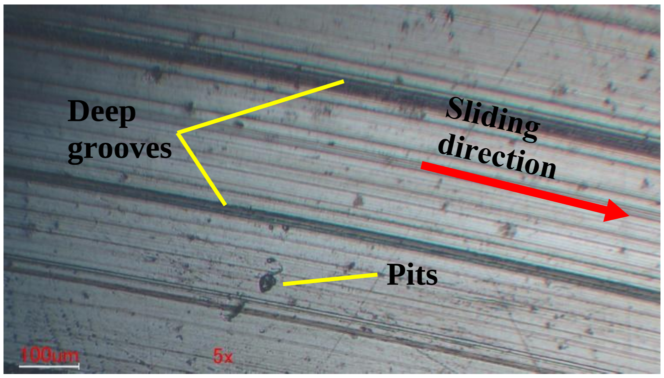
B40 – 60N

- Severe abrasive wear
- Grooves parallel to sliding direction
- Obvious deep grooves



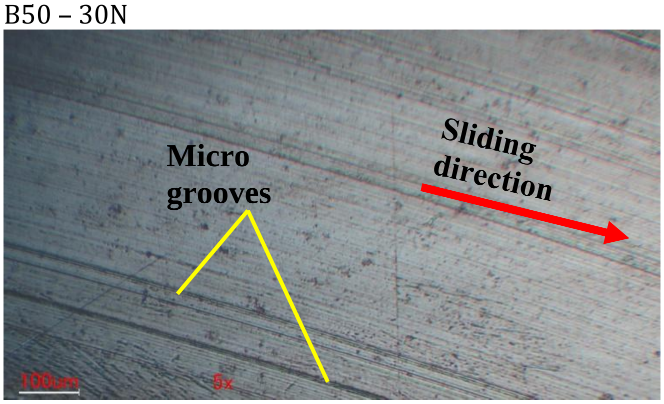
B40 – 90N

- Severe abrasive wear
- Grooves parallel to sliding direction
- Obvious micro grooves



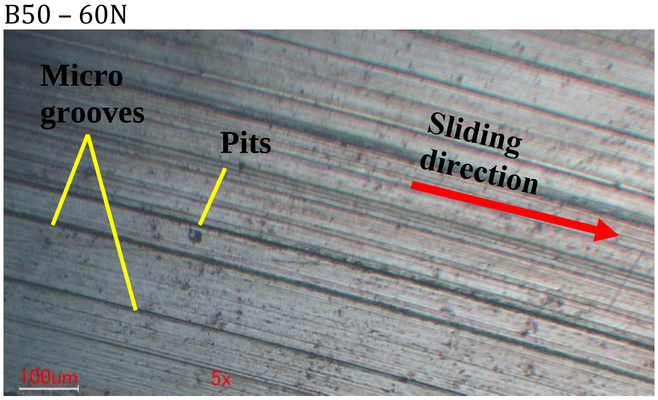
B50 – 30N

- Severe abrasive wear
- Pits (black dots)
- Grooves parallel to sliding direction
- Obvious deep grooves



B50 – 60N

- Mild abrasive wear
- Grooves parallel to sliding direction
- Obvious micro grooves



B50 – 90N

- Severe abrasive wear
- Grooves parallel to sliding direction
- Obvious micro grooves

CONCLUSIONS

Based on this study, the following conclusions can be summarized:

a. As the load increases, coefficient of friction also increases except for B10 lubricant, which probably caused by the lubricant's oxidation and film instability. B30 was considered the most ideal bio-lubricant to be used to minimize the friction between two surfaces for variety of loads.

b. In terms of weight loss of the aluminum wear disc, lubricant with lower viscosity resulted in greater amount of total material removal which was 36.9mg for B10, 17.5mg for B20, 14.6mg for B30, and 8mg each for B40 and B50 lubricant. Thus, lubricant with higher viscosity is preferable to reduce material removal due to sliding contact.
c. The wear rate is lower for lubricant with higher blending ratio. Except for B20, the wear rate of the other lubricants was lower at 90N than that of 60N. The increased load might have caused in more sludge formation or contamination, which have caused the viscosity of the lubricants to increase which resulted in lower wear rate.
d. Abrasive wear with different severity was produced on the surface of the aluminum wear disc. In addition, there were also formation of grooves and pits. The bio-lubricant reduces the effect of grooves, pits, and cracks on the surface of the wear disc especially when B50 was applied, owning to its higher viscosity.

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