WEAR MAPPING MECHANISM MAPPING FOR DIESEL-DILUTED BIOLUBRICANT

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WEAR MAPPING MECHANISM MAPPING FOR DIESEL-DILUTED BIOLUBRICANT

ABSTRACT

As a result of concerns about fossil fuel depletion and climate change, tough legislation requiring automobiles to utilize renewable fuels, mainly bioethanol, have been enacted. In fact, the friction caused by the piston ring and the cylinder wall, which is the biggest source of friction in an engine, is caused by a lot of fuel getting into the lubricant from unburned fuel, which has a lot of heat of vaporization to make it easier for fuel to get into the crankcase. Recently, bio-based lubricant has been mixed with gasoline at ever higher concentrations, and the amount of fuel that builds up in the crankcase is significant. It is important to investigate the tribology of wear mechanism mapping for diesel-diluted bio-lubricant. This research shows how biolubricant and special machines can be used to investigate how things wear. Many goals were met in this study, which looked at how fuel dilution in bio-lubricant affected performance, physicochemical and oil ageing, as well as how it affected the lubricant itself. The fourball tester tribotester machine can be used to look at friction and wear in bio-lubricant oils. Because of its excellent lubricity and resistance to oxidation, the trimethylolpropane trioleate (TMPTO) ester was chosen as the bio-based base stock in this study. The esterification of oleic acid with TMP alcohol yielded TMPTO. From this study, the last goal is to make a wear map of the steel ball. The fourball tester method was used in the research, which is a standard way to figure out how lubricant diesel fuel is used. For each fuel sample, microscopic views of the test ball wear scars, as well as the areas that have been considered when measuring the diameters of the scars, were shown. When make a wear map, compare two samples that are in different conditions, like temperature and rotation speed. This wear map is the main goal of this project.

Keywords: *Tribology, Wear mapping, frequency, bio-lubricant, fuel dilution.*

PAKAI PEMETAAN MEKANISME PEMETAAN UNTUK BIOLUBRICANT DIESEL-CAIR

ABSTRAK

Hasil daripada kebimbangan mengenai kehabisan bahan api fosil dan perubahan iklim, undang-undang keras yang memerlukan kereta menggunakan bahan api boleh diperbaharui, terutamanya bioetanol, telah digubal. Malah, geseran yang disebabkan oleh gelang omboh dan dinding silinder, yang merupakan sumber geseran terbesar dalam enjin. Adalah penting untuk menyiasat tribologi pemetaan mekanisme haus untuk pelincir bio yang dicairkan diesel. Penyelidikan ini menunjukkan cara pelincir bio dan mesin khas boleh digunakan untuk menyiasat cara sesuatu barang dipakai. Banyak matlamat telah dicapai dalam kajian ini, yang melihat bagaimana pencairan bahan api dalam bio-pelincir menjejaskan prestasi, fizikokimia dan penuaan minyak, serta bagaimana ia mempengaruhi pelincir itu sendiri. Mesin tribotester penguji fourball boleh digunakan untuk melihat geseran dan haus dalam minyak bio-pelincir. Kerana pelinciran yang sangat baik dan rintangan pengoksidaan, ester trimethylolpropane trioleate (TMPTO) telah dipilih sebagai stok asas berasaskan bio dalam kajian ini. Pengesteran asid oleik dengan alkohol TMP menghasilkan TMPTO. Daripada kajian ini, matlamat terakhir adalah untuk membuat peta haus bola keluli. Kaedah penguji fourball digunakan dalam penyelidikan, yang merupakan cara standard untuk mengetahui cara bahan api diesel pelincir digunakan. Untuk setiap sampel bahan api, pandangan mikroskopik bola ujian memakai parut, serta kawasan yang telah dipertimbangkan semasa mengukur diameter parut, ditunjukkan. Apabila membuat peta haus, bandingkan dua sampel yang berada dalam keadaan berbeza, seperti suhu dan kelajuan putaran. Peta pakai ini adalah matlamat utama projek ini.

Kata kunci: Tribologi, Pemetaan pakai, kekerapan, bio-pelincir, pencairan bahan bakar.

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LIST OF SYMBOLS AND ABBREVIATIONS

AISI	:	American Iron and Steel Institute.
ASTM	:	American Society for Testing Materials.
DLC	:	Diamond-Like Carbon.
EDS	:	Energy Dispersive X-Ray Spectroscopy.
FC/COF	:	Friction Coefficient.
FTP		Flash Temperature Parameter.
GP/WS_2	:	Graphene/Tungsten Disulfide.
HFRR	:	High Frequency Reciprocating Ring.
RON	:	Research Octane Number.
SAE	:	Society of Automotive Engineers.
SEM	:	Scanning Electron Microscope.
SO	:	Synthetic Oil.
TAN	:	Total Acid Number
TBN	:	Total Base Number
VI	:	Viscosity Index
WSD	:	Wear Scar Diameter
FBL	:	Fresh Bio-based lubricant
DFBL	:	Diluted Diesel Fresh Bio-based lubricant

CHAPTER 1: INTRODUCTION

1.1 Overview

Biogenic fluids have become more popular because of the rise in demand for crude oil, its negative effects on human health, and international calls to cut down on greenhouse gas emissions (GHGs). It is also a problem that fossil fuels are running out and having bad effects on the environment. Across the world, there have been a lot of efforts to use more environmentally friendly fuels in cars to cut down on the use of fossil fuels. Exhaust gas recirculation, ecologically friendly alternative fuels, and controlled burning procedures are only a few strategies to mitigate the detrimental impacts of automobiles on the environment. Biodiesel, on the other hand, seems to be the most likely fuel to solve these problems because of its suitability and similarity to diesel fuel. All the time, people are trying to find new sources of transportation fuel that engines can use (P. Singh & V. Goel ,2018). Lubricants are usually made with petroleum fuels. According to Goel (2018), worldwide demand for lubricants is predicted to expand at a 2.0 percent annual pace by 2020 because there are more than 600 million cars on the road and 7 billion people in the world. More than that, about half of the used lubricants in Europe are not properly thrown away, which harms the environment by evaporation. Constraints imposed by tougher pollution requirements and the high cost of crude oil-based fuels are increasing interest in alternate fuels.

1.2 Background

Various technologies, such as coatings, are now employed to increase the performance of car engines (Quazi et al., 2016b), laser texturing (A Arslan et al., 2016) lowering component weight and altering the composition of automotive lubricants. Lubricants are used for several purposes, including lubricating metal-to-metal contact surfaces in engines. Lubricants preserve engine components such bearings, pistons, rings, cylinder liner, and valve train by coating them. By neutralizing acids with an alkaline agent, lubricants protect engine parts from corrosion. They also transport waste goods or sludge away from the location where they were created. According to McMillan (2004) Lubricants help the engine run more smoothly because they cut down on friction. The interaction of lubricants and fuels in the engine's lubrication system serves a purpose, but it is not the only reason for this interaction. When the engine is running, unburned fuel always makes its wayto the oil sump through the piston ring-cylinder liner system. This eventually makes the lubricant dirty because fuel is mixed with other things, the concentration of oil additives like dispersants, detergents, and other things that protect against wear, corrosion, and oxidation is reduced. Viscosity and the quantity of base oils in the lubricant will decrease as the oil becomes less viscous (Hu et al., 2015a). During short trips and cold starts, the lubricant may have a lot of water in it because bioethanol ishygroscopic and draws water from the air (Boons et al., 2008).

According to H. Kuszewski et al.(2017), numerous methods are used to measure the lubricity of fuels. The most often used technology is the HFRR, which utilizes a loaded steel ball as the operating component. The ball is pushed against a fixed steel plate that is submerged in the test fuel, and it then repeats the cycle at a predetermined speed and stroke. In this procedure, the diameter of the wear worn on the ball is used to determine fuel lubricity. The HFRR method was used to obtain the findings of a study on fuel lubricity. According to P. Singh, V. Goel (2018) the researchers have put a lot of effort into developing bio-lubricants for diesel engines. However, there is relatively little research on tribological features of waste cooking oil (WCO) biodiesel. The purpose of this study is to focus on WCO's perspective in the automobile industry. The potential viability of this bio-based lubricantleads to government restrictions on the use of biogenic fluids in place of mineral oils, such as those imposed by environmental protection groups.

Tribology is a subfield of engineering science concerned with the wear, friction, and lubrication of various machine components as they move in relation to interacting surfaces. A qualified engine tribologist's primary objective is to employ effective and proper lubrication to ensure that all engine sliding components experience the least amount of friction and wear possible. The improved tribological performance of the engine may result in a range of benefits, including increased fuel economy, increased brake power, reduced lubricating oil consumption, reduced exhaust emissions, increased durability, and extended engine life with little maintenance.

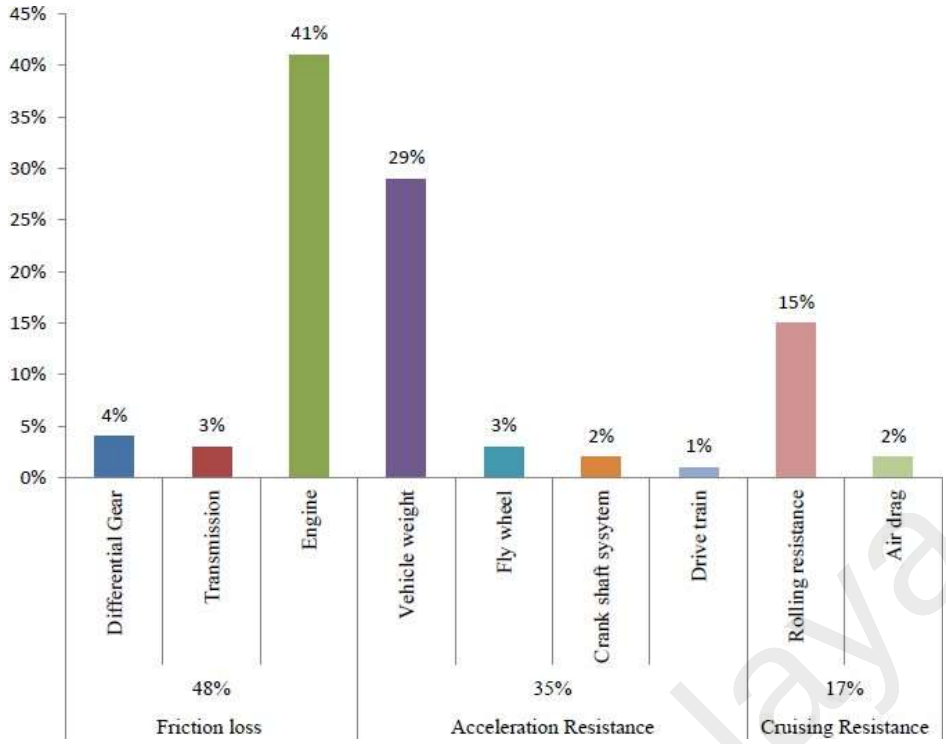


Figure 1.1: Energy consumption in an internal combustion engine

(M. Sudan Reddy Dandu and K. Nanthagopal ,2019)

According to Fig. 1, engine fuel consumption can be lowered by 1.5 percent with a ten percent reduction in mechanical losses. Furthermore, it was discovered that friction losses, which include friction in the piston skirt, piston rings, bearings, valve trains, crankshaft, and transmission, use 48 percent of the energy produced in an engine

1.3 Problem statement

As a result of their low cost, high performance, and ease of production, bio-lubricants are increasingly being used in gasoline engines as an alternative to fossil fuels. Industrialization and modernization have resulted in an increase in global energy demand with growing environmental concerns, it has been determined that sole reliance on petroleum-based products such as fuel and lubricants is unsuitable. These items, which are both nonbiodegradable and harmful to the environment, require research and development to find more sustainable alternatives.

As a result, research into developing alternatives to petroleum-based products has gathered significant momentum in recent years. Particularly in the field of alternative fuels, which have been widely used to partially replace gasoline and diesel. However, most of the bio-based lubricant research is still in its infancy. This could be a result of a lack of initiative to promote bio-based lubricants as a viable alternativeto conventional lubricants. This also results in a dearth of understanding regarding the ability of bio-based lubricant to substitute commercial lubricant in real-world operating conditions.

In this study, the focus will cover an occurrence that is normal in actual lubricant working condition which is fuel dilution. Fuel dilution occurs when unburnt fuel mixed with the lubricating oil causing in fuel contamination hence resulting in deteriorating in lubricant performance. A high rate of fuel dilution in an engine's cylinder wall and piston rings is particularly worrisome because this is the area in which friction happens the greatest with the utilization of alternative fuel, biodiesel and bioethanol may have an interesting effect on the bio-based lubricant as they have a higher water content compared to conventional fuel. The lack of study on the fuel dilution of bio-based lubricant for diesel engine may be the hurdle that hinder bio-based lubricant to not be commercialized. In-depth focus on biodiesel is given as the Malaysian Government is currently using biodiesel as alternative fuel but no initiative to use bioethanol. There have been few studies that have extensively researched the lubricating impact of bio-based lubricants as well as the enhancement of bio-based diluted lubricant's lubricating performance. An investigation of fuel dilution can help researchers and practitioners alike.

1.4 Research Objectives

This experimental investigation examines the influence of bio-lubricant interaction on the tribological behavior of components that are critical in determining friction and wear losses on rotational speed moments. The research has two objectives are as follows:

1. To study the effect of fuel dilution in bio-based lubricant on tribological performance and physicochemical properties
2. To produce wear map mechanism when using bio-based lubricant and fuel-diluted bio-based lubricant.

1.5 Scope of the study

Concerns about the depletion of fossil fuel reserves and climate change have increased efforts to develop alternatives to petroleum-based products. Alternative fuels such as biodiesel and bioethanol have been integrated into commercial engines. These, however, are damaging to the engine oil, as engine oil is more critical in the piston ring and cylinder wall, experience the greatest amount of gasoline dilution from unburnt fuel. The goal of this study is to see how fuel dilution affects engine performance, physicochemical qualities, oil ageing, and wear mechanism of a totally designed biobased lubricant. The engine oil will be diluted with varying concentrations of biodiesel and gasoline.

This study can provide a more holistic guarantee for the use of green technology, as the project's primary focus will be on biodiesel and bio-based lubricants. Fuel dilution is critical because the fuel may contain more water, which accelerates the ageing process of the bio-lubricant. This is because the bio-lubricant is hydrolyzed, which occurs more frequently in the presence of water. Lubricity is determined in a multitude of ways. The most often used method is the four-ball tester, which utilizes a loaded steel ball as the operative element. The ball is propelled by an adequate force against a fixed steel ball immersed in the tested fuel and reciprocates at a predetermined load, temperature, and torque. In this procedure, the diameter of the wear scar on the ball is used to determine the lubricity of the fuel.

This study will investigate the severity of lubricant condition due to fuel dilution. In this study, the fuel will be blended at different concentration and then they will be introduced in the bio-lubricant. The samples will be tested using fourball tribo- tester for their performance and wear mechanism. From this data, a wear map will be produced using varying speed and temperature. The physicochemical properties and chemical structure will also be tested. At the conclusion of the study, a comprehensive wear mapping for bio-lubricant will be introduced, as well as a more in-depth knowledge of the wear process.

1.6 Limitation of study

In this study, the fundamental constraint is the lack of a tribology machine tester since laboratory equipment like the HFRR does not work well. Therefore, throughout this study can use four-ball tester. All these specimens were obtained commercial. This study only use TMP oil as fresh bio-based lubricant and diesel used as sample material and the results are generalized to also apply to other types of bio lubricant. The number of test specimen and sample are also limited however it can be run up to three runs on as good for do error analysis later.Besides, the variable for the experiment also only vary for speed and temperature conditions as the load cannot be varied due to sensor problem on the tester.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

As a result of its advanced automotive technology, North America has emerged as the world's leading manufacturer of bio-based lubricants. Asia Pacific is predicted to grow at the quickest rate in the next years as a consequence of various national programmes to boost domestic manufacturing, such as India's 2014 'Made in India' programme. These programmes will aid in the development of a number of growing Asian economies by promoting the use of bio-based lubricants in industrial and non-industrial sectors (Grand View Research, 2016). Chevron, ExxonMobil, Royal Dutch Shell, British Petroleum, Castrol, Petronas Lubricants International, and Kluber International all compete in the bio- based lubricant industry. Once bio-based lubricants are more widely marketed, these businesses progressive research and development (R&D) activities on bio-based lubricants may influence market dynamics. The demand of energy in transportation sector has hiked with the growth of population and it keeps increasing. This chapter reviews the tribological analysis of automotive engine, friction analysis and energy distribution, wear analysis of engine components, fuel dilution in automotive lubrication and the effect of dilution on the physicochemical attributes and performance of lubricants was investigated.

2.2 Tribological Analysis of Automotive Engine

2.2.1 Friction analysis and energy distribution

Friction losses in an IC engine are between 10% and 15% due to the piston assembly,bearings, and valve train. The coefficient of friction varies with engine speed and load (Allmaier et al., 2015). Friction can be as low as 10% at high loads and as high as 30% or more at low loads. Figure 2.1 depicts the fraction of total fuel energy utilized by gasoline engines, with mechanical friction accounting for around 4% to 15% of total fuel energy (Richardson, 2000a). This estimate is based on normal engine running and excludes very extreme conditions, such as idling and extremely light loads, where the majority of fuel energy is needed to overcome friction. Modern engines have thermal efficiency ranging from 38% to 50%. Accordingly, mechanical friction accounts for between 10% and 30% of engine power production, although it can reach 100% while the engine is idle. A further 40 percent of the engine's gross (indicated) power production can be lost to pumping and auxiliary losses in addition to mechanical friction, according to stachowiak and batchelor (2005). Rubbing friction accounts for approximately 75% of mechanical losses (Heywood, 1988).

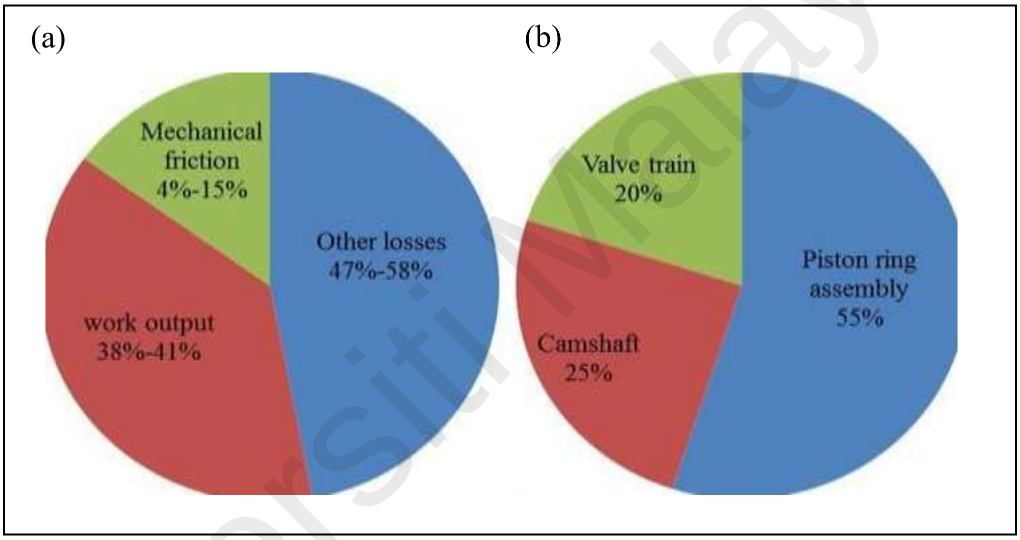


Figure 2.1: Image of (a) distribution of total energy, (b) distribution of friction in a fired engine (Richardson, 2000b)

2.2.2 Wear analysis of engine components

The assessment of damaged surfaces caused by metal-to-metal contact in engine components is referred to as wear analysis. In general, operating circumstances impacting engine component wear include load, speed, temperature, and lubrication. Figure 2.2 depicts the four major forms of wear that commonly occur in engine sliding components: adhesive wear, abrasive wear, fatigue wear, and corrosive and oxidative wear.

2.2.2.1 Abrasive wear

Between the two surfaces, abrasive wear occurs. Damage to a moving mating surface is caused by contamination in the form of an abrasive groove. Plowing in the sliding section removes a specific amount of surface material. Abrasive wear is caused by two distinct processes. It's called two-body abrasion when metal bumps on one surface cut into another metal surface right through it. Due to insufficient lubrication, the contact occurs during the boundary lubrication regime. When a particle or bit of worn debris becomes trapped in one of the metal surfaces and is squeezed between the two, three-body abrasion occurs. Scratching and ploughing can occur when the particle size exceeds the fluid film thickness.

2.2.2.2 Adhesive wear

Material transfer from one touching surface to another is referred to as adhesive wear. It occurs when asperities on two metal surfaces that are in close proximity spot-weld together and then swiftly break apart the metal in small, discrete spots owing to high loads, temperatures, or pressures. Various factors, including relative motion, plastic deformation, and direct contact between the rubbing surfaces, all contribute to adhesive wear.

2.2.2.3 Fatigue wear

During rolling and sliding, this phenomenon happens when a treated metal is removed from the surface of the material by cracking and pitting, or when the material's surface is weakened because of cyclic elastic loading or tension. Fatigue wear particles are generated when a worn-off surface is split by the periodic creation of microcracks on the surface, causing the surface to become split.

2.2.2.4 Corrosive and oxidative wears

Corrosion products are formed when corrosive gases or liquids react chemically with the contact surface. When solid materials come into touch with their corrosive environment, a wear process is triggered and occurs. The tribochemical reaction causes a reaction layer to form on the surface of the material. This layer breaks down the substance's chemical bonds, which are then broken down by friction. Oxidative wear is a related phenomenon that happens when unlubricated metal surfaces scrape against each other in the presence of air or oxygen. The primary distinction between corrosive and oxidative wear is that during oxidative wear, oxide particles combine with metal, forming a debris layer. The use of bioethanol as a vehicle fuel produces a slew of corrosive wear issues in engines. Bioethanol is a hygroscopic substance that readily absorbs water. Water concentrations as little as 1% can result in considerable increases in wear (Gwidon & Andrew, 1993).

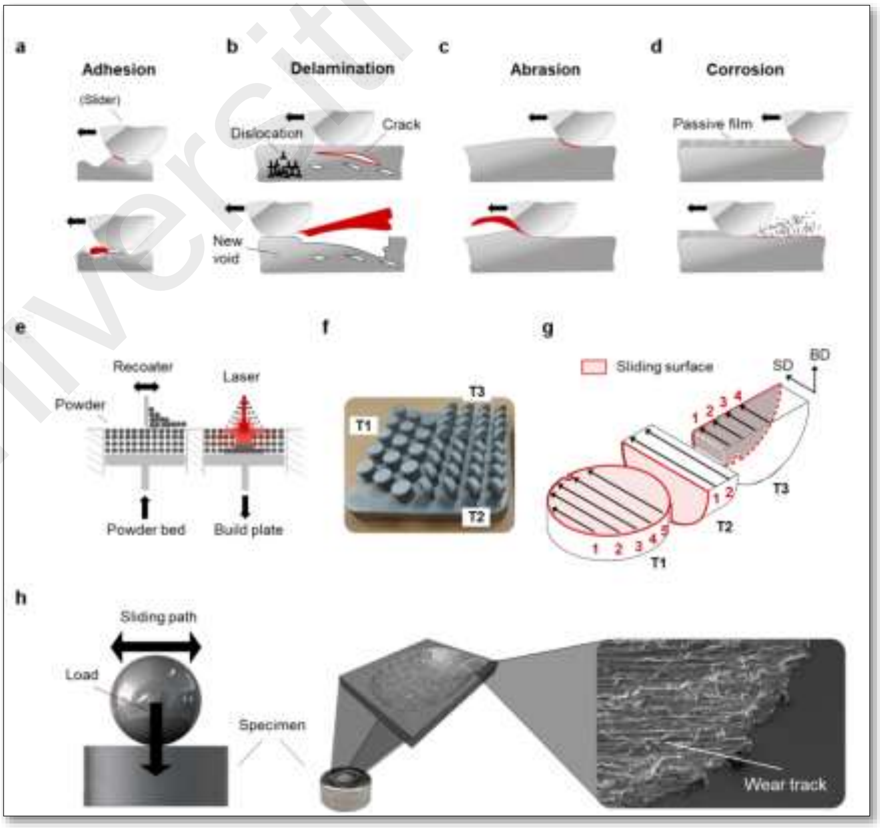


Figure 2.2: Image of wear commonly happened on sliding engine components (Koji Kato& Adachi, 2000)

2.3 Fuel dilution in automotive lubricant

On the other hand, Figure 2.3 shows the influence of gasoline on an engine and the effect of lubricant in the piston-ring-cylinder system on an engine. When it comes to automotive lubricants, particularly those used in direct-ignition engines, fuel dilution is a big concern. When unburned gasoline accumulates in the engine crankcase via the cylinder walls, it causes unburned fuel dilution. For a variety of reasons, fuel does not entirely burn inside the combustion chamber of gasoline and diesel engines when they are running. A small amount of unburned fuel departs the engine through the exhaust, while a larger amount impinges on the cold walls of the combustion chamber and is scraped into the oil pan, where it is mixed with the lubricant (S. Shanta et al., 2011). The modes of injectionand the qualities of the fuel have been recognized as the sources of fuel dilution (Gu, 2014; Wattrus, 2013b). Previous research has demonstrated that even a little amount of gasoline dilution can damage the lubricant's physicochemical qualities such as viscosity, total base number (TBN), total acid number (TAN), flash point, oxidation stability, and engine oil additive concentration. This influences the lubricant's lubricating capabilities (S. Shanta et al., 2011; Uy et al., 2011).

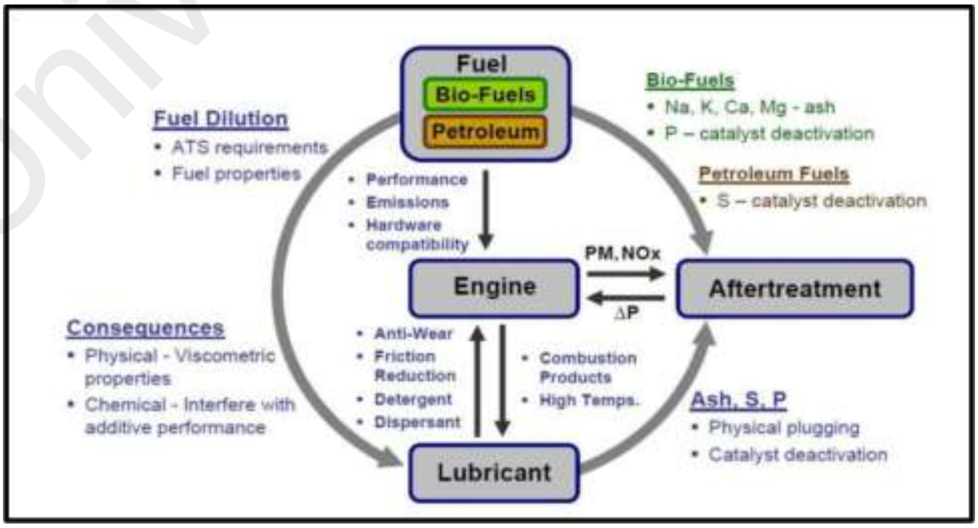


Figure 2.3: Effect of biofuel and lubricant on the engine (Gili et al., 2011)

As previously stated, lubricating oil degradation is exacerbated by fuel dilution, which is a result of fuel quality. Due to bioethanol's high boiling point, engines fueled with it will have considerable starting problems in cold conditions. As a result of this literature review, researchers recommend that investigations into the optimize fuel mixtures like bioethanol and biodiesel blends such as gasoline at various blending concentrations, such as gasoline-bioethanol, be conducted include an examination of fuel properties such as boiling point, heat of vaporization, distillation temperature, and penetrating and solvency properties, as these are all factors affecting the increase in engine oil fuel dilution rates.

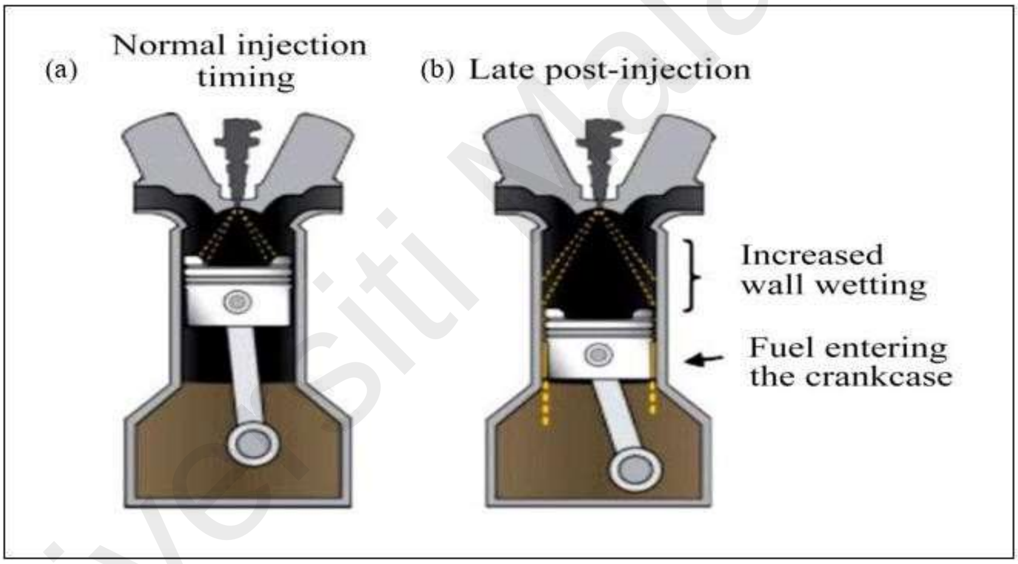


Figure 2.4: Fuel dilution of lubricants based on the modes of injection (Wattrus, 2013a)

2.3.1 Fuel dilution rate of lubricant

A significant amount of gasoline dilution in the lubricant shows that the lubricant has been seriously contaminated. It is well established that fuel dilution decreases the lubricant's quality, and it is important to note that ensuring the lubricant's quality is crucial for guaranteeing optimal performance of lubrication throughout the operating cycle of engine. The limitation design of fuel dilution is generally less than 5% by weight, and any higher degree of dilution is inappropriate since it results in a considerable fall for both the oil viscosity and the concentration of oil additive. This, in turn, diminishes the lubricant's film thickness (Gu, 2014). The impact of gasoline rate dilution towards the properties of automotive lubricants has been studied extensively. According to research, mineral oils characteristics diminish dramatically at 1% fuel dilution and completely disintegrate at 7% fuel dilution. By comparison, whereas synthetic oils enhance their stability resistance at 1% fuel dilution, they lose practically all their lubricating qualities at 7% fuel dilution (Gur'yanov, 2007). Two factors affect the amount of fuel dilution: the rate at which fuel leaves the oil and therate at which fuel enters the oil. This occurs when the fuel does not evaporate and stays in liquid form in the cylinder. The pace at which the oil evaporates is essential in establishing the total dilution rate. It is critical to establish the degree of gasoline dilution and keep it below 5% to maintain the lubricant's effectiveness.

2.3.2 Effect of fuel dilution on the physicochemical properties and performance of automotive lubricants

The growing rate of fuel dilution and the increasing content of biodiesel may result in a shift toward lubricated surface wear mechanisms. Bio-based lubricant diluted builds up in the lubricant lowers the capacity of a lubricant to minimize wear and friction on engine parts. In this part, we'll discuss how bioethanol dilution affects vehicle lubricants' physicochemical properties and performance. The past research on the influence of gasoline dilution on the tribological parameters of engine oil is summarized in Table 2.1.

Table 2.1: Previous studies of lubricant diluted with fuel contaminant

Authors	Methods/Material	Conditions	Results
Assessment of lubricating oil degradation in small motorcycle engine fueled with Gasohol.			
(Tippayawong & Sooksarn, 2010)	- Engine Testing - Bench Wear tester - Mineral oil - Synthetic oil - Gasoline/Gasohol	- Mileage: 3000km - Load: 33N - Speed: 500rpm - Temp:25°C	-Drop Viscosity: 20%-45% -Gasohol Wear: 10% higher -Mineral oil: higher wear -Synthetic oil: Lower wear -Friction (unknown)
The effect of bio-derived fuel blend dilution on the friction and wear behaviour of marine engine oil.			
(Ajayi et al., 2016)	- Engine testing - Unidirectional sliding - Reciprocating sliding - Four-ball wear test - Gasoline, Ethanol Isobutanol - Engine oil: 10W-30	- Load:15N - Velocity: 0.1cm/s - 20.0cm/s - Speed: 10-300rpm, -Frequency: 0.1-5Hz -Four-ball load: 15kg - Speed: 1200rpm, - Temp: 70°C - Time:1h	- Dilution: 3.7%-6% - Viscosity drop: E0: 30%-43% E10: 25%-42% i-B16: 28-46% - No effect on Friction - Slightly affect wear and reduce load-carrying capacity
The frictional response of piston rings while lubricated with the separated stages of lubricant contamination with ethanol and water was investigated using a tribometer.			
(P. De Silva et al., 2011a)	- Plint TE77 -Lubricant: Shell Helix HX7, SAE 5W-30, no friction modifier - Ethanol 95% purity, Water	- Duration: 2h - Liner Temp: 70°C - 110°C, Test Temp: 25-40°C - Speed: 2000rpm -Load: 150N(4 MPa) - Stroke length: 5mm -Cold-start/warm up/ short-journey	-Friction reduction (Separated phase of lubricant-ethanol-water) -Viscosity decreased -Implication: Fuel economy in a fired gasoline engine
The influence of surface texturing, roughness, and fuel type on the tribological reaction of fresh and worn engine oils.			
(Cousseau et al., 2015)	- Tribotest (ball on discs) - Ball: AISI 52100 - Discs: AISI H13 - Engine oil: 5W30 - E22, E100 7%water	- Duration: 20min - Test sample: 3ml - Temp: 40°C - Load: 35 N -Stroke length: 5mm - Frequency: 10 Hz - Max speed: 0.159m/s	-No effect on friction significantly -Slight effect on wear E22 is more oxidized -May cause oxidative wear

2.3.3 Effect on lubricant properties

2.3.3.1 Viscosity

When polluted with bio-based lubricant, the viscosity is significantly reduced. Previous research found that a small amount of diesel diluted bio-based lubricant decreases motor oil viscosity (Spikes & Costa, 2016). Another study looked at the effect of ethanol contamination on engine oil quality by adding 2%, 5%, and 10% adding hydrate and anhydrous ethanol to base and designed oils has several advantages, respectively. The results show that addinga trace quantity of ethanol to the oil, particularly anhydrous ethanol, viscosity of the base and formulated oils is reduced by this method (Costa & Spikes, 2015). The results showed a significant decrease in oil viscosity for Saab 95 and 93 automotive engines running on E85, resulting in a loss of oil lubricity.

2.3.3.2 Total base number and total acid number

The total base number (TBN) is a lubricant's alkalinity value that indicates the lubricant's capacity to resist corrosion. The TBN is critical in neutralizing the total acid number (TAN), which is a measure of the lubricant's proclivity for oxidation. When the engine is running, acidic compounds are created because of fuel combustion and lubricant oxidation, which reduces the TBN and increases the TAN of the lubricant. Several studies have investigated the effect of bio-diesel dilution on the lubricant's TBN and TAN. Jakóbiec and Mazanek (2009) investigated the TBN and TAN compositions of SL/CF SAE 5W-30 motor oil. The trials were conducted on a motor vehicle engine running on two different types of fuel: (1) gasoline 95 percent (v/v) and (2) gasoline with a 5% (v/v) ethanol addition. The testing mileage ranged between 5000 and 30000 kilometres. Additionally, other researchers observed that ethanol gasoline has a greater oxidation level, which raises the TAN of the engine oil (Friedl & Stimming, 2013; Yusoff et al., 2015).

2.3.4 Effect on tribology performance

2.3.4.1 Friction

It has also been studied how tainted lubricants for automobiles due to the presence of ethanol and water affect the friction qualities Per R. De Silva (2012), ethanol and water contamination influenced the lubricant's friction qualities during cold start, warm up, and short trips. Surprisingly, results obtained using a tribometer demonstrated Lubricating the region between the piston rings and the cylinder liner results in a considerable decrease in friction that has been polluted with ethanol and water, as opposed to the prescribed oil used in this experiment. When ethanol and water are added to a lubricant, the lubricant's friction-reducing properties increase.

2.3.4.2 Wear

When two sliding surfaces come into touch with each other, the substance on one of them wears away. Additionally, some studies have examined the impact of bio-based lubricant dilution on engine wear parameters. Ajayi et al. (2016) studied the influence of gasoline dilution rate on the friction and wear behavior of three lubricants exposed to various type of fuels. The experiments were conducted in a boundary lubrication regime. Additions of modest concentrations to engine oil appear to have little effect on the degradation process, according to the results of this study. Some particles were found at high ethanol concentrations, although engine deposits were found at low ethanol concentrations. Sludge and engine deposits should be avoided since they clog valves and orifices.

2.4 Bio-based Lubricants

The term "bio-based lubricant" refers to lubricants made from bio-based materials such as animal fats, vegetable oils, or any other ecologically friendly hydrocarbon. Biodiesel has been shown in previous study to improve the tribological qualities of diesel when combined. Despite these benefits, bio-based lubricant use is still restricted today due to significant hurdles associated with its performance, manufacturing scale, and lack of government assistance. The oxidative stability and low temperature qualities of some bio-based lubricants, notably crude vegetable oils, are substandard.

2.4.1 Bio-based Lubricants Interactions

In order to function well in engine applications, the lubricant must be able to withstand the extreme circumstances that are common in them, such as high temperatures, high pressure, and continual exposure to acidic pollutants, which can cause the oil's consistency to deteriorate over time. As a result, it is critical to consider these variables while developing bio-based engine lubricants. Until now, research has been undertaken to determine lower-cost manufacturing techniques and alternative feedstocks while utilizing a country's resources, but the number of studies conducted has been extremely limited. The environmental friendliness of vehicle bio-based lubricants has been established (Igartua et al., 2009).

Lubricant waste disposal and mismanagement have long been a source of worry for the environment because to its slow breakdown rate and high toxicity. Due to the large range of potential uses, research into bio-based lubricants has increased dramatically during the past few years. Green chemistry advancements have been the primary driver of the creation of ecologically friendly lubricants. Over the last decade, the dependability of biodegradable lubricants has risen dramatically to the point that some now exceed conventional lubricants. The word "environmentally acceptable" refers to the lubricating products' biodegradability, toxicity, and renewability (Soni & Agarwal, 2014).

There are four fundamental factors that are frequently utilized to determine if a substance is biodegradable. In the case of a particular material, either of the following laws may apply: (1) vegetable oils (triglyceride esters) and synthetic esters are more biodegradable than pure hydrocarbons; (2) high viscosity and/or molecular weight reduce biodegradability; (3) more polar groups increase dispersibility; and (4) branched hydrocarbon chains decrease biodegradability (Canter, 2020). Because lubricants are mostly water-insoluble compounds, the ECD 301B biodegradation test is extensively utilized (DOFO Chemicals, 2005). Regrettably, because bacterial and microbe populations vary according to region, season, and natural environment, the OECD 301B test may have low reproducibility.

Mannekote and Kailas (2011) conducted research in which they examined the tribological qualities of fresh and aged coconut and palm oils during a 100-hour endurance test. The studies indicated that fresh bio-based lubricants have comparable anti-wear qualities to conventional motor oil. However, because vegetable oil has a low oxidative stability and lacks additives, fluctuations over time were detected during the endurance test. When used to fuel a single cylinder, four-stroke (4T) diesel engine, Cheenkachorn and Fungtammasan (2010) and Reddy, Kabra, Kunchum, and Vijayakumar (2014) discovered that palm-based engine oil blends performed similarly to conventional engine oils in terms of engine power and emissions. They are, however, an attractive alternative to the fact that the engine oil is sustainable and non-toxic to the environment, hence demonstrating superior tribological features.

The most often employed alcohol for transesterification is TMP, which results in the creation of TMP ester. Transesterification of TMP can be accomplished using vegetable oil fatty acid methyl esters (FAMEs), biodiesel, estolides, or even waste cooking oil. The derivation of TMP from FAME has been shown to result in a decrease in pour points and an increase in oxidative stability without affecting the viscosity or lubricity of the product when sodium methoxide is used as a catalyst, the resultant TMP ester's oxidative stability is further increased, as observed in a few investigations (Ghazi et al., 2009; Gunam Resul et al., 2012). In comparison to other TMP esters, palm oil ME-based TMP ester exhibited superior low temperature capabilities, with a pour point as low as -37 °C (Yunus, Fakhru'l-Razi, Ooi, Omar, & Idris, 2005).

In recent years, tri-esters produced from various alcohol esters have been evaluated for use in the manufacturing of bio-based lubricants (Gryglewicz et al., 2013; Kamalakar et al., 2013; Kamalakar, Sai Manoj, Prasad, & Karuna, 2015; Nagendramma, 2011). According to Gryglewicz et al. (2013), the usage of 2-ethyl hexanol (2-EH) resulted in an ester with a higher pouring point (-31.3 °C) when compared to NPG and TMP. Additionally, when NPG and TMP transesterification of FAMEs are utilized, a longer reaction time is required. Padmaja et al. (2012) synthesized a novel class of unsaturated medium chain fatty acid polyol esters through transesterification of 10-undecenoic acid (10-UDA) with three different esters (TMP, PG, and PE). Among the three final products, TMP-based esters demonstrated superior lubricating qualities in terms of pour point, flash point, and oxidative stability.

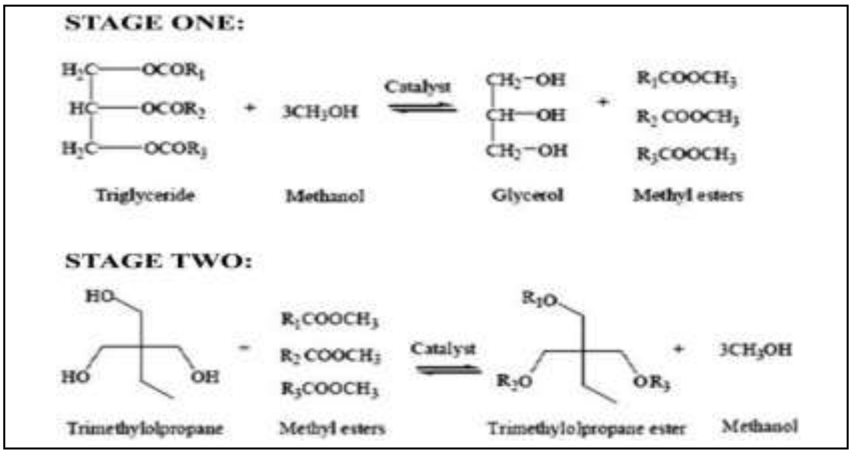


Figure 2.5: Overall transesterification process for TMP ester

(Heikal, Elmelawy, Khalil, & Elbasuny, 2016)

2.4.2 Tribological Characteristics of Bio-based Lubricant

As an alternative lubricant source, bio-based lubricants provide various benefits over mineral-based lubricants, including renewability, environmental friendliness, biodegradability, and low toxicity. Numerous trials have been conducted todetermine the dependability of various lubricants. While the testing methods and equipment employed varied, the primary purpose remained the same: to determine the capacity of a certain bio-based lubricant to decrease friction and wear. Because friction and wear are inextricably related, a material's tribological behavior is essentially defined by its coefficient of friction (COF) and the consequent wear scar diameter on testing interfaces.

In general, vegetable oil-based lubricants (pure or chemically modified vegetable oils) are proven to be more lubricious than mineral oil-based lubricants,particularly when it comes to boundary lubrication, as various studies have demonstrated (Jagadeesh & Satish, 2012; Krzan, 2010; Sapawe, Syahrullail, & Izhan, 2014; Syahrullail et al., 2014). This is primarily because fatty acid molecules in vegetable oils may react with metal surfaces to generate a metallic soap layer with poor shear strength. This straightforward response can be illustrated in Figure 2.6. Theapplication of this metallic soap coating efficiently reduces the friction coefficient(COF) between surfaces (Bowden & Tabor, 2001).

However, the same studies have also reported increase in the volume of wear when bio-based lubricants were used on tribotesting interfaces. The continuous sliding motion would result in the metallic soap film being continuously extracted. The metallic soap film reformation is then replicated by the same chemical reaction repeatedly, resulting from increased wear (Bowden & Tabor, 2001). The increased in wear was also contributed by the corrosive effect of peroxides and free fatty acids as products of oxidation (Jagadeesh & Satish, 2012; Syahrullail et al., 2014).

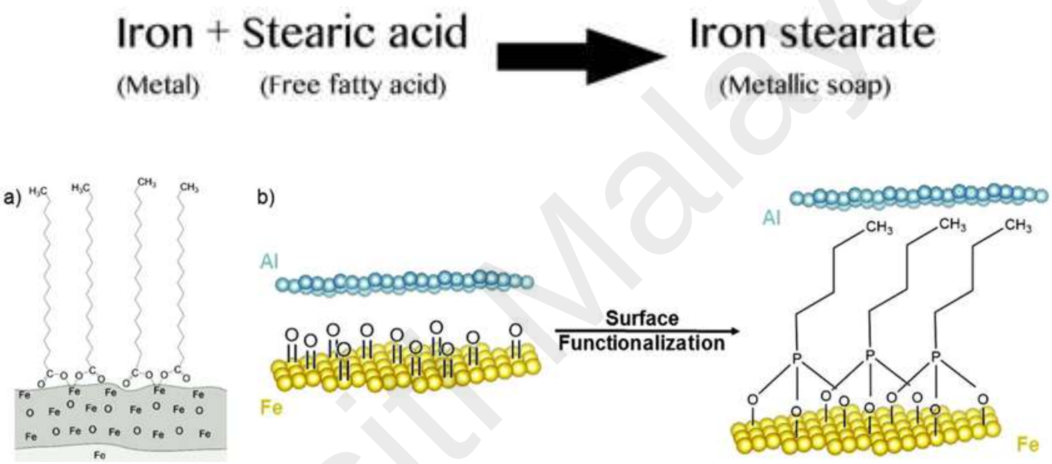


Figure 2.6: Formation of metallic soap

Chemically modified vegetable oils (CMVOs) are more helpful than pure vegetable oil when used as a plain lubricant, particularly in terms of friction and wear. This is mostly since CMVOs have a greater viscosity than their unmodified counterparts, which allows for more effective fluid film shaping during operation. Additionally, CMVOs have excellent oxidative stability, which considerably reduces the development of oxidation products (free fatty acids and peroxides), hence reducing overall wear. Lubricants resources that come from renewable sources superior anti-wear and lubricity qualities and include a high proportion of long-chain fatty acids (C18 and higher) (Bowden & Tabor, 2001; Reeves et al., 2015).

Low COF values and little wear may be achieved with vegetable oils with a high oleic acid content (C18:1), which generates a thick monolayer of fatty acids that decreases Contact with asperity and protection of metallic surfaces throughout an operation (Reeves et al., 2015).

2.5 Tribological investigation of various experimental setups

Over the years, many experimental settings have been used to study tribological inquiry interactions, including laboratory simulations, IC engine dynamometers, and tribological bench tests. Previously, researchers struggled to establish any meaningful relationships between the various testing parameters (engine speed and load) and tribological properties seen during actual engine dynamometer testing. As a result, laboratory tribological bench tests are favored since they allow for the customization of test conditions and provide consistent final findings. Additionally, laboratory bench testing is far less expensive as compared to the complexity and high expense of engine changes.As a result, studies on tribological behavior of piston-ring-cylinder-liner contact are few and far between used laboratory bench testing. Table 2.2 summarizes experimental research in which vehicle contact was simulated in a controlled tribo-testing setting.

Table 2.2: Automotive experimental setup simulation using tribometers

Tribotester	Lubricant	Contact Geometry	Temp.	Load	Sliding Speed	Ref.
High-stroke, Reciprocating Tribometer	SAE 30	Actual piston ring-cylinder liner segment	70 °C	160 N	500 rpm	(Gullac & Akalin, 2010)
Pin-on-Disc Tribometer	SAE 20W40, Biolubricant	White cast iron disc-alloyed cast iron pin	120 °C	50 N	300 rpm	(S Arumugam & Sriram, 2012)
HFRR	SAE 20W40, Biolubricant	Actual piston ring-cylinder liner segment	60 °C	80 N	10 Hz	(S Arumugam & Sriram, 2013)
HFRR	SAE 15W40	Actual piston ring-plate (cylinder liner material)	20, 40, and 100 °C	240 N	10 Hz	(Truhan, Qu, & Blau, 2005)
Pin-on-Disc Tribometer	SAE 20W50	IC engine rod bearing piece-disc	25 °C	1.6 kg	77 rpm	(Ettefaghi, Ahmadi, Rashidi, & Mohtasebi, 2013)
Reciprocating Tribometer	Group III base oil with additives	Actual piston ring-cylinder liner segment	100 °C	-	25 Hz (1500 rpm)	(Morina et al., 2011)
High-stroke, Reciprocating Tribometer	SAE 15W40	Actual piston ring-cylinder liner segment	70 °C	160 N	240 rpm	(M. Gulzar et al., 2016)
Universal Mechanical Tester	SN/GF-5 engine oil	Actual piston ring-cylinder liner segment	100 °C	50, 100, 250, 400 N	10 Hz	(C. Xue, Wang, Wang, Wang, & Yan, 2019)
Pin-on-Disc Tribometer	SAE 15W40	AISI 316 disc-AISI 304 pin	25 °C	5 kg	300 rpm	(Balakumar, Sriram, & Arumugam, 2018)
Reciprocating Tribometer	SAE 15W40	Actual piston ring-cylinder liner segment	80 °C	100, 300 N	10 Hz	(Grabon, Pawlus, Wos, Koszela, & Wieczorowski, 2018)

2.6 Wear mapping

Under specific sliding conditions, wear mapping can be utilized to depict wear and friction data in an understandable form that allows for prediction of the expected pattern of wear. For example, an abrasive wear map may be created by employing degree of penetration (of asperities) and shear strength at the contact surface as the critical parameters. There are numerous circumstances that can be employed in constructing a wear map. However, majority wear maps have been generated under room temperature circumstances, and few have considered sliding at high temperatures or the impact of different surfaces. Figure 2.7 illustrates a wear map based on sliding speed and temperature differences.

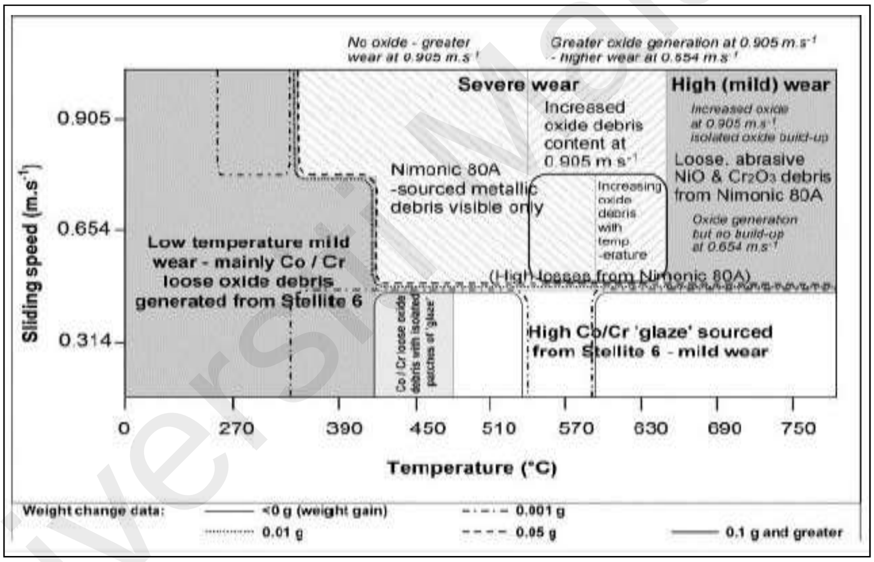


Figure 2.7: Example of wear map using different speed and temperature.

Wear maps may be used to see the mechanical changes that occur on the worn surfaces of a material and its counterpart over time and under a variety of operating situations. It is also necessary to grasp the wear mode and wear processes of the material on the worn surface and counter face to comprehend the material degradation mechanisms and chemical effects in contact. Hernandez (2012) utilized the wear and friction data to create a wear map characterizing the wear behavior of tool steel because of changes in temperature, as seen in Figure 2.8. Additionally, it discusses the primary processes of wear found at each temperature.

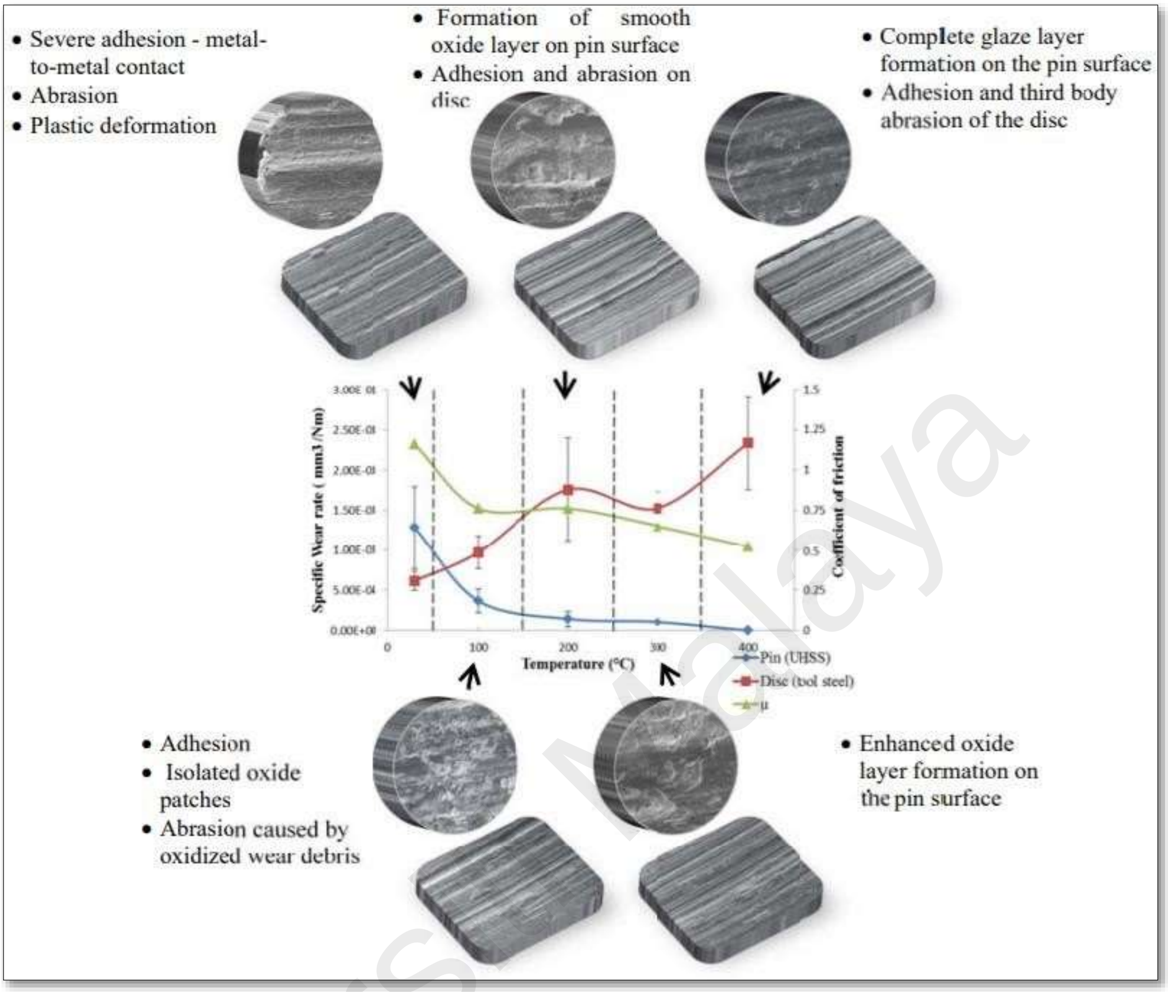


Figure 2.8: mechanism wear map for UHSS and tool steel. Worn surfaces of pin and disc specimens are represented by round and square-shaped schematics respectively. (Hernandez,2012)

2.7 Research gaps

1. The discussion of the tribological behavior of bio-based lubricants in conjunction with diesel was diluted and studied insufficiently to offer a definite knowledge in this sector.
2. A lack of research on the dilution of bio-based lubricant in diesel engines may be a barrier to commercialization. A special emphasis is placed on biodiesel because the Malaysian government is now using it as an alternate fuel source but has taken littleattempt to exploit other resources.
3. There are a few discussions about wear mapping mechanism on bio lubricant and the parameter condition for research is varied such as temperature, speed, load etc.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter provides an overview of the materials and methodology. Figure 3.1 represents an overview of this project research. For achieving the set objectives as mentioned before, tribology testing will be used for provides the friction and wear evaluation and the worn surfaces were collected for surface analysis using SEM machine. Below is the flow chart of research methodology.

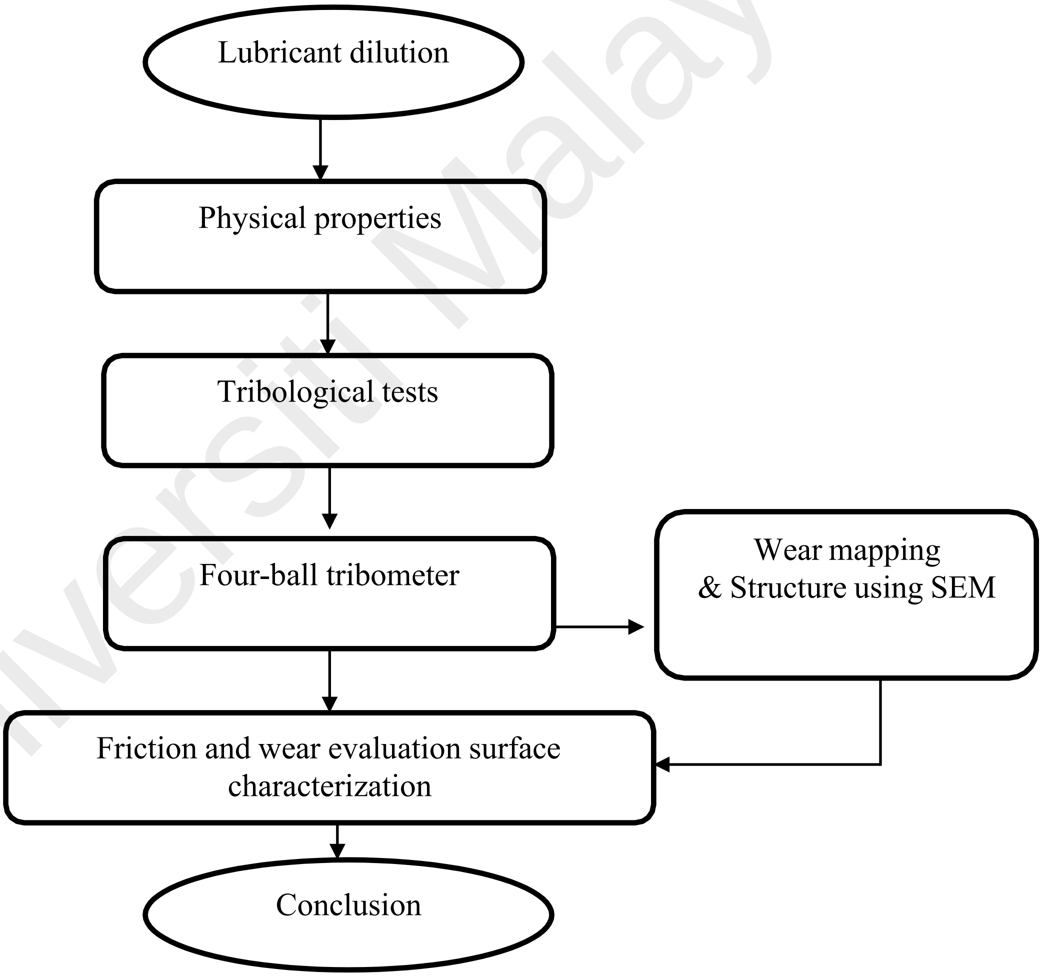


Figure 3.1: An overview of project

3.2 Material preparation

This section is explained on material used for base oils on this research project and metal specimens for tribotesting. Material preparation is very important steps for this project to find wear mechanism and properties on fuel dilution.

3.2.1 Material Lubricant sample

The trimethylolpropane trioleate (TMPTO) ester was chosen as the bio-based base stock in this investigation because to its high lubricity and resistance to oxidation. TMPTO was produced by esterifying oleic acid with TMP alcohol. Recent years have seen a surge interest in synthetic polyol esters derived from natural oils and fats. This is mostly because the raw ingredients used are affordable and organic, and the finished goods are ecologically friendly. TMPTO is an easily biodegradable compound with an overall biodegradability of greater than 80% (Beran, o, & Kmiecik, 2008; Lieira del Ro, López, Fernández, & Garca, 2019). The sample TMPTO utilised in this research is seen in Figure 3.2.

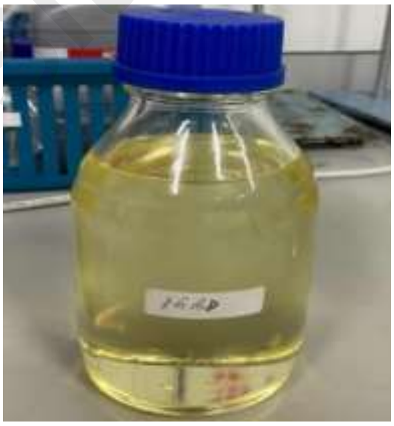


Figure 3.2: Base oil TMP

From the conducted literature review, the pros and cons of using different types of bio-based oils for various lubricant applications are well highlighted. Bio-based oils produced through chemical modifications, such as TMP esters, is suitable for IC engine lubrication application owing to their improved properties of having good oxidative and thermal stability. Nevertheless, like the conventional engine oils, the performance of TMP esters still needs to be improved through the incorporation of additives due to the harsh lubrication environment within IC engine. For this study, the molecular structure, and physicochemical properties of TMPTO are presented in Figure 3.3 and Table 3.1 respectively. The tribological performance of TMPTO was evaluated and its physicochemical properties are presented in Table 3.1.

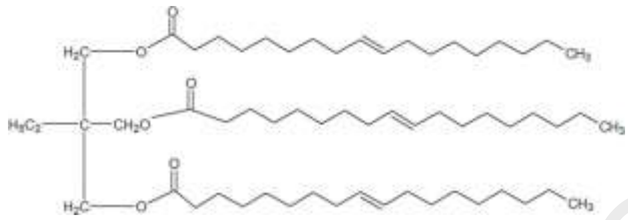


Figure 3.3: Molecular structure of TMPTO

Table 3.1 : Physicochemical properties of selected base oils in this study

Base oil	Density (kg/m3) @ 15ºC	Kinematic viscosity (mm^2/s)		Viscosity Index	TBN (mgKOH/g)	TAN (mgKOH/g)
		40ºC	100ºC			
TMP	0.928	59.855	11.360	187	0.45	0.34

Sample preparation also need to do with diesel diluted add in bio-based lubricant. This research project has been added 5% of diesel into the base oil TMP to make comparison between fresh base bio-lubricant and added the diluted diesel. Figure 3.4 below shows the lubricant sample for diesel diluted bio-based lubricant.

Figure 3.4: Base oil with 5% diesel diluted with bio-lubricant

3.2.2 Metal specimens for tribotesting

In this study, several metal specimens were used specifically for tribotesting purposes such as steel balls, steel plates, cylindrical steel rollers, cast iron plates and engine piston ring segments. The diameter of steel balls of 12.7 mm was used for fourball tribotesting. The specifications of all the metal specimens used in this study are presented in Table 3.2 and Figure 3.4 for steel ball use on this study.

Table 3.2: Specification of metal specimens used in this study

Properties	**Fourball test**
	Steel ball
Materials	AISI 52100
Dimension	12.7 mm (d)
*Hardness	64-66 HRC
[a]surface roughness	*0.1 (CLA)
*Poisson's ratio	-
*Modulus of elasticity	-
*Bulk density (kg/m^3)	7810

* Information provided by the manufacturers.

[a] Surface roughness for steel plate and cast iron plate were measured using Alicona Infinite Focus 3D surface analyzer. For others, information was provided by manufacturers.

Figure 3.5: AISI 52100 Steel ball

3.3 Tribological testing

3.3.1 Fourball Wear Preventive Testing

The tribological behaviors were investigated in this work utilizing a Four-ball Tribometer. It investigated the wear and frictional properties of fresh and diluted engine lubricants. Evaluation of boundary lubrication lubricant samples for wear prevention efficacy conditions was determined using the **DUCOM TR-30H fourball tribometer** in accordance with ASTM D4172-B. To mimic ball-on-ball point contact geometry, four AISI 52100 chrome steel balls were employed. As seen in Figure 3.6, one ball was put into the top collet, while the remaining three balls were assembled in the test-oil cup and tightened with tension varying from 2.8 to 5.6 Nm. As shown in Table 3.3, the fourball test condition is as follows. To eliminate surface contamination, the steel balls and ball pots were carefully cleaned with toluene and wiped with a lint- free cloth prior to each test.

Table 3.3: Operating conditions of high frequency reciprocating ring.

Parameter	Value
Load	392 N ± 2 N
Rotational Speed	1200 rpm ± 60 rpm
Duration	60 minutes ± 1 min
Operating Temperature	75˚C ± 2˚C

Despite the fact that ball-on-ball point contact does not reproduce any of the contact geometry seen in an IC engine, fourball tribometers are nevertheless frequently utilised in the automotive and lubricant sectors for the early phases of lubricant development. It is regarded as a useful and cost-effective test for determining the efficacy of base oils and additives. Until today, the fourball test has been regarded as a standard screening test by the community and has been integrated into several national standards such as ASTM and DIN.

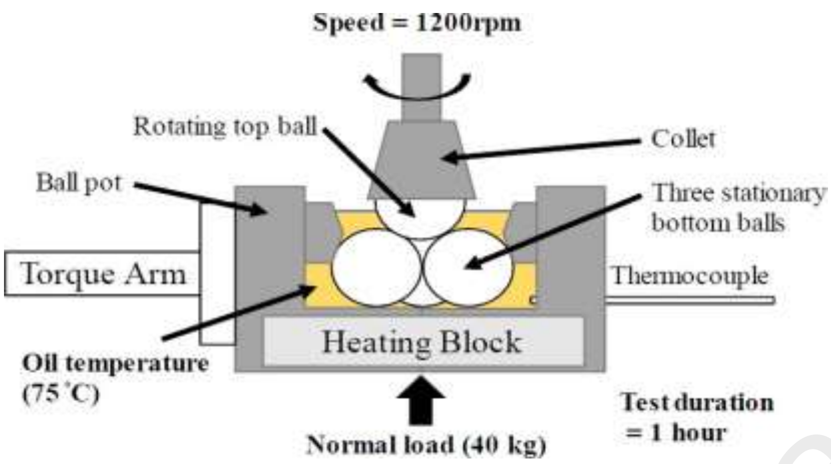


Figure 3.6: Schematic diagram of fourball tribotest

Following the tribotest, the coefficient of friction (COF) for each estimated value wascomputed using Equation 3.1, where r, W, and T denote the distance in millimeters (mm), the applied load in kilograms (kg), and the frictional torque in kilograms.mm, respectively. The distance (r) between the centre of the lower ball contact surface and the axis of rotation is 3.67 mm, and the frictional torque (T) value was determined using the load cell on the test rig. Then, using a calibrated optical microscope, the resultant wear scar diameter (WSD) on the stationary balls was analyzed. The average COF value was calculated by averaging the COF readings from the experiment's commencement to the latest COF value recorded (60th minute). Table 3.3 lists the mechanical parameters of the steel balls utilized. For WSD, the average of three diameter measurements of the resultant wear scar on steel balls was used.

$$\mu = \frac{T.\sqrt{6}}{3.W.r}$$ equation 3.1

Figure below shows the fourball tester used for this study and tools and equipment for this research at Tribology lab, University of Malaya.

Figure 3.7: Four ball tester in Tribology Lab University Malaya

Figure 3.8: Load support plate

Figure 3.9 : Tools and equipments

3.4 Tribological analyses

3.4.1 Analysis of Worn Surface

To provide an insight regarding the lubrication mechanism of all tested lubricant samples, the substrate specimens were analyzed using several surface characterization techniques such as scanning electron microscopy (SEM). SEM analysis was carried out to examine the morphology and general appearance of the worn surfaces. The equipment works by utilizing focused electron beam across the sample surface to provide a high- resolution image. At a wide range of magnifications, it is an effective surface examination tool. In this study, Phenom ProX (Phenom- World, Netherlands) scanning electron microscope was used which has the electron optical magnification range from 80X up to 150,000X.

Figure 3.10: Phenom ProX

The high vacuum mode with a 15kV acceleration voltage was used in this investigation. Figure 3.10 shows how a scanning electron microscope (SEM) can be used in the lab to look for wear on a steel ball. After the tribological test, the wear patterns were analyzed with a SEM, the most widely used tool for performing surface analytical procedures. Using a highly concentrated scanning electron beam, high-resolution photographs of surface topography were captured with a good depth of field. The friction and wear properties of each gasoline diluted oil were demonstrated by photographing and discussing three separate wear scar surfaces.

3.5 Error analysis

When used to describe a measuring element in engineering, the term "error" does not always imply a mistake. Error analysis is essential owing to the probability of mistakes happening during the experiment because of the selection of instruments, testing conditions, ambient conditions, observation, calibration, and data collection (Mofijur et al., 2014). To explore the repeatability of measurements, repeatability research must collect at least two measurements per participant under similar conditions for a suitably selected sample. This requires that themeasurements be made using the same technique or by the same observer or rater. The purpose is to quantify the agreement and reliability of measurements conducted using that particular technique or observer. The test sample was done three times and the findings averaged. The best estimate of the time in this case is the average or mean. Uncertainty is acceptable if it is less than or equal to 5%.

$$\text{Average(mean)} = \frac{x_1 + x_2 + ... + x_N}{N}$$

equation 3.2

Repeat a measurement numerous times and average the findings whenever possible. This average value is the closest approximation to the "actual" value. The more times you repeat a measurement, the more accurate this estimate will be. This average is the best estimate of the width of the sheet of paper available, although it is far from precise. When we calculate the average of N measurements, the uncertainty associated with this average is the standard deviation of the mean, sometimes referred to as the standard error (SE).

$$s = \sqrt{\frac{\left(\delta x_1^2 + \delta x_2^2 + \ldots + \delta x_N^2\right)}{(N-1)}} = \sqrt{\frac{\sum \delta x_i^2}{(N-1)}}$$

equation 3.3

Approximate the real mean value, we would have to average an endless number of measurements, and even then, we cannot be certain that the mean value is accurate, since there will always be some systematic error introduced by the measuring tool, which can never be completely calibrated. This study will aid in the reduction of mistake in friction wear analysis.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter describes the results of lubricant physical properties, coefficient of friction analysis, wear analysis and wear mapping. Based on the results and conclusions, there are four key parts that describe those findings.

4.2 Lubricant Properties Analysis

As shown in Table 4.1, the physical properties of all prepared samples, including viscosity, density, and viscosity index (VI), were determined using a viscometer in comparison to two different lubricants: fresh bio-based lubricant (FBL) TMP and diesel diluted with fresh bio-based lubricant (DFBL) TMP. Viscosity is a critical feature of automobile engine oil; It must be high enough to obstruct internal flow while remaining low enough to prevent major energy loss (Ljubas et al., 2010). Viscosity is increased when used oil deteriorates due to oxidation or solid impurities but decreases When oil is utilized, it must be diluted with a lower viscosity oil or with gasoline to make it work.

Table 4.1 : Physical properties for lubricant sample

Sample	Temperature (˚C)	Dynamic Viscosity ,μ (Mpa.S)	Kinematic Viscosity,V (Mm^2/S)
Fresh Bio-based lubricant (FBL) At 15˚C Density (ρ): 0.9280 g/cm3 Viscosity index : 187.0	40	54.554	59.855
Fresh Bio-based lubricant (FBL) At 15˚C Density (ρ): 0.9280 g/cm3 Viscosity index : 187.0	100	9.9031	11.360
Diesel diluted with fresh bio-based lubricant (DFBL) At 15˚C Density (ρ) : 0.9240 g/cm^3 Viscosity index : 190.4	40	46.652	51.421
Diesel diluted with fresh bio-based lubricant (DFBL) At 15˚C Density (ρ) : 0.9240 g/cm^3 Viscosity index : 190.4	100	8.8199	10.173

According to Table 4.1, when synthetic oil containing diesel is diluted with bio-based lubricant, the viscosity decreases dramatically. This is because diluted fuels have a lower viscosity. It may be mentioned that dilution of the fuel has a considerable influence on the viscosity of the oil. It might have two opposing effects: one favorable and one harmful. Engine friction is projected to be reduced as a result of reduced viscosity, which is intended to improve total engine efficiency. The decrease in lubricating oil viscosity also results in a decrease in the film thickness of motor oil. As a result, according to Ajayi (2016) the contact surface will be pushed fartherinto the boundary lubrication regime. Over time, this will lead to a buildup of friction and wear.

Figure 4.1: Viscometer

4.3 Coefficient of Friction Analysis

Prior to the different sample of lubricant used on this experiment, the tribological performance of the FBL and DFBL was first evaluated using fourball tribo-testers with constant load is 40 kg and different two different speed which are 900 rpm and 3600 rpm and several temperature parameters to be observed. The results obtained from this part were used as the reference in determining the degree of improvement in terms of reducing scuffing and scraping for both lubricants in this study.

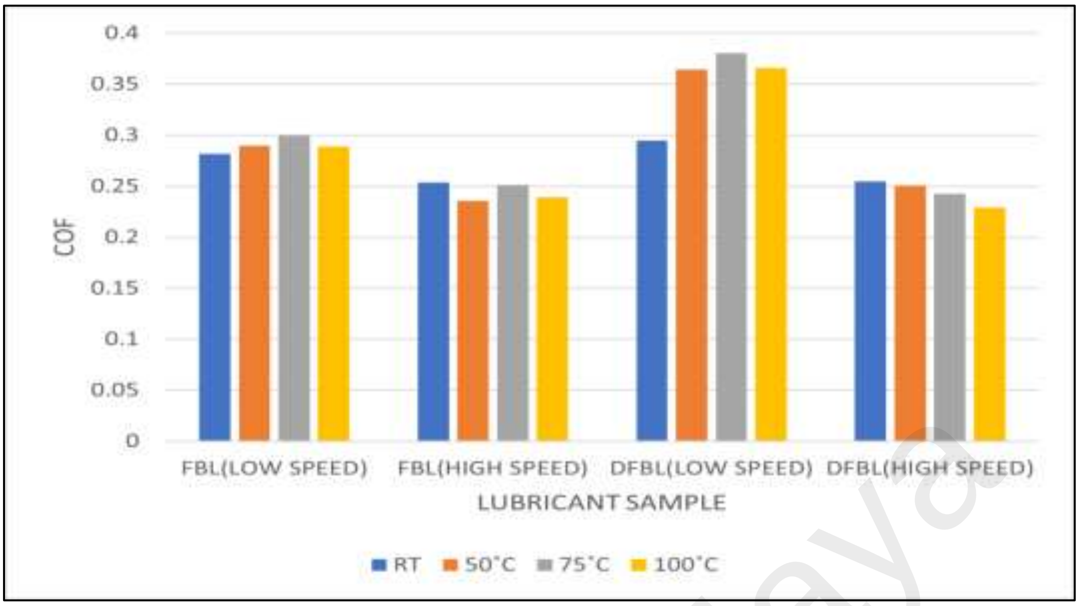


Figure 4.2: Bar chart on variation of COF over FBL and DFBL with different speed and temperature.

The change in COF over samples of FBL and DFBL with varying speeds and temperatures during wear preventative experiments using a fourball tribometer is depicted in Figure 4.6. To begin, when comparing low speed performance of different lubricants, adding diluted diesel to the bio-based lubricant results in the greatest COF value, which is approximately 10% higher on average than fresh bio-lubricant. This is due to the high polarity ester groups, which form a strong bond with metallic surfaces, resulting in a more efficient antifriction ability of the lubricant. For higher speeds, it appears that FBL producesa slightly fluctuating COF trend, whereas DFBL produces a decreasing COF trend. Therefore, the bar chart indicates that DFBL at low speeds produces the largest COF because the addition of diesel alters the physical features of the bio-based lubricant, particularly viscosity, which results in a high COF. A probable explanation for this event is the recurrent development and breakdown of the TMPTO due to the tribofilm's instability atincreasing temperatures, as previously described (Zulkifli et al., 2013; Zulkifli, Masjuki, et al., 2014). Additionally, it was discovered that the lubricant layer thickness decreases with rising temperature for ester-based oils, lowering their efficiency at reducing friction (He et al., 2015).

The use of diesel oil helps mitigate the tribological effect of bio-based lubricants on engine oil. It can be shown that all samples of additional diesel dispersion oil exhibit decreasing friction coefficient trends and diminish gradually with operation duration (figure 4.2). The average friction coefficient of samples of diesel diluted oil dispersed in TMP base oil. Friction and wear loss reduction are a result of the coupled nanocomposite additives' synergistic lubricating properties (Cai et al., 2016; Zheng etal., 2017). This fuel dilution may improve the discharge of anti-wear and friction characteristics during rotating and sliding operations because of its decreased grain size and homogenous dispersion (Y. B. Guo & Zhang, 2016). Additionally, a greater physical adsorption on the spinning balls' surfaces and a local hydrodynamic effect may minimize interference between asperities and in the lubricant wear test, contact resistance helps to stabilize the friction behavior by increasing contact resistance. (Lin et al., 2013).

Material remover and plastic deformation of surface material occurred in the DFBL sample because of excessive heat generation during surface rubbing with a relatively high average COF. While such wear losses are possible with TMP (FBL), because the sliding test length increases abrasive wear and because the presence of free fatty acid, which promotes corrosion on the steel surface, these results may be explained. While the polar nature of TMPTO contributes to a lowerCOF than DFBL, the base oil itself has little wear prevention capacity. Thus, appropriate additives must be applied to further enhance TMPTO's wear-resistance. These additives are critical because they often have a significantly better surface affinitythan basic oils, allowing for the formation of a stronger and more stable tribo-film.

Additionally, it is possible that this is because the impacts of physical adsorption as well as local hydrodynamics of these fuel-oil molecules were very weak, resulting in a drop in the viscosity of these studied oil mixes. Surfaces that experienced significant contact stress underwent plastic deformation, increasing contact area while simultaneously reducing stress. (Lin et al., 2013). In summary, a little quantity of diesel in bio-lubricant may temporarily boost the lubricity of the lubricant but will increase friction when combined with other lubricant and oil additives. Additionally, there may be oxidation between diesel and bio-based lubricant, reducing the lubricating efficacy.

4.4 Wear analysis

Wear production due to the geometry of line contacts is a more accurate description of wear that always occurs at most machineries than point contact geometry wear generation, since line contact geometry of interacting interfaces is more typically seen than point contact geometry wear generation. In this way, information on wear mechanisms and surface morphology may be gathered and examined through the use of this testing technique. The result wear analysis on SEM images shown as below table.

Table 4.2: Wear analysis on SEM images of steel ball using FBL and low speed 900 rpm with constant load, 40 kg

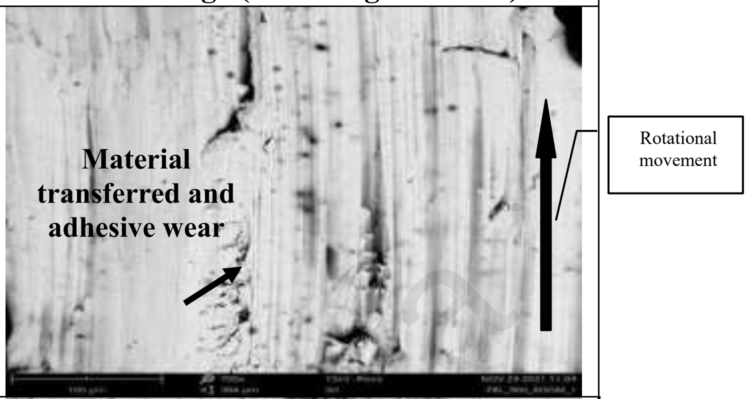
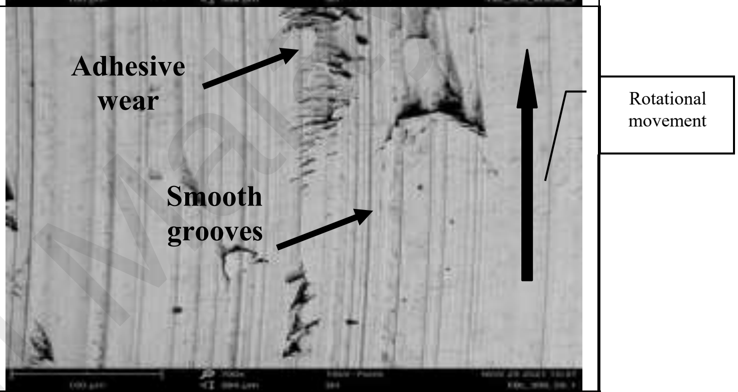
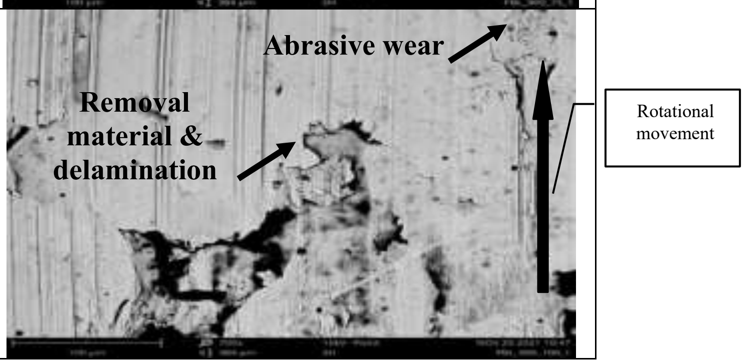
No	Temperature (˚c)	COF	SEM image (700x magnification)
1	ROOM	0.282	
2	$50^{O}C$	0.289	
3	$75^{O}C$	0.299	
4	$100^{O}C$	0.288	

Table 4.3: Wear analysis on SEM images of steel ball using FBL and high speed 3600 rpm with constant load, 40 kg

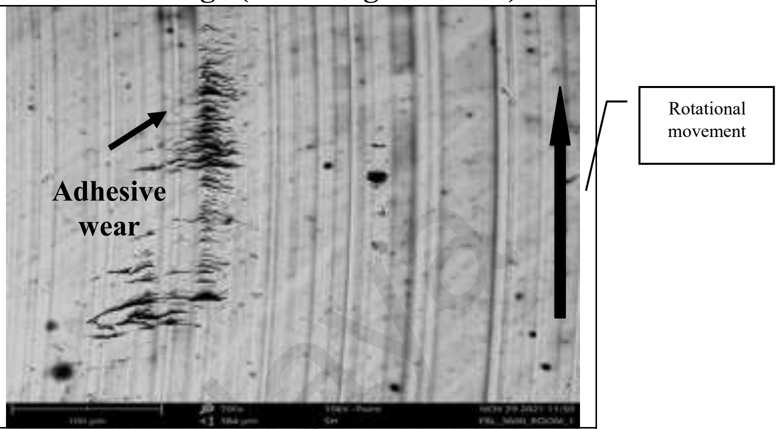
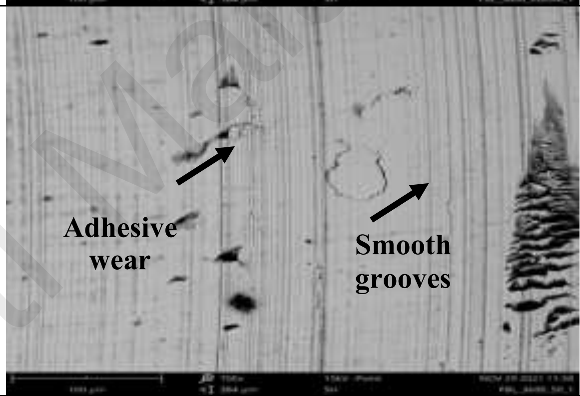
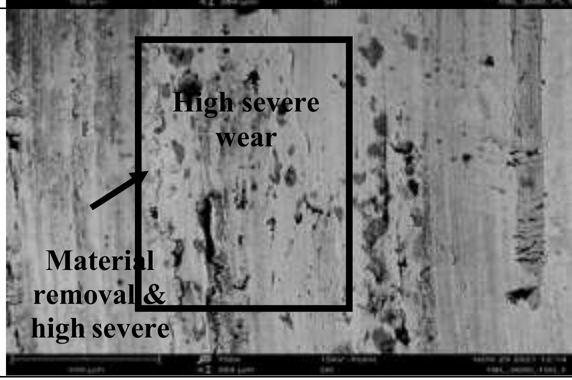
No	Temperature (˚c)	COF	SEM image (700x magnification)
1	ROOM	0.253	
2	$50^{O}C$	0.235	
3	$75^{O}C$	0.251	
4	$100^{O}C$	0.239	

Table 4.4: Wear analysis on SEM images of steel ball using DFBL and low speed 900 rpm with constant load, 40 kg

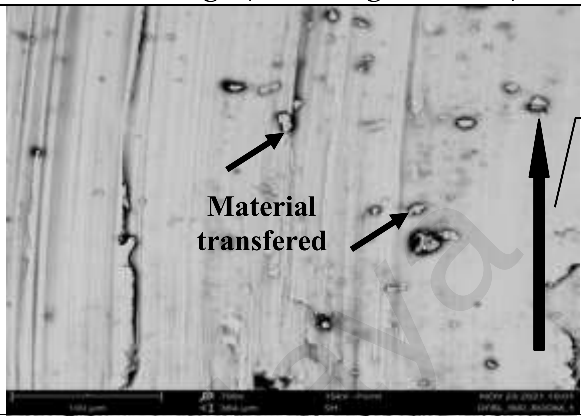
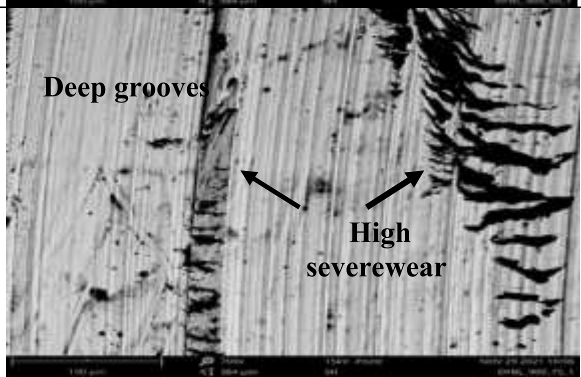
<table>
<tr><th>No</th><th>Temperature (˚c)</th><th>COF</th><th>SEM image (700x magnification)</th></tr>
<tr><td>1</td><td>ROOM</td><td>0.294</td><td>
</td></tr>
<tr><td>2</td><td>$50^{O}C$</td><td>0.364</td><td>
</td></tr>
<tr><td>3</td><td>$75^{O}C$</td><td>0.380</td><td>
</td></tr>
<tr><td>4</td><td>$100^{O}C$</td><td>0.365</td><td>
</td></tr>
</table>

Table 4.5: Wear analysis on SEM images of steel ball using DFBL and high speed 3600 rpm with constant load, 40 kg

No	Temperature (˚c)	COF	SEM image (700x magnification)
1	ROOM	0.254	
2	$50^{O}C$	0.250	
3	$75^{O}C$	0.242	
4	$100^{O}C$	0.229	

As shows on table 4.2, 4.3, 4.4 and 4.5 represent the SEM images of worn steel ball after doing four ball tribometer. Degree of wear is highly affected by several condition which are effect of temperature, diesel addition and rotational speed which all this explained in details later sub section.

4.4.1 Effect of Temperature

At high temperatures, the lubricant's volatility and flash point are important characteristics. It is the tendency of lubricant to evaporate, and it is the temperature at which the generated vapor may be ignited in the presence of air that is known as its flash point. A high-temperature lubricant qualities should be volatile and have a flash point higher than the temperature at which it will be used. The cloud point and pour point of a lubricant are frequently connected with its lubricant qualities at low temperatures. Cloud point refers to the temperature at which the lubricant begins to appear hazily or foggy in appearance. It occurs as a result of the crystallization of wax within the lubricant when the temperature of the environment lowers.

According to table 4.2 and 4.3 which using FBL as lubricant sample it shows that at low speed for room temperature the ball surface indicated mild abrasive wear compared to high speed. On the worn surface table above, the tiny grooves in the rotation direction were clearly visible. For temperature 100^{O}C, when comparing high speed and low speed balls, it was discovered that the high-speed balls had more severe surface damage. However, during temperature 75^{O}C, both speed condition on fresh bio-based lubricant shows very slightly and mild abrasive wear because this is standard temperature ASTM D4172-B for the four-ball test.

For Dilute diesel fresh bio-based lubricant (DFBL) as present on table 4.4 and 4.5, it shows that for low speed on room temperature the worn surface is slightly seen on surface and there is delamination. While, on temperature 100^{O}C surface for speed condition shows mild abrasive wear. On the other hand, chemical reactions between the lubricant and the worn surface of the ball tested with bio-based lubricant diluted synthetic oil appear to take place on the worn surface of the ball, which may result in the lubricity of the oil is affected by chemical wears such as oxidative and corrosion wear. This is because bioethanol has a larger oxygen level inside the oil, which increases the oxidation of the fuel-oil combination.

Thus, when the test was conducted at a high temperature shows on 75^{O}C will shows less wear on surface for both sample lubricant used in machineries or engines to prevent clogging of filters. Nevertheless, the TMP ester derived from palm oil exhibited remarkable results demonstrating that chemical modification may successfully counteract the poor low temperature attributes of crude vegetable oils.

4.4.2 Effect of Diesel Addition

As previously stated in Table 4.1, the addition of diesel had no effect on the viscosity and density of the base oils. This can be attributed to the little quantity of diluted diesel added to the base oils, which results in negligible viscosity and density changes. However, because to the very viscous nature of diesel, the kinematic viscosity decreases when diesel is introduced to the TMP sample lubricant. The Viscosity Index (VI) of a lubricant reveals the influence of temperature variation on the viscosity value. Additionally, as seen in Table 4.1, TMP and its mixes with diesel had a greater VI than FBL (TMP alone). Due to the greater VI of bio-based lubricants, the inclusion of components of fatty acid chains results in a larger overall molecular weight (Salimon, Salih, & Yousif, 2012).

Visual inspection showed on table 4.4 and 4.5 using DFBL represent that SEM images shows the worn scar is higher severe wear compared to use fresh FBL sample lubricant. The film thickness of the lubricating oil is known to be reduced by the addition of diluted diesel (Costa & Spikes, 2015). Because of the oil additive concentration that may build the lubricating film, fresh bio-based lubricant with diesel diluted (DFBL) oil that was free of fuel mixture contamination a higher lubricating performance. TMP fuel dilution, on the other hand, had a negative influence on lubricating properties (weakening lubricant detergency, creating acid and corrosion, and disturbing oil film strength, enabling metal asperities to touch each other, boosting engine wear), increasing friction and wear. Furthermore, gasoline dilution lowers oil viscosity and the concentration of engine oil additives, thereby impairing lubricant performance (Agarwal et al., 2014). Oil film formation and load-bearing capability are both affected by insufficient oil viscosity. This may result in too much wear of bearings, journals, and other moving components (Agarwal et al., 2014).

4.4.3 Effect of Speed

The influence of wear parameters on temperature and diesel addition was previously studied in the preceding sub section. This demonstrates that the rotating speed impact is also one of the degree of parameters affecting the wear on the steel ball during the test. Two speeds are used as variables in this experiment: low and high, 900 rpm and 3600 rpm, respectively. This is to demonstrate the difference in wear conditions between low and high speeds during the test. As seen in Table 4.2, when the FBL sample is operated at low speed, the worn surface exhibits moderate abrasive wear and delamination occurs as the temperature increases. However, when the standard temperature of 75^{O}C is reached, the wear is slightly less than on the other surface. Additionally, at low speeds on DFBL, the wear is somewhat abrasive and material removal occurs in some locations, indicating that a chemical reaction is occurring on thesurface.

Besides that, on high rotational speed for FBL samples it shows the surface of steel ball getting worst due to high rotational speed on the surface while temperature keep increasing while for DFBL samples the steel ball surface shows the wear is slightlybetter than the DFBL on low-speed condition. Thus, the chemical reaction takes place together with rotational load on the surface. Thus, additional diesel and high rotational speed can affect the wear characteristic and give the damage on the surface.

4.5 Wear Mapping

The function of the wear map is to enable the prediction of wear mechanism of the lubricated surfaces at certain conditions. However, little effort is being made now to develop a wear map for fresh bio lubricant and fuel diluted bio lubricant. Wear maps are an effective technique to convey wear data in an easy-to-understand format. The map permits prediction of the wear mode for a given contacting condition. For instance, it is possible to utilize wear maps to depict wear data in an intuitive manner, which allows for prediction of the most likely mode of wear when certain sliding circumstances are encountered. There are numerous conditions that can be used to create a wear map. In addition to other combinations of load and speed can be utilized to get the desired wear. The important criteria in Kato and Hokkirigawa's abrasive wear map are degree of penetration (of asperities) and shear strength at the contact interface. However, most wear maps have been developed at room temperature, with just a handful including high ambient temperatures or the impact of different surfaces. Figures 4.7 and 4.8 illustrate a result wear analysis of a wear map utilizing a fresh bio-based lubricant (FBL) and a diluted bio-based lubricant (DFBL) at varying rotational speeds and temperatures.

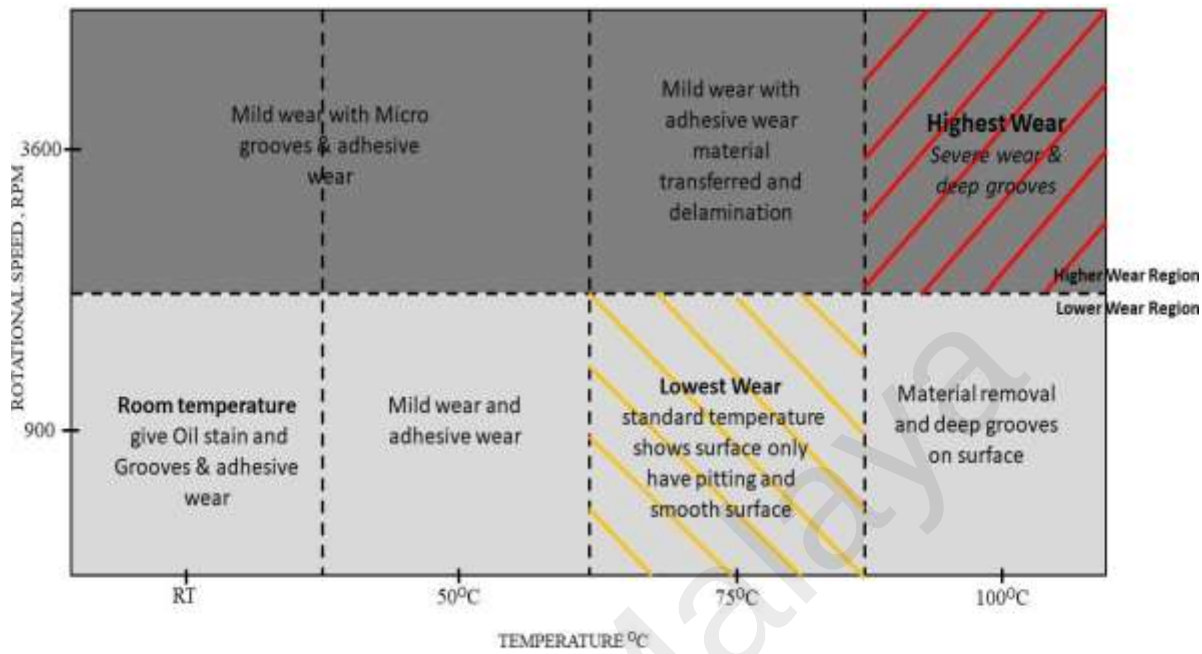


Figure 4.7: Wear map using FBL

The setup has been done using varying condition such as temperature and rotational speed. From above figure 4.7, using FBL lubricant sample it shows that two different region which high wear and low wear. As the darker grey shows at high rotationalspeed region whereas lighter grey at low rotational speed areas which means during high rotational speed the wear always occurs on surface is higher than low rotational speed. Moreover at 100˚C and 3600 rpm rotational speed there was stripes pattern areas at figure stated there was highest wear which means it going through the severe wear on the surface which can refer at table 4.3. However, as figure above at 75˚C and 900 rpm the lowest wear will happen on surface and smooth surface during this condition. The worn scar and wear mechanism will be noted and gathered as figure 4.2.

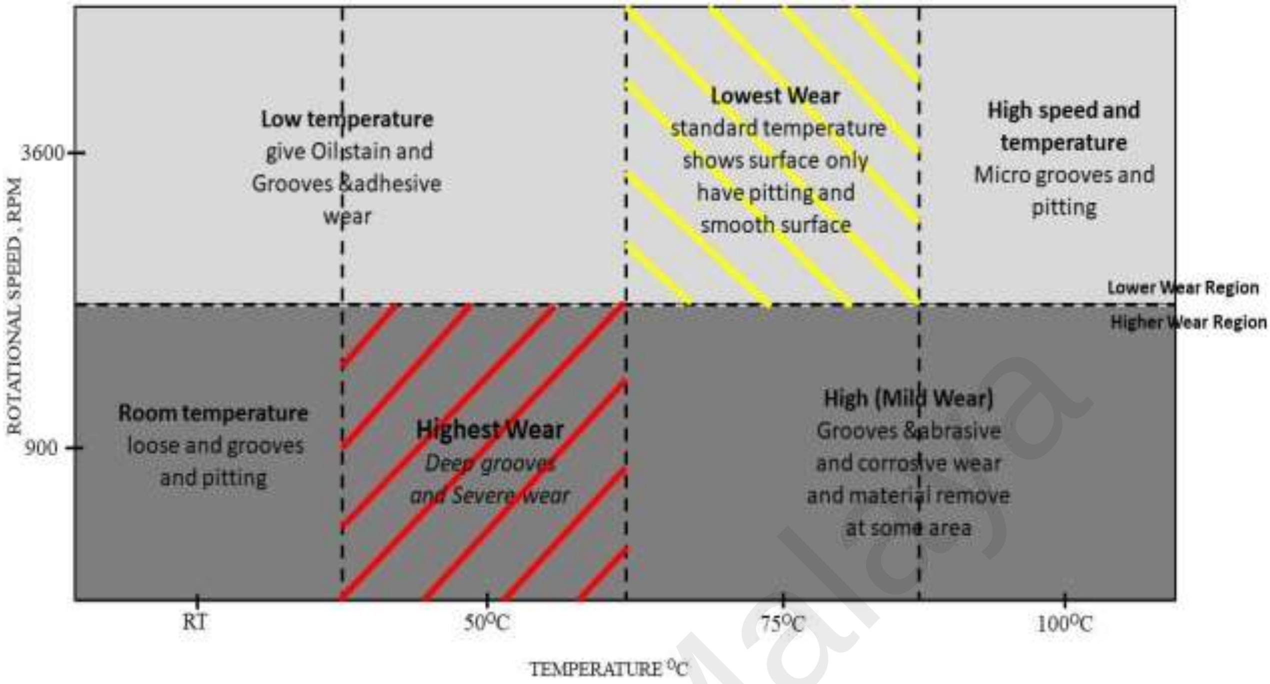


Figure 4.8: Wear map using DFBL

From above figure 4.8, using Diluted Fresh Bio-based lubricant (DFBL) lubricant sample it shows that two different regions which high wear and low wear. As the darker grey located and took place at low rotational speed region whereas lighter grey at high rotational speed areas which means during low rotational speed the wear always occurs on surface is higher than high rotational speed. Moreover, at 50˚C and 900 rpm rotational speed there was stripes pattern areas at figure stated there was highest wear which means itgoing through the severe wear on the surface which can refer at table 4.4. However, as figure above at 75˚C and 3600 rpm the lowest wear will happen on surface and smooth surface during this condition. All this analysis has been referring at the result on worn scar at table 4.5. The worn scar and wear mechanism will be noted and gathered as figure 4.8.

To sum up the wear mapping analysis for both lubricant samples, during low speed at FBL (TMP) the additive speed can function properly which as speed increase, wear also increase and many surface interactions will takes place. Besides, as seen at figure 4.7, the high speed will be higher wear region which it is proven as higher speed the wear will produce on surface interaction. However, for DFBL sample bio-based lubricant, the diesel diluted will disturb the additive lubricant used because of that during the low speed there will be higher wear region as shown at figure 4.8. It is because the addition of diesel on additive will reduce the physiochemical properties of FBL and as speed increase, lubrication layer formed is strong enough to reduce asperities contact thus the region for high speed will be lower wear region.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this experimental work, bio-based lubricant blends were used to evaluate the tribological properties of diesel engine oil. This project had been done and the objectives of the project have been fulfilled. Although many obstacles and resistance occurred throughout of this project duration. This project is assumed to be successful as targeting for study on tribology of wear mechanism. As the discussion and reference reading are carried out, the research project proceeds in accordance with the objectives that were previously set. This project's approach and decision-making process will be influenced by the issues that have been researched and considered. The conclusions can be drawn as follows:

- The addition of diluted diesel to the new bio-based lubricant reduces its viscosity. When diluted diesel oil is added to new FBL, it marginally increases friction and significantly increases wear. According to the SEM results, the worn surface of the ball tested with DFBL samples exhibits higher surface degradation than the fresh FBL tested. In terms of friction and wear behavior, using FBL highest wear occur at high speed and temperature while DFBL highest wear at low temperature and low rotational speed region.
- The wear mapping has construct to show between FBL and DFBL with two condition such temperature and rotational speed which can affect the properties of materials and sample and it clearly shows at the wear mapping. High and low severe wear region have been identified and discussed.

5.2 Recommendations

This research was done to better understand the friction and wear characteristics of bio-based lubricant (FBL) and diluted bio-based lubricant (DFBL) engine oil, as well as to improve tribological performance. In this context, the following suggestion for future development might be made.

1. Testing for wear and fraction was carried out using a four-ball machine and high frequency reciprocating ring. Testing for wear and friction, fuel dilution, and oil degradation should be done with a bioethanol-fueled engine to ensure engine durability.

2. Furthermore, this investigation is limited to bio-based lubricant fuel. It is also suggested that various alcohol fuel mixes or biodiesel fuel blends be researched further.

3. Based on the results of this experimental investigation, it is advised that a study on bio-based lubricant resistant engine oil manufacturing for greater bioethanol-fueled engines be conducted.

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