WEAR CHARACTERISTICS OF SK11 IN ENGINE OIL AND NANOPARTICLES-ENHANCED ENGINE OIL

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**A report submitted
in fulfillment of the requirements for the degree of
Bachelor of Mechanical Engineering (Automotive)**

Faculty of Mechanical Engineering

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2017

DECLARATION

I declare that this project entitled "Wear Characteristics of SK11 in Engine Oil and Nanoparticles-Enhanced Engine Oil" is the result of my own work except as cited in the references.

Signature : ………………………………

Name : KASMIAH BINTI LASUNU

Date : ………………………………

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical in Engineering (Automotive).

Signature : ……………………………………………………..

Name of Supervisor : …………………………………………………….

Date : ……………………………………………………..

DEDICATION

To my lovely beloved mother, family and friends.

ABSTRACT

An experiment investigation was carried out to distinguish the wear characteristics of SK11 ball bearing in SAE 15W-40 diesel engine oil and enhance with 0.5 vol. % of hBN nanoparticles. In this project, the lubricant used were the conventional SAE 15W-40 diesel engine oil and the SAE 15W-40 diesel engine oil dispersed with 0.5 vol. % of hBN nanoparticles using the sonication technique. The tribological test using the Four Ball Tester were performed. The total sample were 27 for each lubricant. The WSD were analyzed using the MPS-3080 digital microscope. It was observed from the result that the wear rate of the SK11 ball bearing reduced at speed of 300 rpm at low temperature after added with the nanoparticles. Meanwhile, there are also at 100°C, there are no significant reduction in wear rate even after added with nanoparticles additive.

ABSTRAK

Satu experimen telah di jalankan untuk mengkaji ciri-ciri kehausan pada bola SK11 dalam minyak enjin diesel SAE 15W-40 dan dalam minyak enjin diesel SAE 15W-40 di tambahbaik dengan 0.5 vol. % nanopartikel hBN. Dalam projek ini, bahan pelincir yang di gunakan ialah minyak enjin diesel SAE 15W-40 dan minyak enjin diesel yang di tambah baik dengan 0.5 vol. % nanopartikel hBN menggunakan teknik sonifikasi. Ujikaji tribologi telah dijalankan denagn menggunakan penguji tribo empat-bola. Sebanyak 27 sampel telah di uji mengguna kan kedua-dua pelincir. Penurunan diameter telah di analisis menggunakan mikroskop digital iaitu MPS-3080. Daripada pemerhatian, kadar kehausan bola SK11 telah berkurang pada kelajuan 300 rpm di suhu yang rendah iaitu 27°C selepas minyak pelincir di tambah dengan nanopartikel hBN. Pada suhu 100° C tiada perubahan yang ketara pada kadar kehausan walaupun selepas di tambah dengan nanopartikel.

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VI	-	Viscosity Index
WSD	-	Wear Scar Diameter
hBN	-	hexagonal Boron Nitride
FBT	-	Four Ball Tester
COF	-	Coefficient of Friction
SN	-	Signal to Noise
TAN	-	Total Acid Number
TBN	-	Total Base Number
SEM	-	Scanning Electron Microscope
SWCNT	-	Single Walled Carbon Nanotubes
MWNTs	-	Multi Walled Nanotubes
Sn	-	Tin
Fe	-	Iron
Cu	-	Copper
Ag	-	Silver
Ti	-	Titanium
Ni	-	Nickel
Co	-	Cobalt
Pd	-	Palladium
Au	-	Gold
ZrO2	-	Zirconium dioxide
TiO2	-	Titanium dioxide
Fe3O4	-	Iron (II, III) oxide
Al2O3	-	Aluminium oxide
ZnO	-	Zinc oxide
CuO	-	Copper oxide
WS2	-	Tungsten sulphide
CuS	-	Copper sulphide

MoS_2	-	Molybdenite
LaF_3	-	Lanthanum fluoride
CeO_2	-	Cerium (IV) oxide
$La(OH)_3$	-	Lanthanum hydroxide
Y_2O_3	-	Yttrium (III) oxide
$CeBO_3$	-	Cerium Boride
SiO_2	-	Silicone dioxide
$CaCO_3$	-	Calcium carbonate
PTFE	-	Polyetrafluoroethylene

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Tribology is the study of something that is rub to each other and it was not a new field. It includes the friction, wear and lubrication. (Ludema, K.C. 2012). The focus for the project is about wear. Wear is a surface damage that occur due to the removal of material during sliding contact of two surfaces. Wear can occur because of several mechanisms which includes abrasion and adhesion. (Girard. L. et al., 2015).

It is an avoidable to have friction and wear in every mechanical system and this is where the lubricant play an important part as it assists in reducing wear and friction under the boundary condition. Lubricant usually consists of two main components which are 90% base oil and 10% additives. Additives are chemical compound added to the lubricant to improve the lubricant performance and one of it was nanoparticles additives.

Until recently, nanoparticles have become the most promising additives as it helps increase tribological properties of a lubricating oil only just in a small amount of concentration between 0.2% and 3% vol into the lubrication oil. (Abdullah et al., 2014[c]). Ilie. F., et al found that the optimum concentration for TiO_2 under new process (NP) is 0.4 wt% and under traditional process (TP) is 0.5 wt% for their anti-wear abilities. They also proved that even in NP and TP, both TiO_2 nanoparticles show greater anti-wear abilities compare to only with the base oil. It is also proven that larger wear scar diameter of steel ball that lubricated with RBD palm olein compared with the ones that lubricated with paraffinic mineral oil. However, both lubricant indicates abrasive wear occurred on all worn surfaces and suggested that it was due to the formation of tribochemical films between the rubbing surface and the cooling effect of the lubricants which reduce the adhesion. (Syahrullail.S et al., 2013).

Girard. L. et al run a wear test that demonstrate that the scar size of bearing lubricated with engine oil was a lot smaller compared with the scar size of bearing lubricated with mineral oil. There are also studies showed that the dispersing of nanoparticles into an engine oil could increase the anti-wear abilities of the engine oil. For example, a 15W40 diesel engine oil added with 0.5 vol % of hBN nanoparticles as additives result in low wear rate by

58% which was in good quantitative agreement with the coefficient of friction. The worn surfaces obtain also showed a smoother surface ($R_a = 0.043$ µm) of ball when lubricated with 15W40 diesel engine oil with 0.5 vol % of hBN nanoparticles compared to conventional diesel engine oil. (Abdullah et al., 2014[a]).

Other research showed that the worn surface of a ball bearing that was lubricated with SAE 15W40 diesel engine oil had severe adhesive wear due to not enough support at the high-pressure contract area and result in plastic deformation. (Abdullah M. I. H. C. et al., 2016). Wu Y.Y. et al showed that a smoother worn surface when CuO nanoparticles was added to the standard oil compared when the standard oil without any nanoparticles where the trace of worn surfaces was formed by wear debris. The worn surfaces on the ball bearing have the characteristics of adhesive wear and some abrasive wear when lubricated with conventional diesel engine oil and showed only a slight of adhesive wear when the engine oil added with nanoparticles as an additive. (Abdullah M.I.H.C et al., 2016).

Other than that, when the unmodified CuO + paraffin oil to well modified CuO + paraffin oil showed a reduction on wear scar diameter (WSD) from 1200mm to 600mm. This shows that the paraffin oil + CuO with modified suspensions have well wear behavior like shown in Figure 1.1. (Asrul, M. et al., 2013)

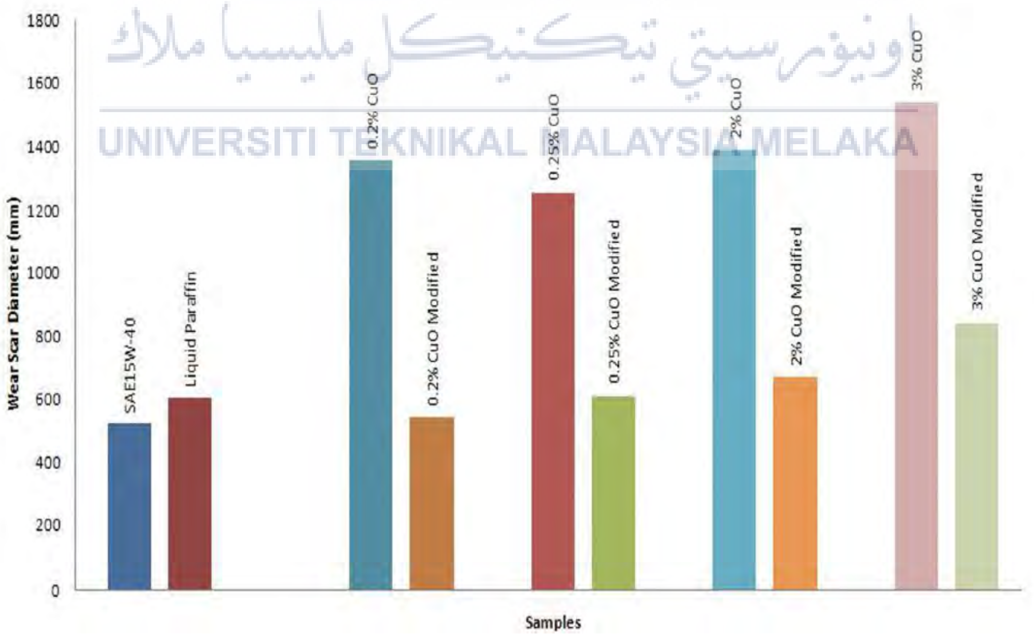


Figure 1.1 Wear scar diameter (mm) as a function sample (Asrul, M. et al., 2013)

1.2 PROBLEM STATEMENT

In general, as observed from previous research, there were a lot of studies that focusing on tribological properties of the engine oil when added with nanoparticles. Other than that, there are also studies that investigated more on the friction and wear characteristics about other nanoparticles such as Ni, CuO, TiO_2 and less studies on hBN nanoparticles. Hence, the goal of this project is to find out the wear characteristics of SK11 ball bearing in SAE 15W-40 diesel engine oil and enhance SAE 15W-40 diesel engine oil with hBN nanoparticles as an additive.

1.3 OBJECTIVE

The objective of this project is as follow:

1. To distinguish the wear characteristics of SK11 ball bearing in SAE 15W-40 diesel engine oil enhanced with and without hBN nanoparticles as an additive.

1.4 SCOPE OF PROJECT

The scopes of this project are:

1. Conduct the experiment using Four Ball Tester with two different lubricants which are SAE 15W-40 diesel engine oil and nanoparticles-enhanced engine oil using hBN nanoparticle.
2. An analysis will be done to differentiate the wear characteristics of the ball bearing after taken out from the Four Ball Tester machine by using the Inverted microscope.

1.5 GENERAL METHODOLOGY

The actions that need to be carried out to achieve the objectives in this project are listed below.

1. Literature review

   Journals, articles, or any materials regarding the project will be reviewed.
2. Preparation of sample.

   The lubricants needed are diesel engine oil SAE 15W-40 and 0.5% nanoparticles-enhanced engine oil.
3. Experiment.

   The experiment will be conducted by using the Four Ball Tester to distinguish the wear characteristics on the ball bearing. The experiment will be conducted by using the Standard Test Method with different load, speed and temperature.
4. Analysis.

   Analysis will be presented to differentiate wear of the ball bearing.
5. Report writing

   A report on this research will be written at the end of this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Lubricants and Lubrication

Principle of bearing a sliding load on a friction reducing film can be said as a lubrication. (Nehal et al., 2011). Whereas the substance composed by the film is called a lubricant, and to apply it called lubricate. Lubricant play an important role in decreasing the negative effect of tribological process related to friction and wear and increase in temperature in tribomechanical system. (Sreten et al., 2013). Other than that, more critical function also carried out by lubricant such as cooling, cleaning and suspending, and shield metal surface against corrosive damage.

Lubricant consists of base oil fluid and an additives package. Base oil function as a fluid for lubricant to separate a surface of moving parts by providing fluid films. Besides minimizing friction, it also eliminates heat and wear particles from the system. An additive on the other hand, are added to enhance the lubricant characteristics. (Nehal et al., 2011).

Base oil in lubricant mainly synthesized from three different types of base oil such as mineral oil, synthetic oil and biological oil and most widely used in industry is mineral oil. It is majorly used in industry due to their substances which are petroleum based fluids and utilized for machineries which requires its temperature be moderated. For synthetic oils, used to lubricate at high or low temperatures. Finally, biological oil are types of lubricant oil typically utilized in food or pharmacological industry where the risk of contamination need to be minimized. (Shahnazar et al., 2015).

As important the roles of base oil in lubricant, however, the important of additives also cannot be neglected because only suitable additives can be added to the base oil to enhance certain properties for example oxidation stability, anti-corrosion and anti-wear as well as stability against biological degradation. However, a lot of recent studies on lubricant added with nanoparticles and many have proven their research. (Shahnazar et al., 2015).

2.1.1 Lubricant Regimes

Typically, lubrication regimes consist of three main parts that are:

- Boundary lubrication
- Mixed lubrication
- Hydrodynamics lubrication

First is boundary lubrication happened when a solid surface is so closed or in direct contact which result in high coefficient of friction and thus resulting in high wear. Second regimes that are mixed lubrication occur when a surface in irregular contact at medium speeds and load and only a few sharp surfaces are brought in contact. Lastly was the hydrodynamics lubrication which either occurs at high speed or at light loads. The friction and wear does not exist because the two surface were separated by a film of lubrication. The Stribeck curved below showed the lubrication regimes and its relation between friction coefficients. The symbols indicate (μ) the friction coefficient versus the dimensionless parameter (η V/L), where η is the fluids dynamic viscosity, L is the normal load applied and V is the relative sliding speed. (G. Les et al., 2015).

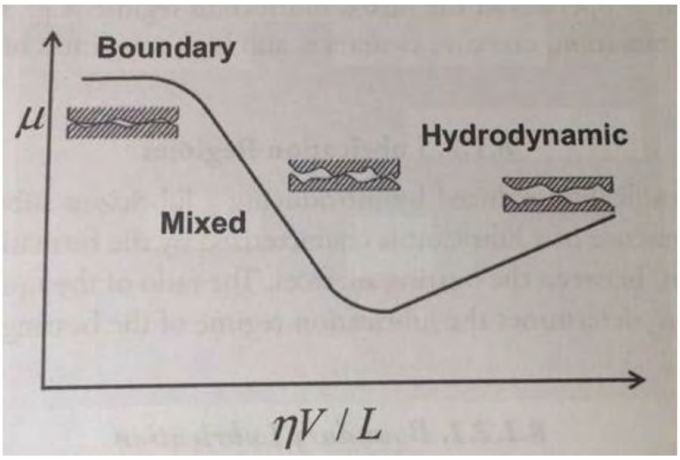


Figure 2.1 Stribeck curve with lubrication regimes and relationship between friction coefficients.

2.2 Nanoparticles as Additives in Engine Oil.

Nano lubrication is one of the most advanced lubrication technologies besides thin film coating and gas lubricant. Nano lubricants have been a main choice in industry because they are relatively insensitive to temperature and that their reaction to tribochemical are limited compared to the conventional additives. Only a low concentration of nanoparticles between 0.2% and 0.3% vol into lubricating oil are enough to improve the tribological properties. (Abdullah et al., 2015). Nanoparticles also has a potential in emission reduction as well as improving fuel economy. Their particle size also a merit for them because it allow them to enter the contact region easily for load bearing and lubricating. It also showed that some nanoparticles like $CaCO_3$, it exhibits optimal performance under high frequency for bigger sizes whereas smaller ones more suitable for higher load and lower frequency. Morphology of nanoparticles also played an important role on friction reduction but also has a subtle effect on antiwear performance. (Dai et al., 2016). Even past studies have shown that nanoparticles have powerful tribological properties than conventional solid lubricant additives. (Shahnazar et al., 2015). The tribological properties of paraffin oil and biolubricant added with TiO_2 nanoparticles additives were investigated by (Zulkifli et al., 2013) and their result showed adding TiO_2 in (trimethylolpropane) TMP ester good friction-reduction and wear scar diameter reduced by 11%. The same results also showed when the tribological properties of an API-SF engine oil and base oil with CuO and TiO_2 and nano-diamond nanoparticles used as an additives. (Wu et al., 2007).

There are a lot of research about nanoparticles additives which basically aim to improve the tribological performance of the lubricating oils. For an instances, load-carrying capacity and wear reduction of liquid paraffin were enhanced when surface-modified TiO_2 nanoparticles were added. (Xue et al., 1997). (Zhou et al., 2001) stated there are formation of film on the surface when they investigated the tribological behaviour of LaF3 nanoparticles as an oil additives.

(W. Dai et al., 2016) has classified nanoparticles into seven types according to their chemical elements that is carbon and it derivatives, metal oxide, metals, sulphides, rare earth compounds, nanocomposites and others. Table 2 below are the detailed information about each category that have been listed.

Table 2.1 A summary of nanoparticles as lubricant additives

Types	Nanoparticles
Carbon and its deravatives	Graphene, diamond, SWCNT, MWNTs
Metals	Sn, Fe, Cu, Ag, Ti, Ni, Co, Pd, Au
Metal oxide	ZrO_2, TiO_2, Fe_3O_4, Al_2O_3, ZnO, CuO
Sulfides	WS_2, CuS, MoS_2, $NiMoO_2S_2$
Rare earth compound	LaF_3, CeO_2, $La(OH)_3$, Y_2O_3, $CeBO_3$
Nanocomposite	Cu/SiO_2, Cu/ graphene oxide, Al_2O_3/SiO_2, serpentine/$La(OH)_3$, Al_2O_3/TiO_2
Others	$CaCO_3$, $ZnAl_2O_4$, Zeolite, ZrP, SiO_2, PTFE, Hydroxide, BN, serpentine

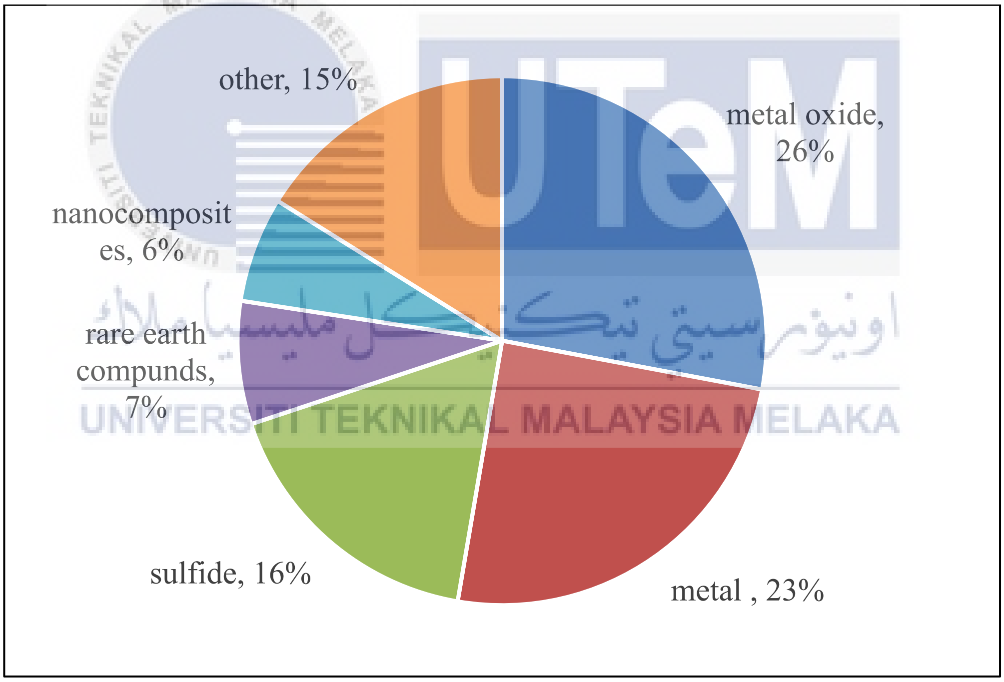


Figure 2.2 Statistics of nanoparticles worked as lubricant additives.

2.3 Hexagonal Boron Nitrate (hBN) Nanoparticles

Boron-based nanoparticles have been under a spotlight due to its load carrying and anti-wear behaviour. It also been a favourite and best candidate to be used as a lubricant oil additives because they were thermally stable and environmental friendly. (Shahnazar et al., 2016).

Table 2.2 Physical properties of hBN nanoparticles (Abdullah et al., 2016)

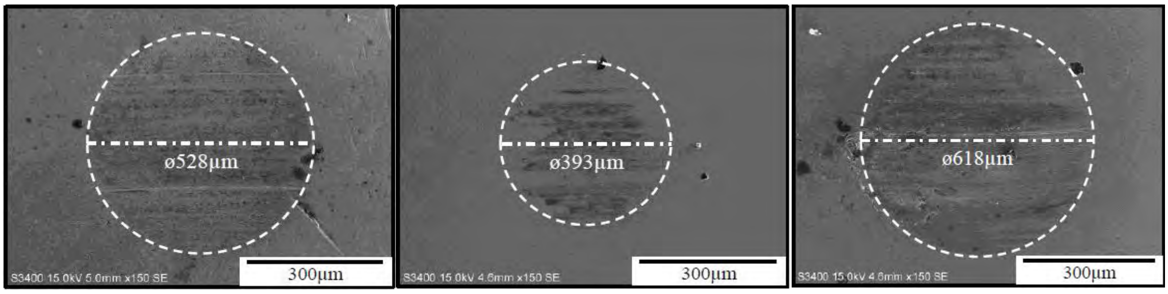
[a]Properties	hBN nanoparticles
Appearance	White powder
Average diameter particle size (nm)	70
Density ($kg.m^{-3}$)	2.3
Maximum use temperature in air (°C)	1800
Thermal conductivity ($W.m^{-1}.K^{-1}$)	27
Thermal expansion coefficient @25 °C-1000 °C	1×10^{-6}/°C (parallel to press air)

[a]From manufacturer.

With its ultra-flat surface, the hexagonal boron nitrate (hBN) with less than 2% lattice mismatch with graphite could be great additives. It is also show its low friction behaviour to not only layered structures but also to contact interface between layered even when single-layered without even sliding. (Shahnazar et al., 2016).

2.3.1 Effect of hBN nanoparticles on the Coefficient of Friction (COF) and as a Friction Modifier.

(Abdullah et al., 2014[a]), has studied the effect of hBN/Al_2O_3 nanoparticles additives on the tribological performance of engine oil and the result showed that engine oil with hBN nanoparticles has lower COF compared to engine oil with Al_2O_3 nanoparticles even though it shows greater influence in signal-to-noise (SN) ratio.



(a) (b) (c)

Figure 2.3 Wear scar diameter of a ball under lubrication of (a) 15W40 diesel oil, (b) with 0.5 vol % of hBN nanoparticles additives, and (c) with 0.5 vol % of Al_2O_3 nanoparticles additives. (Abdullah et al., 2014[a]).

In the past studies (Abdullah et al., 2015), investigated the potential of hBN as a friction modifier and wear reduction, the results showed that the average steady state coefficient of friction was reduced by 53% when the engine oil dispersed with hBN nanoparticles.

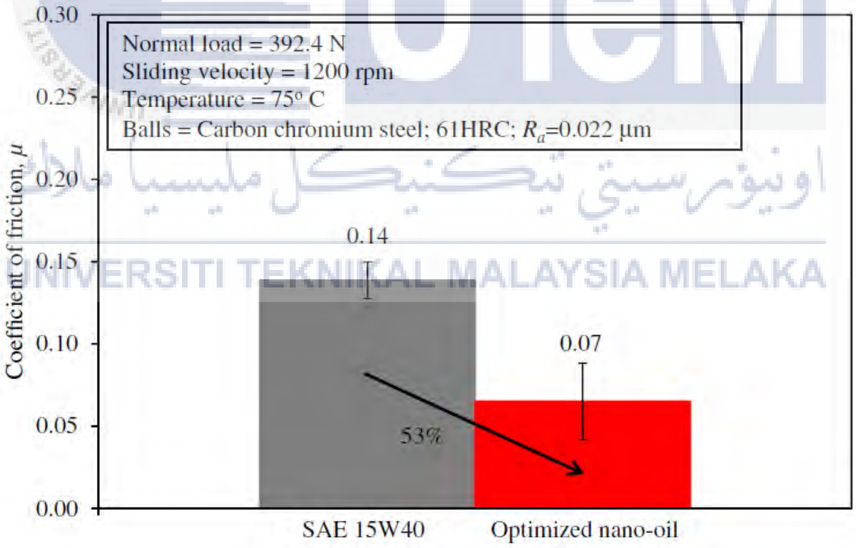


Figure 2.4 Average steady state coefficient of friction between conventional diesel engine oil and optimized nano-oil. (Abdullah et al., 2015).

2.3.2 Effect of hBN nanoparticles on Wear Properties.

It is proved by (Abdullah et al., 2014[a]) that the wear rate are reduced by 58% by using hBN nanoparticles additives in engine oil as shown in Figure 6 below. Even smoother worn surface obtains when using hBN nanoparticles as additives as shown in Figure 7.

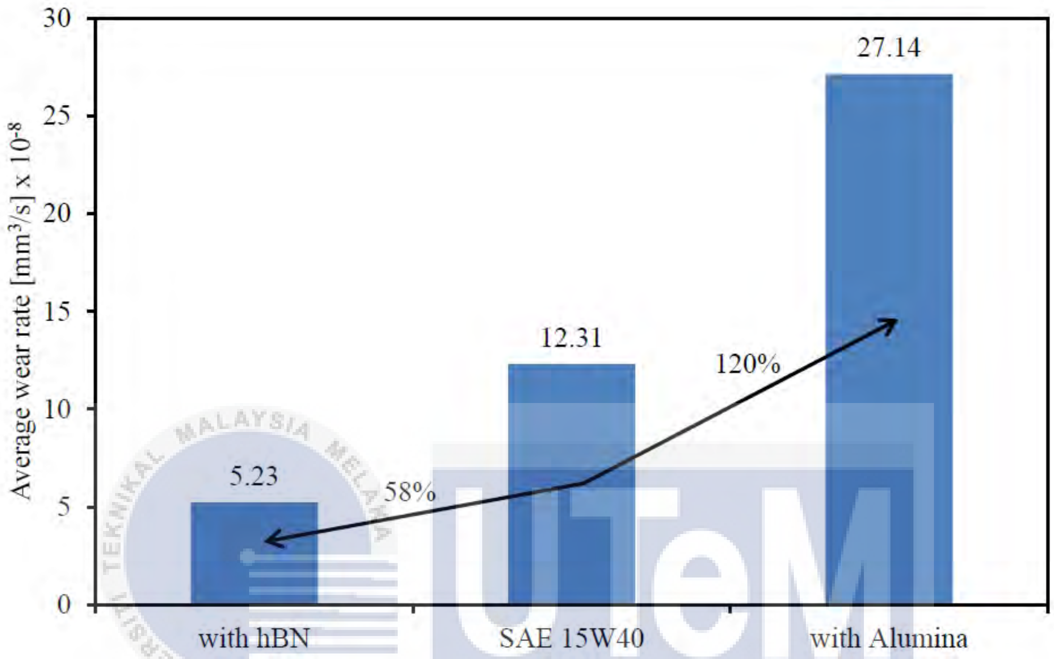


Figure 2.5 Wear rates of ball materials under different types of lubricant additives.

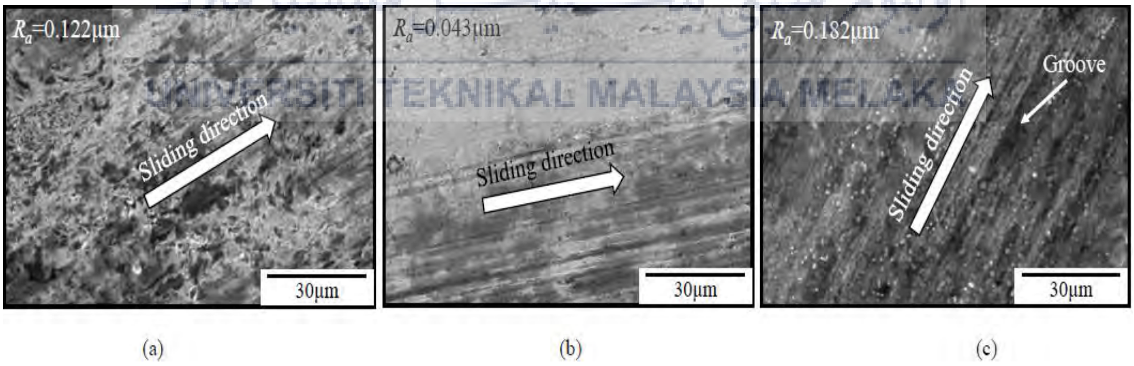


Figure 2.6 Worn surfaces on a ball under lubricated conditions in SEM micrograph (a) 15W40 diesel engine oil, (b) with o.5 vol % of hBN nanoparticles additives and (c) with 0.5 vol % of Al_2O_3 nanoparticles additives.

2.3.3 Effect of hBN nanoparticles on Engine Oil Properties

Engine oil properties includes Viscosity Index (VI), Total Acid Number (TAN),Total Base Number (TBN) and flash point temperature. Both (Abdullah et al., 2014[b] and Abdullah et al., 2014[c]) showed that hBN nanoparticles were well dispersed compared to Al_2O_3 nanoparticles which was agglomerated when observed using Scanning Electron Microscopy (SEM).

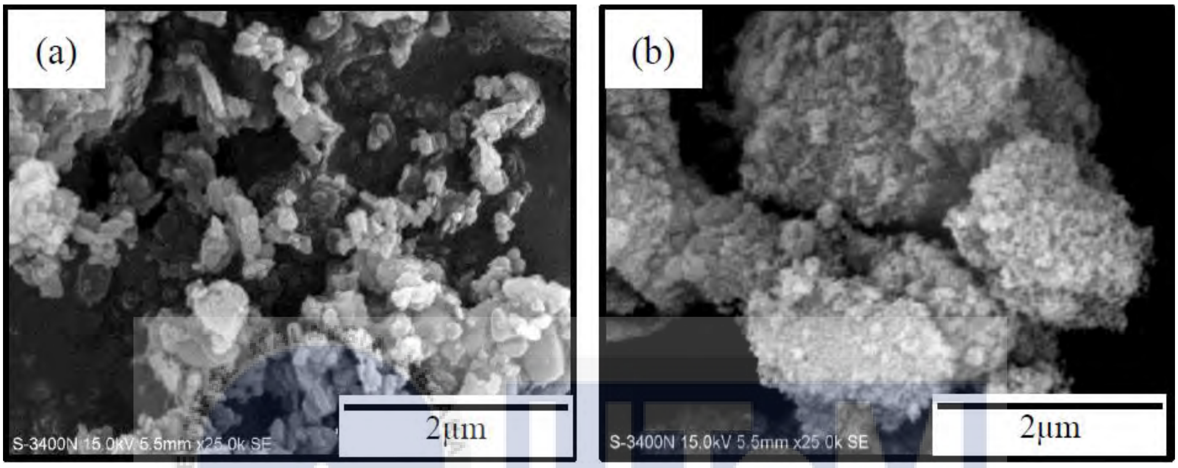


Figure 2.7 SEM micrograph of (a) hBN nanoparticles and (b) Al_2O_3 nanoparticles.

In terms of kinematic viscosity, it increased a little bit when put at pressure 40° C and 100°C compared with diesel engine oil without nanoparticles like as shown in Figure 9 below. (Abdullah et al., 2014[b] and Abdullah et al., 2014[c]).

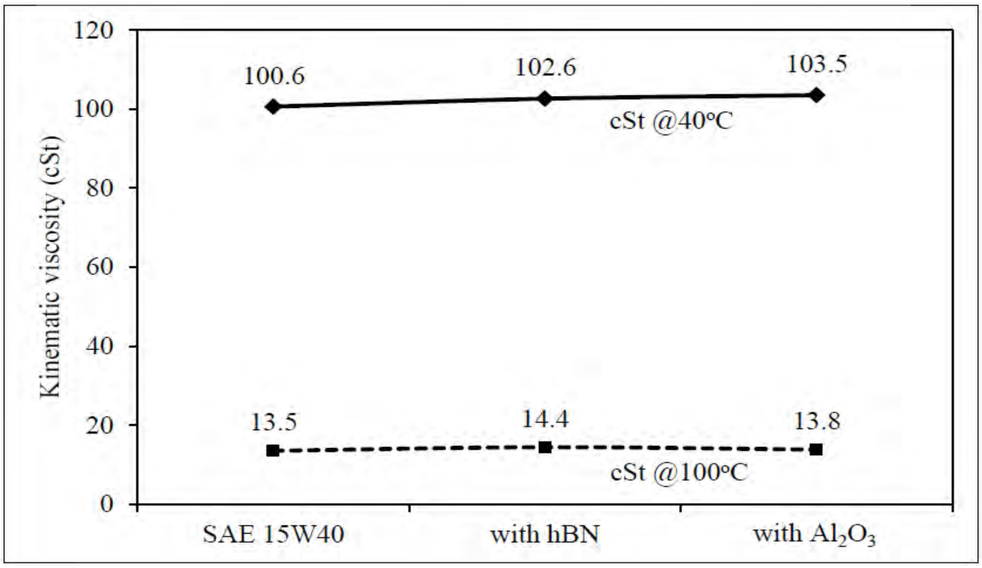


Figure 2.8 Kinematics viscosity measured at 40°C and 100°C.

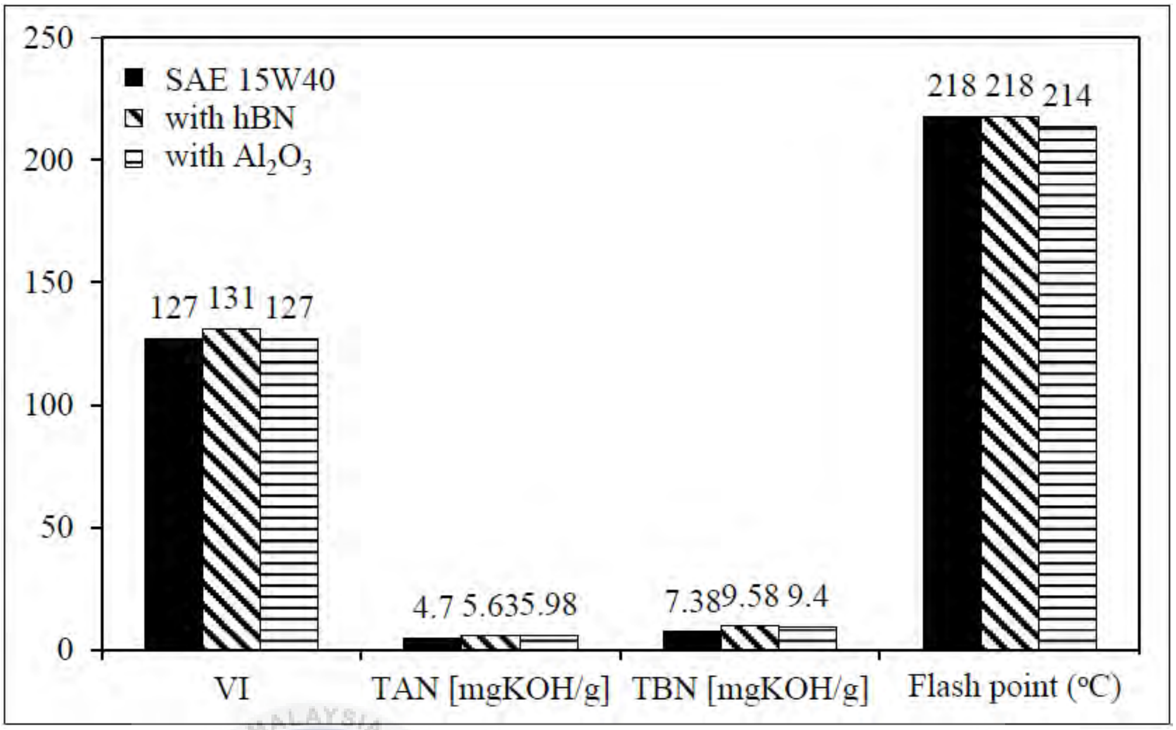


Figure 2.9 The oil properties comparisons between SAE 15W40, with hBN and Al_2O_3 nanoparticles.

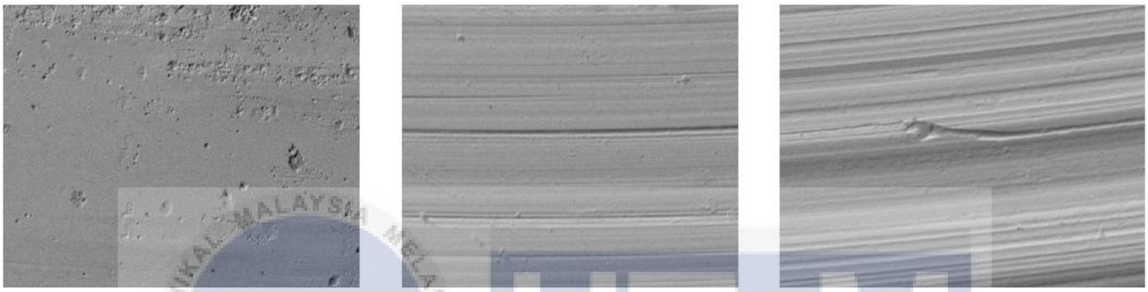
Figure above showed that, improvement approximately 3% on the VI value when using nano-oil with hBN nanoparticles compared with conventional diesel engine oil and with Al_2O_3 nanoparticles additives. It was said that it may due to the lower thermal expansion coefficient of hBN nanoparticles that is 1×10^{-6}/°C that result in good effect in thermal stability properties. (Abdullah et al., 2014[b] and Abdullah et al., 2014[c]).

In terms of TAN value, both nanoparticles showed negative results that is increment approximately 20% and 27% for hBN and Al_2O_3 nanoparticles respectively. Both of it are not preferable value compared to conventional diesel engine oil. This is because TAN value indicates the existence of naphthenic acid corrosion problem. When corrosion occur it may interrupt the engine component as well as caused hazards emission to the environment. (Abdullah et al., 2014[b] and Abdullah et al., 2014[c]).

The negative effect with increasing TAN value can be eliminate by increasing the TBN. Higher TBN value much more effective in suspending wear-causing contaminants and the corrosive effect can be reduced. Flash point is the lowest temperature for the lubricant to vaporize to form an ignitable mixture in air. There is no different in flash point between conventional diesel engine oil and with hBN nanoparticles additives, but slight decreased for nano-oil with Al_2O_3 nanoparticles. (Abdullah et al., 2014[b] and Abdullah et al., 2014[c]).

2.4 Effect of Temperature and Normal Load on the Wear Characteristic.

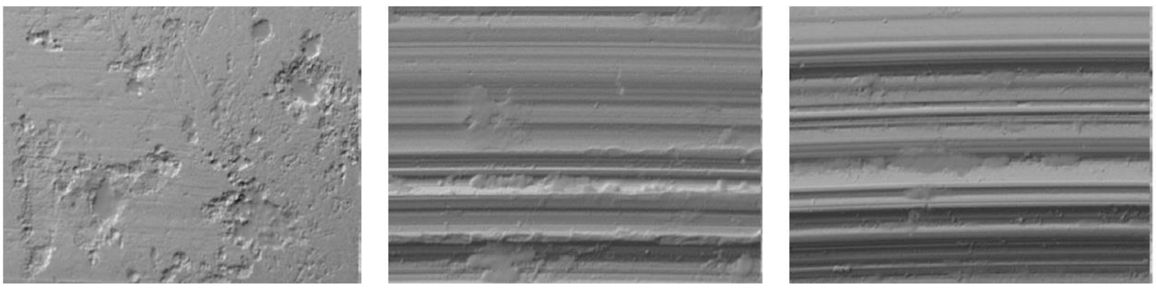
Golshokouh et al, showed that when temperature at 75°C, the surface of ball bearing lubricate with Jatropha oil covered with small pit due to material transfer between contact part and several parallel grooves was observed at 95°C and 105°C as shown in Figure 2.11.



(a) 75°C (b) 95°C (c) 105°C

Figure 2.10 Wear scar on the balls surface at different temperature of Jatropha oil

Other than that, when normal load applied on the ball specimen lubricate with Jatropha oil, the results showed micro cutting on the ball surface due to abrasive wear. As the load increases, deep parallel grooves and material transfer were discovered on the ball surface.



(a) 300 N (b) 400 N (c) 500 N

Figure 2.11 Wear scar on the balls surface at different loads of Jatropha oil.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology used in this project to obtain data that will satisfied the objective. This project involves three main process which are Four Ball Tester experiment (FBT), sonication process to prepare the nano-oil and Wear Scar Diameter (WSD). The project started by looking through past project that has been done by others such as reading an articles and journal that have the similarity with this project. The result will show the characteristics of the wear obtain on the surface of the ball bearing.

3.2 General Experimental Work

3.2.1 Nanoparticles Material

For this project, the nanoparticles used was hBN nanoparticles which the properties of this additives as mention in Table 2.2.

3.2.2 Lubricant Sample Preparation

For this study, there are two types of lubricant will be used in the FBT experiment. First lubricant was the conventional diesel engine oil which are SAE 15W-40. Second lubricant was a nano-oil that is conventional engine oil with hBN nanoparticles as an additive. The nano-oil was prepared by dispersing an optimum composition that is 0.5 vol % of 70 nm hBN nanoparticles in SAE 15W-40 diesel engine oil. 0.5 vol % of hBN nanoparticle is equal with 1.15g of hBN nanoparticles and this was obtained by utilizing the density formula as shown below. The composition of second lubricant consist of 0.5 vol % hBN nanoparticles and 99.5 vol % of SAE 15W-40 diesel engine oil.

$$\rho = m / v$$

$$2.3 \text{ g / vol} = m / 0.5 \text{ vol}$$

$$m = 1.15 \text{ g of hBN nanoparticles}$$

The technique used to prepare the nano-oil is sonication technique which is the dispersion of hBN nanoparticles into the diesel engine oil using an ultrasonic homogenizer (Sartorius Labsonic P) for 20 minutes with 50 percent amplitude an active interval of 0.5. To prevent the sedimentation of nanoparticles, the sample was stabilized using 0.3 vol % of surfactant that is oleic acid. There are no significant effect of the surfactant on tribological performance of the lubricants. (Abdullah M.I.H.C. et al., 2016). The method for preparation of the sample are shown in Figure 3.2.2.2.

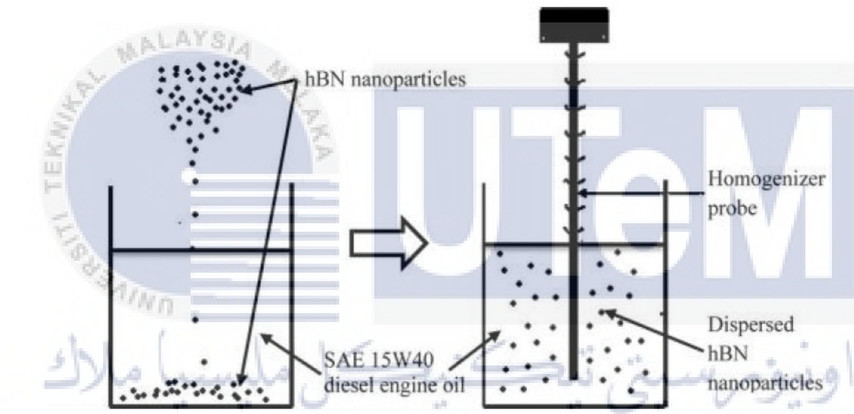


Figure 3.1 Illustration on the preparation of nano-oil (Abdullah M.I.H.C. et al., 2016).

Below are the two samples lubricant the conventional SAE 15W-40 diesel engine oil and SAE 15W-40 diesel engine oil with 0.5 vol % of hBN nanoparticles.

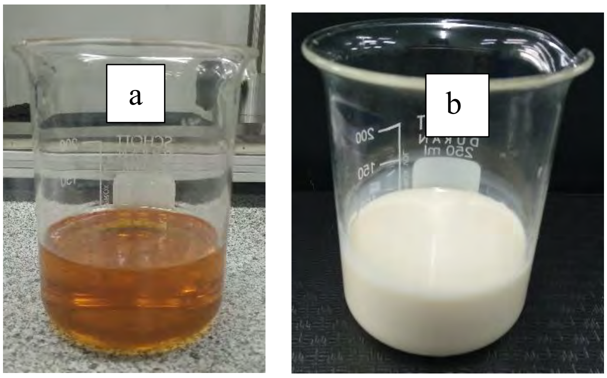


Figure 3.2 (a) SAE 15W-40 diesel engine oil (b) SAE 15W-40 diesel engine oil with 0.5 vol % of hBN nanoparticles.

3.2.3 Tribological Test

The purpose of this experiment was to examine the wear characteristics and COF of ball bearing for two types of lubricant under various applied load, speed and temperature. The mechanical properties of ball bearing used in this FBT experiment shown in Table 3.1. The test parameter load, speed, temperature and lubricant used were recorded in Table 3.2 and Table 3.3.

Table 3.1 Mechanical properties of the carbon-chrome steel ball (Abdullah M.I.H.C. et al., 2016)

Properties of Carbon-chromium steel ball	
Hardness (H), HRC	61
Density (ρ), g/cm^3	7.79
Surface roughness, (R_a), µm	0.022

Table 3.2 Test parameter at different load, temperature, speed for SAE 15W-40

Load, N	Speed, rpm	Temperature , °C
100	100	27
		50
		100
	300	27
		50
		100
	500	27
		50
		100
300	100	27
		50
		100
	300	27
		50
		100
	500	27
		50
		100
500	100	27
		50
		100
	300	27
		50
		100
	500	27
		50
		100

Table 3.3 Test parameter at different load, temperature, and speed for SAE 15W-40 enhance with 0.5 vol % of hBN nanoparticles.

Load, N	Speed, rpm	Temperature, °C
100	100	27
		50
		100
	300	27
		50
		100
	500	27
		50
		100
300	100	27
		50
		100
	300	27
		50
		100
	500	27
		50
		100
500	100	27
		50
		100
	300	27
		50
		100
	500	27
		50
		100

3.2.4 Procedures of FBT experiment.

Below are the procedures of the FBT experiment and all the related apparatus are shown in the figures and table below.

1. All four balls bearing are cleaned thoroughly along with the clamping parts upper and lower balls and the ball pot using acetone. They are later then wiped with dry tissues so that no trace of any solvent remained when the lubricant was pour into the pot.
2. One of the steel ball bearing are later inserted into the ball chuck and the chuck will be inserted into the spindle of the test machine.
3. The other three of the steel ball bearing were placed into the ball pot assembly and the assembly was tightened using a torque wrench to prevent the bottom steel balls from moving during the experiment.
4. After that, the test lubricant was poured into the ball pot assembly until it filled all the voids in the test cup assembly.
5. Then the assembled ball pot components were put onto the non-friction disc in the four balls machine as shown in Figure xx. The load applied slowly to avoid shock loading.
6. The first test that was carried out was for room temperature so it does not necessary for the thermocouple attached to the apparatus. But for temperature other than room temperature, the thermocouple must be attached to the apparatus so that it can heat up to the desired temperature.
7. After the desired temperature was reached, simultaneously the timer and the drive motor was start.
8. After an hour, the heater and the drive motor was turned off automatically and the oi cup assembly was removed from the machine.
9. Drained the test oil from the test cup and the ball bearing was put inside a plastic bag with a little test oil to avoid it from rust before the WSD test were carried out.
10. The steps were repeated for each lubricant using a new ball bearing for each testing parameter.

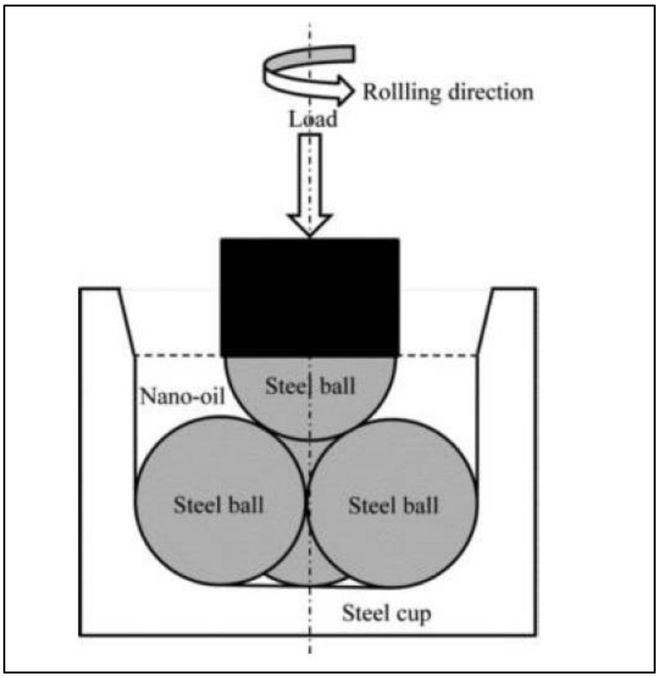


Figure 3.3 Schematic diagram of a four-ball tribometer (Abdullah M.I.H.C. et al., 2016)

3.2.5 Wear Scar Diameter

The wear scar diameter of all the three bottom ballaz bearing and top was measured to determine the lubricity performance of the test lubricant. The wear scar diameter was measured by using the MPS-3080 digital microscope. The volume of the ball's worn material was calculated by using the following equation:

$$V = (\pi h^2 /3)\ (3R - h) \tag{1}$$

$$h = R - \sqrt{R^2 - a^2} \tag{2}$$

where, (V) is the wear volume in mm^3/s, (R) is the radius of the ball in mm, (a) is the radius of the wear scar in mm and (h) is the height of wear scar in mm. By using the following equation:

$$k = V / t \tag{3}$$

where, (k) is the wear rate in mm^3 /s and t is the sliding time in seconds, the wear rate was then calculated. (Abdullah M.I.H.C. et al., 2016). The qualitative data from examining the ball bearing surfaces were used to characterize the nature of the wear in each test.

3.2.6 Wear Scar Diameter Procedures

1. Installed the software MPS-3080 digital microscope into the computer.
2. The apparatus was set up.
3. The USB wire of the microscope was connected into the computer.
4. Put the first ball bearing into the ball bearing holder under the microscope.
5. The magnifying glass was then controlled to get the clear image of the wear as shown in the computer.
6. After wear was identified, key in the magnifying range and then captured the image of the wear.
7. Double clicked at the image that has been captured, then the diameter of the wear scar was obtain using the tools provided in the software.
8. Steps 4 to 7 were repeated by using the second and the third ball bearing for all 54 samples.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Wear Rate Calculation

Table 4.1 and Table 4.2 shows wear rate for both SK11 ball bearing in 15W-40 diesel engine oil and 15W-40 diesel engine oil with 0.5 vol. % of hBN nanoparticles for all 54 samples. Below shows the sample calculation to find the wear rate,

$$k = V/t$$

$$V = (\frac{\pi h^2}{3})(3R - h)$$

$$h = R - \sqrt{R^2 - a^2}$$

Sample 1 (100N, 100rpm and 27°C)

R = 6.35 mm

a = 0.102 mm

t = 3600 s

h = 6.35 - $\sqrt{(6.35)^2 - (0.102)^2}$

= 0.819×10^{-3}mm

V = $\frac{(\pi(0.819\times10^{-3})^2)}{3}$ (3(6.35) – 0.819×10^{-3})

= $1.338\times 10^{-5}\ mm^3$

k = 1.338×10^{-5} / 3600

= $0.372 \times 10^{-8}\ mm^3$

Table 4.1 Wear rate of SK11 in 15W-40 diesel engine oil

Load, N	Speed, rpm	Temp. °C	Radius, a (mm)	Wear Scar Diameter, d (mm)	Height, h (m)×10^{-3}	Volume, V (mm^3)×10^{-5}	Wear rate,k (mm^3/s) ×10^{-8}
100	100	Room	0.102	0.204	0.819	1.338	0.372
		50	0.166	0.332	2.170	9.393	2.609
		100	0.115	0.230	1.041	2.162	0.601
	300	Room	0.131	0.262	1.351	3.642	1.012
		50	0.127	0.254	1.270	3.217	0.894
		100	0.111	0.222	0.970	1.877	0.521
	500	Room	0.140	0.280	1.543	4.749	1.319
		50	0.115	0.230	1.041	2.162	0.601
		100	0.115	0.230	1.041	2.162	0.601
300	100	Room	0.155	0.310	1.892	7.140	1.983
		50	0.156	0.312	1.917	7.330	2.036
		100	0.159	0.318	1.991	7.907	2.196
	300	Room	0.174	0.348	2.384	11.337	3.149
		50	0.163	0.326	2.092	8.730	2.425
		100	0.167	0.334	2.196	9.619	2.672
	500	Room	0.172	0.344	2.330	10.829	3.001
		50	0.197	0.394	3.057	18.640	5.178
		100	0.194	0.388	2.964	17.523	4.868
500	100	Room	0.181	0.362	2.580	13.277	3.688
		50	0.183	0.366	2.637	13.870	3.853
		100	0.201	0.402	3.182	20.195	5.611
	300	Room	0.215	0.430	3.641	26.441	7.345
		50	0.223	0.446	3.917	30.601	8.500
		100	0.226	0.452	4.023	32.280	8.967
	500	Room	0.211	0.422	3.507	24.531	6.814
		50	0.210	0.420	3.473	24.058	6.683
		100	0.250	0.500	4.923	48.336	13.427

Table 4.2 Wear rate SK11 in 15W-40 with 0.5 vol. % hBN nanoparticle

Load, N	Speed, rpm	Temp. °C	Radius, a (mm)	Wear Scar Diameter, d (mm)	Height, h (m)$\times10^{-3}$	Volume, V (mm^3)$\times10^{-5}$	Wear rate,k (mm^3/s) $\times10^{-8}$
100	100	Room	0.103	0.206	0.835	1.391	0.386
		50	0.106	0.212	0.885	1.562	0.434
		100	0.108	0.216	0.918	1.681	0.467
	300	Room	0.100	0.200	0.787	1.236	0.343
		50	0.111	0.222	0.970	1.877	0.521
		100	0.115	0.230	1.041	2.162	0.601
	500	Room	0.109	0.218	0.936	1.748	0.486
		50	0.128	0.256	1.290	3.320	0.922
		100	0.122	0.244	1.172	2.740	0.761
300	100	Room	0.159	0.318	1.991	7.907	2.196
		50	0.155	0.310	1.892	7.140	1.983
		100	0.173	0.346	2.357	11.081	3.078
	300	Room	0.141	0.282	1.566	4.892	1.359
		50	0.174	0.348	2.384	11.337	3.149
		100	0.180	0.360	2.552	12.991	3.609
	500	Room	0.174	0.348	2.384	11.337	3.149
		50	0.180	0.360	2.552	12.991	3.609
		100	0.188	0.376	2.784	15.460	4.294
500	100	Room	0.202	0.404	3.213	20.591	5.720
		50	0.187	0.374	2.754	15.128	4.202
		100	0.222	0.444	3.881	30.042	8.245
	300	Room	0.200	0.400	3.150	19.791	5.498
		50	0.219	0.438	3.778	28.468	7.908
		100	0.236	0.472	4.387	38.385	10.663
	500	Room	0.246	0.492	4.767	45.322	12.589
		50	0.243	0.487	4.651	43.143	11.984
		100	0.244	0.488	4.690	43.869	12.186

4.2 Wear Rate, k Analysis

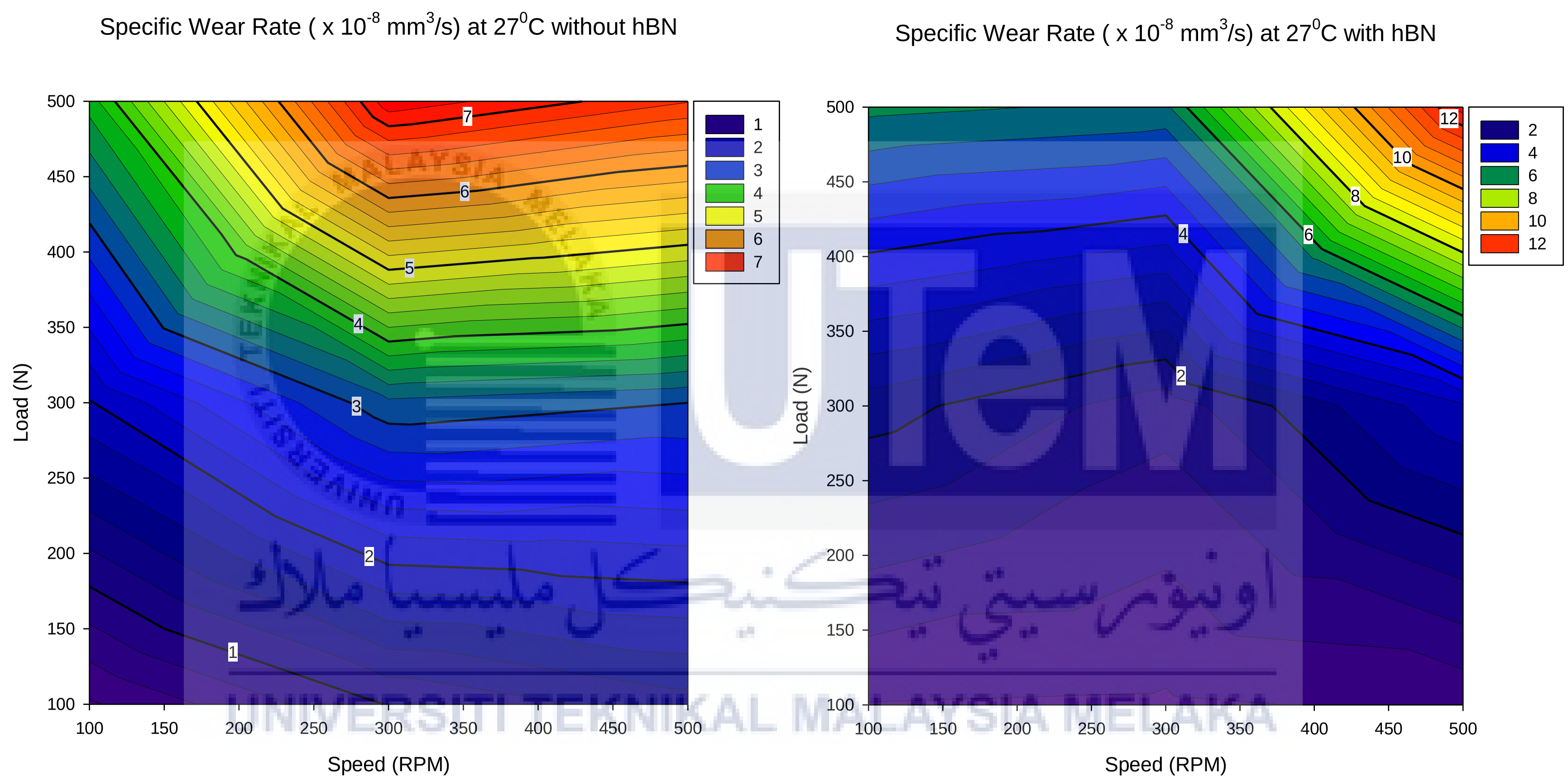


Figure 4.1 Wear rate, k of SK11 (a) in SAE 15W-40 diesel engine oil (b) with 0.5 vol. % hBN nanoparticle at 27˚ C

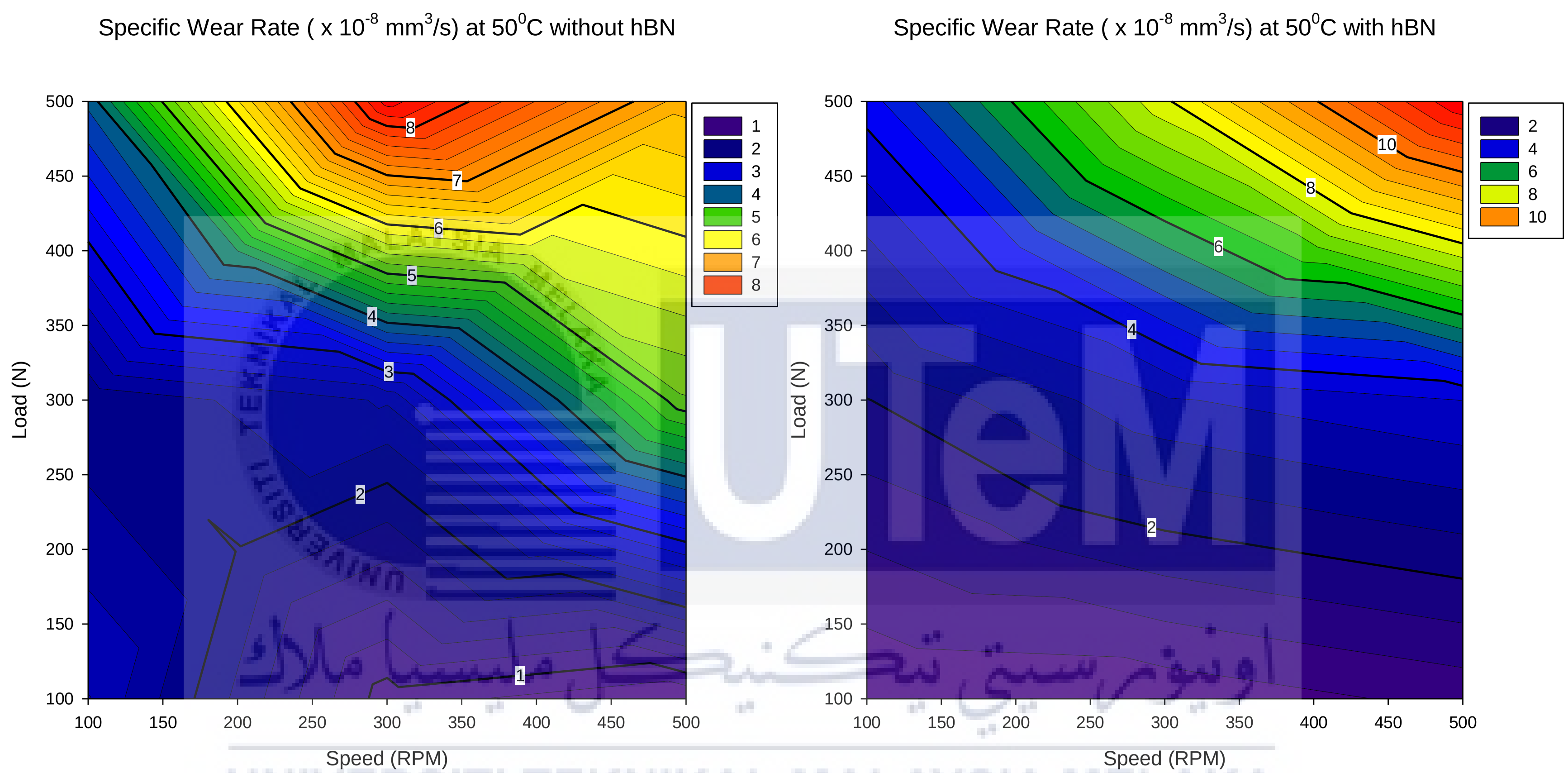


Figure 4.2 Wear rate, k of SK11 (a) in SAE 15W-40 diesel engine oil (b) with 0.5 vol. % hBN nanoparticle at 50˚C

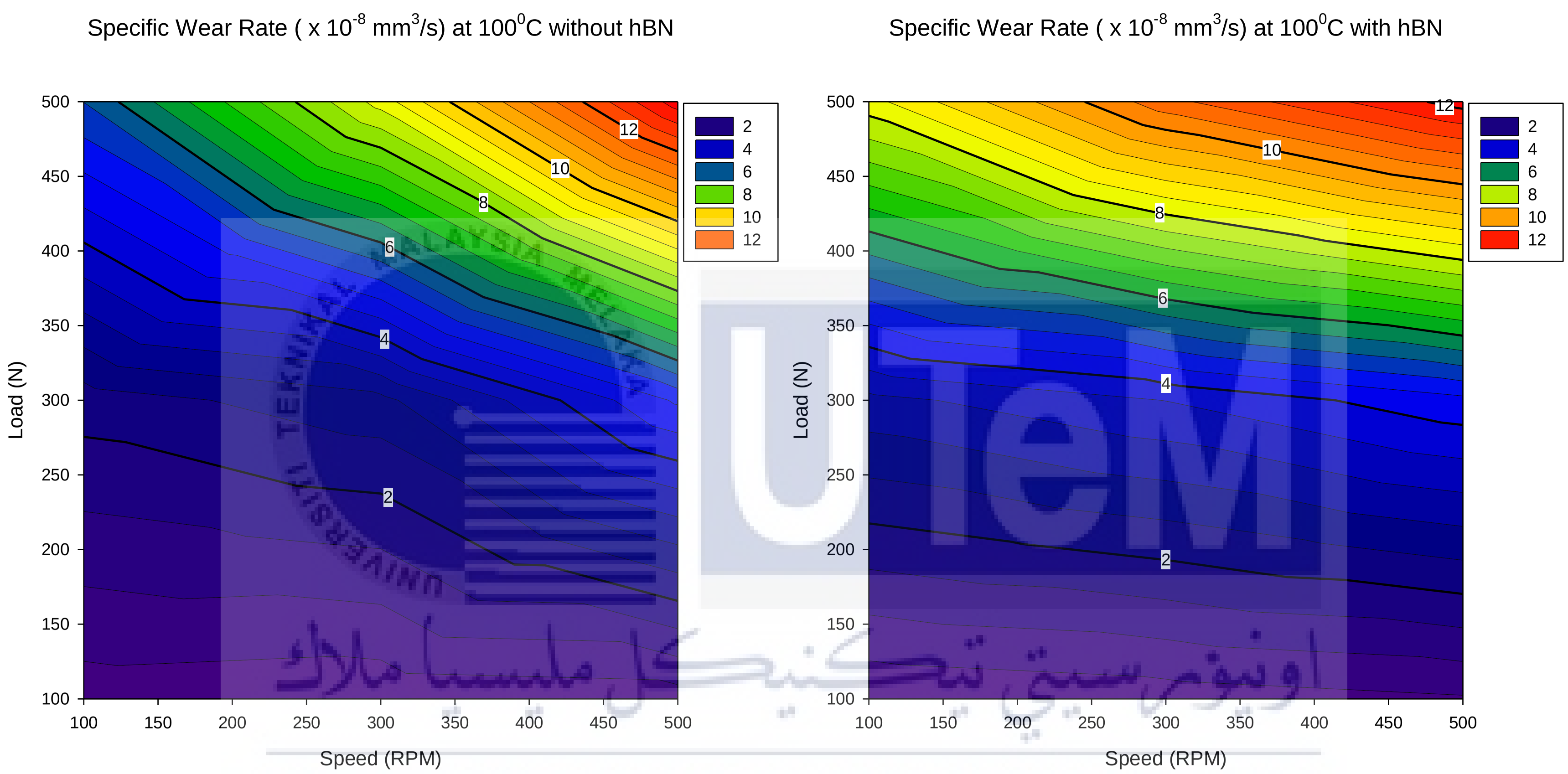


Figure 4.3 Wear rate, k of SK11 (a) in SAE 15W-40 diesel engine oil (b) with 0.5 vol. % hBN nanoparticle at 100˚ C

Figure 4.1 shows the comparison of wear rate for SK11 in both with and without nanoparticles in the lubricant. The conventional diesel engine oil shows that, at high load and high speed it recorded the highest wear rate which is 6.814×10^{-8} $mm^3. s^{-1}$. Whereas, the wear rate of SK11 with nanoparticles in the lubricant recorded the highest value also at high load and high speed which is 12.589×10^{-8} $mm^3. s^{-1}$ It shows an increment in wear rate of SK11 when using the lubricant added with nanoparticles compared to conventional diesel engine oil at low temperature. Thus, it can be wrapped up that, at low temperature, the hBN nanoparticle does not react actively with the base oil which in this experiment was the SAE 15W-40 diesel engine oil to reduce the wear rate of SK11.

Figure 4.2 shows the graph of the wear rate versus the applied load and speed for both the SAE 15W-40 diesel engine oil and with 0.5 vol. % of hBN nanoparticles at 50° C. At 100 rpm, the wear rate of SK11 shows an increment as the load increases for both lubricant with and without hBN, shows a very significant different where the value of wear rate drop from 2.609×10^{-8} $mm^3.s^{-1}$ under SAE 15W-40 to 0.434×10^{-8} $mm^3.s^{-1}$ with 0.5 vol. % of hBN nanoparticles. At 300N and 500 rpm, the wear rate value of SK11 for both lubricant with and without nanoparticles reduced by approximately 30% from 5.718×10^{-8} $mm^3.s^{-1}$ to 3.609×10^{-8} $mm^3.s^{-1}$ respectively. For load at 500N, 300 rpm, the wear rate reduced by approximately 7% from 8.5×10^{-8} $mm^3.s^{-1}$ to 7.908×10^{-8} $mm^3.s^{-1}$ lubricated with and without hBN nanoparticles respectively. However, hBN nanoparticles show an increment of 44% in wear rate of SK11 at 500 rpm under same load from 6.683×10^{-8} $mm^3.s^{-1}$ without hBN nanoparticles to 11.984×10^{-8} $mm^3.s^{-1}$ with hBN nanoparticles. This can be said when temperature at 50° C, at 300 rpm with high load, 500N, hBN nanoparticles become a good reducing wear agent but at 500 rpm and 500N it increases the wear rate.

Figure 4.3 shows the graph of the wear rate versus the applied load and speed for both the SAE 15W-40 diesel engine oil and with 0.5 vol. % of hBN nanoparticles at 100° C. From both graph, it show the same trend as the speed and the load keep on increasing, the wear rate also increasing. But the different was, the wear rate of SK11 lubricated under SAE 15W-40 recorded smaller value of wear rate compared to lubricate with addition of 0.5 vol. % hBN nanoparticles. The only significant changes recorded at this temperature was at 100N, 100 rpm, where the wear rate reduced by approximately 22% from 0.601×10^{-8} $mm^3.s^{-1}$ under SAE 15W-40 to 0.467×10^{-8} $mm^3.s^{-1}$ with 0.5 vol. % of hBN nanoparticles.

From the explanation above, it can be said that the hBN nanoparticles does not performed efficiently at high temperature of 100°C and high load of 500N even though there has a slight reduction can be observed from Figure 4.1 where at 500N with speed of 300 rpm. From the result also, it shows that the most effective temperature for hBN nanoparticles to reduce the wear rate of SK11 is at 50°C

4.3 Wear Scar Diameter Analysis

Table 4.3 Wear scar diameter of SK11 in SAE 15W-40 diesel engine oil at 27° C

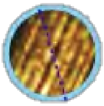
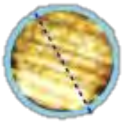
 100N, 100rpm, 0.204 mm	 100N, 300rpm, 0.262 mm	 100N, 500rpm, 0.280 mm
 300N, 100rpm, 0.310 mm	 300N, 300rpm, 0.348 mm	 300N, 500rpm, 0.34 mm
 500N, 100rpm, 0.362 mm	 500N, 300rpm, 0.430 mm	 500N, 500rpm, 0.422 mm

Table 4.4 Wear scar diameter of SK11 in SAE 15W-40 diesel engine oil with 0.5 vol. % of hBN nanoparticles at 27° C

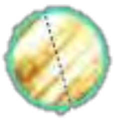
 100N, 100rpm, 0.206 mm	 100N, 300rpm, 0.2 mm	 100N, 500rpm, 0.218 mm
 300N, 100rpm, 0.318 mm	 300N, 300rpm, 0.282 mm	 300N, 500rpm, 0.348 mm
 500N, 100rpm, 0.404 mm	 500N, 300rpm, 0.4 mm	 500N, 500rpm, 0.492 mm

Table 4.5 Wear scar diameter of SK11 in SAE 15W-40 diesel engine oil at 50° C

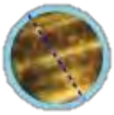
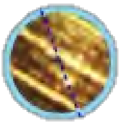
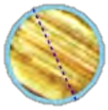
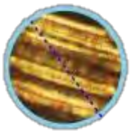
 100N, 100rpm, 0.332 mm	 100N, 300rpm, 0.254 mm	 100N, 500rpm, 0.230 mm
 300N, 100rpm, 0.312 mm	 300N, 300rpm, 0.326 mm	 300N, 500rpm, 0.394 mm
 500N, 100rpm, 0.366 mm	 500N, 300rpm, 0.446 mm	 500N, 500rpm, 0.420 mm

Table 4.6 Wear scar diameter of SK11 in SAE 15W-40 diesel engine oil with 0.5 vol. % of hBN nanoparticles at 50° C

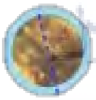
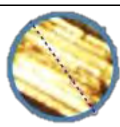
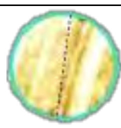
 100N, 100rpm, 0.212 mm	 100N, 300rpm, 0.222 mm	 100N, 500rpm, 0.256 mm
 300N, 100rpm, 0.310 mm	 300N, 300rpm, 0.348 mm	 300N, 500rpm, 0.360 mm
 500N, 100rpm, 0.374 mm	 500N, 300rpm, 0.438 mm	 500N, 500rpm, 0.487 mm

Table 4.7 Wear scar diameter of SK11 in SAE 15W-40 diesel engine oil at 100° C

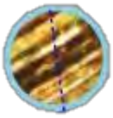
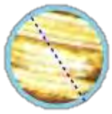
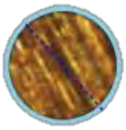
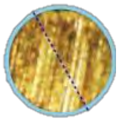
 100N, 100rpm, 0.230 mm	 100N, 300rpm, 0.222 mm	 100N, 500rpm, 0.230
 300N, 100rpm, 0.318 mm	 300N, 300rpm,0.334 mm	 300N, 500rpm, 0.388 mm
 500N, 100rpm, 0.402 mm	 500N, 300rpm, 0.452 mm	 500N, 500rpm, 0.5 mm

Table 4.8 Wear scar diameter of SK11 in SAE 15W-40 diesel engine oil with 0.5 vol. % of hBN nanoparticles at 100° C

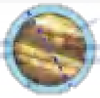
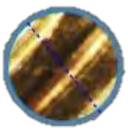
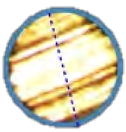
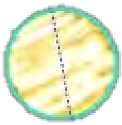
 100N, 100rpm, 0.216 mm	 100N, 300rpm, 0.230 mm	 100N, 500rpm, 0.244 mm
 300N, 100rpm, 0.346 mm	 300N, 300rpm, 0.360 mm	 300N, 500rpm, 0.376 mm
 500N, 100rpm, 0.444 mm	 500N, 300rpm, 0.472 mm	 500N, 500rpm, 0.488 mm

Table 4.3 and Table 4.4 both recorded the WSD of SK11 lubricate with and without hBN nanoparticles at 27° C. From both tables, it can be observed that at speed of 100 rpm,

it show an increasing of WSD in the surface of SK11 as the load increasing from 100 N, 300 N and 500 N. Whereas the same case at speed of 500 rpm where the WSD also increase as the load increases but a slight reduction recorded at speed of 100 N, 500 rpm where the WSD reduce from 0.280 mm (SAE 15W-40) to 0.218 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles). However, the most significant WSD reduction recorded was at speed of 300 rpm where the reduction at 100 N from 0.262 mm (SAE 15W-40) to 0.200 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles), at 300 N from 0.348 mm (SAE 15W-40) to 0.282 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles) and at 500 N from 0.430 mm (SAE 15W-40) to 0.400 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles). This can be said that, hBN nanoparticles effectively reduce the WSD of SK11 surface at speed of 300 rpm at 27°C.

Table 4.5 and 4.4 recorded the WSD of SK11 at 50°C lubricate under SAE 15W-40 and with 0.5 vol. % of hBN nanoparticles. The WSD reduce at speed of 100 rpm at 100 N and 300 N from 0.332 mm (SAE 15W-40) to 0.212 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles) and 0.312 mm (SAE 15W-40) to 0.310 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles) respectively. However, a slight increase at 500 N from 0.366 mm (SAE 15W-40) to 0.374 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles). At speed of 300 rpm, there has a slight reduction recorded at 100 N from 0.254 mm (SAE 15W-40) to 0.222 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles) and keep on increasing after that at 300 N and 500 N. Whereas at speed of 500 rpm, the WSD recorded a fluctuating values as at 100 N it increases from 0.230 mm (SAE 15W-40) to 0.256 mm (SAE 15W-40) with 0.5 vol. % of hBN nanoparticles) then reduce at 300 N from 0.394 mm (SAE 15W-40) to 0.360 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles) then again increase at 500 N from 0.420 mm (SAE 15W-40) to 0.487 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles).

Table 4.7 and 4.8 show a WSD of SK11 for both lubricant with and without hBN nanoparticle. At speed of 100 rpm, the most significant WSD value change was at 100 N from 0.230 mm (SAE 15W-40) to 0.216 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles) also for 300 N and 500 N both show an increasing in WSD. At speed of 300 rpm, there are no reducing in WSD even after added with hBN nanoparticles to the base oil. Whereas at speed of 500 rpm, it recorded a slight reduce at 300 N from 0.388 mm (SAE 15W-40) to 0.376 mm (SAE 15W-40 with 0.5 vol. % of hBN nanoparticles).

CHAPTER 5

CONCLUSION

As a conclusion, the objective of the project to distinguish the wear characteristics of SK11 ball bearing in SAE 15W-40 diesel engine oil enhanced with and without hBN nanoparticles as an additives is successfully achieved by undergoes the three phase that are experiment using Four Ball Tester, the making of nano-oil using sonication technique and lastly determination of wear scar diameter using the MPS-3080 digital microscope. From the results and discussion made, best said that at low temperature, 27°C, hBN nanoparticles manage to reduce the wear rate at 100 N for all range of speed that has been set and it clearly can be observed that the wear rate reduced at 300 rpm for every load in temperature. At the temperature of 50°C, the wear rate only reduce after being added with the nanoparticles additives at 100 N for all range of speed but not efficiently helpful in reducing wear rate at high load and high speed that are 500 N and 500 rpm. At 100°C, the result indicate that even after added with hBN nanoparticles, the wear rate still increasing in values and simply can said that the hBN nanoparticles not effective at high temperature. Therefore, after all the analysis has been done, the objective are completed.

REFERENCES

Abdullah, M.I.H.C., Abdollah, M.F., Amiruddin, H., Tamaldin, N., Nuri, N.R.M., Effect of hBN/Al_2O_3 nanoparticle additives on the tribological performance of engine oil, Jurnal Teknologi, 3 (2014) 1-6.

Abdullah, M.I.H.C., Abdollah, M.F., Amiruddin, H., Nuri, N.R.M., Tamaldin, N., Hassan, M., Rafeq, S.A., Effect of hBN/Al_2O_3 nanoparticle on engine oil properties, Energy Education Science and Technology Part A: Energy and Research, (2014) 3261-3268.

Abdullah, M.I.H.C., Abdollah, M.F., Amiruddin, H., Nuri, N.R.M., Tamaldin, N., Hassan, M., Rafeq, S.A., Improving engine oil properties by dispersion of hBN/Al_2O_3 nanoparticle, Applied Mechanics and Materials Vol. 607 (2014) pp 70-73.

Abdullah, M.I.H.C., Abdollah, M.F., Amiruddin, H., Nuri, N.R.M., Tamaldin, N, The potential of hBN nanoparticles as friction modifier and antiwear additives in engine oil, Mechanics and Industry 17, 104 (2016).

Abdullah, M.I.H.C., Abdollah, M.F., Amiruddin, H., Nuri, N.R.M., Tamaldin, N., Effect Of hexagonal boron nitride nanoparticles as an additive on the extreme Pressure properties of engine oil, Industrial Lubrication and Tribology 68/4 (2016) 441-445.

Asrul, M., Zulkifli, N.W.M., Masjuki, H.H., Kalam, M.A., Tribological properties and lubricant mechanism of nanoparticle in engine oil, Procedia Engineering 68 (2013) 320-325.

Bustos, E.G., Guadarrama, M.A.F., Castro, G.A.R., Vargas, O.AG., Hernandez, E.A.G., Silva, I.C., The wear resistance of boride layers measured by the four-ball test, Surface and Coatings Technology, 215 (2013) 241-246.

Cerny. J., Strnad, J., Sebor, G., Composition and oxidation stability of SAE 15W-40 engine oils, Tribology International 34 (2001) 127-134.

Dai, W., Kheireddin, B., Gao, H., Liang, H., Roles of nanoparticles in oil lubrication, Tribology International 102 (2016) 88-98.

Farhanah, A.N., Bahak, M.Z., Engine oil wear resistance Journal of Tribology, 4 (2015) 10-20.

Girard, L., Kibrya, N., Hwang, K., Wang, W., Wear Testing, (2015).

Golshokouh, Syahrullail, S., Ani, F.N., Influence of Normal load and temperature on tribological properties of Jatropha oil, Journal of Technology (Science and Engineering) 71:2 (2014) 145-150.

Wan, Q., Jin, Y., Sun, P., Ding, Y., Tribological behavior of a lubricant oil containing boron nitride nanoparticles, Procedia Engineering 102 (2015) 1038-1045.

Wu, Y.Y., Tsui, W.C., Liu, T.C., Experimental analysis of tribological properties of lubricating oils with nanopartilces additives, Wear 262 (2007) 819-825.

Kalam, M.A., Masjuki, H.H., Varman, M., Liaquat, A.M., Friction and wear characteristics of waste vegetable oil contaminated lubricants, International Journal of Mechanical and Materials Engineering, 6 (2011), No 3, 431-436.

Kothavale, B.S., Evaluation of extreme pressure properties lubricating oils using four ball friction testing machine, International Journal of Advanced Engineering Technology (2011) 56-58.

Lesniewski, T., Krawiec, S., The effect of ball hardness on four ball wear test results, Wear 264 (2008) 662-670.

Ludema, K.C., 2012. Tribology, in *Handbook of Lubrication and Tribology,* 2nd ed., vol II CRC Press., p-1.

Peric, S., Bogdan, N., Trifkovic, D., Vuruna, M., An experimental study of the tribological characteristics of engine and gear transmission oils, Journal of Mechanical Engineering, 59 (2013) 7-8, 443-450.

Shahnazar, S., Bagheri, S., Hamid, S.B.A., Enhancing lubricant properties by nanoparticles additives, International Journal of Energy, 41(2016) 3153-3170.

Syahrullail, S., Wira, J.Y., Nik, W.B.W., Fawwaz, W.N., Friction characteristics of RBD palm olein using four ball tribotester, Applied Mechanics and Materials vol. 315 (2013) pp 936-940.

Syahrullail, S., Wira, J.Y., Nik, W.B.W., Fawwaz, W.N., Tiong, C.I., The effect of sliding speed on friction and wear of RBD palm olein, Applied Mechanics and Materials vol. 315 (2013) pp 951-955.