A STATISTICAL MODEL FOR DETERMINING FRICTION AND WEAR OF SK11 BALL BEARING IN NANOPARTICLES-ENHANCED ENGINE OIL

NOR HASRIN NADIA BINTI ALIAS

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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This report is submitted
in fulfillment of the requirement for the degree of
Bachelor of Mechanical Engineering (Automotive)

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DECLARATION

I declare that this project report entitled “A Statistical Model For Determining Friction And Wear Of SK11 Ball Bearing In Nanoparticles-enhanced Engine Oil” is the result of my own work except as cited in the references

Signature	:	....
Name	:	....
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 Engineering (Automotive).

Signature :. ....

Name of Supervisor : ....

Date : ....

DEDICATION

To my beloved family and friends.

ABSTRACT

Hexagonal Boron Nitride is one of nanoparticles types that widely used in tribology industry for improvement in tribological performance. In order to reduce the COF and wear scar of ball bearing, hBN is added into the engine oil. So, the Four-Ball Tester experiment is running in order to predict the friction and wear reduction of SK11 ball bearing. The experiment is carried with loads of 100N, 300N, 500N, speed of 100 rpm, 300 rpm, 500 rpm and temperature at room temperature, 50°C and 100°C. In addition, the portable microscope will be used to test the wear scar diameter or the worn that form on the surface of ball bearing. Hence, this experiments were conducted based on Taguchi method. A L9 Orthogonal array was selected for design of experiment. The analysis that conducted for this experiment is ANOVA which is used in investigating the influence of applied load, speed and temperature on friction coefficient and wear rate. Besides, the regression model were developed for COF and wear rate. In this research, it is observed that applied load has the highest influence in COF and wear rate followed by speed and temperature. Lastly, the experimental result were validated by the confirmation tests.

ABSTRAK

Heksagon Boron Nitride adalah salah satu jenis nanopartikel yang digunakan secara meluas dalam industri tribologi untuk meningkatkan prestasi bahan. HBN ditambah ke dalam minyak enjin untuk mengurangkan pekali geseran dan kadar kehausan bebola. Jadi, eksperimen "Four-Ball Tester" dijalankan untuk memastikan pengurangan pekali geseran dan kadar kehausan bebola jenis SK11. Eksperimen ini dijalankan dengan menggunakan parameter yang berbeza iaitu beban 100N, 300N, 500N, kelajuan 100 rpm, 300 rpm, 500 rpm dan suhu pada suhu bilik, 50 ° C dan 100 ° C. Di samping itu, mikroskop mudah alih juga digunakan untuk menguji diameter kehausan bebola yang terbentuk di atas permukaan bebola. Oleh itu, eksperimen ini telah dijalankan menggunakan kaedah Taguchi. L9 Orthogonal pelbagai telah digunakan untuk reka bentuk eksperimen. Analisis yang dijalankan untuk eksperimen ini adalah ANOVA yang mana telah digunakan dalam menyiasat pengaruh beban, kelajuan yang digunakan dan suhu ke atas pekali geseran dan kadar kehausan bebola. Selain itu, model regresi juga telah dibentuk untuk pekali geseran dan kadar kehausan bebola. Dalam kajian ini, didapati bahawa beban yang dikenakan memberikan pengaruh yang tertinggi kepada pekali geseran dan kadar kehausan dan diikuti oleh kelajuan dan suhu. Akhir sekali, keputusan eksperimen telah disahkan dengan menggunakan ujian pengesahan.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

hBN	Hexagonal Boron Nitride
DOE	Design of Experiment
ANOVA	Analysis of Variance
OA	Orthogonal Array
COF	Coefficient of Friction
WSD	Wear Scar Diameter
S/N	Signal to Ratio
CuO	Copper Oxide
WVO	Waste Vegetable Oil
SEM	Scanning Electron Microscopy

CHAPTER 1

INTRODUCTION

1.0 BACKGROUND OF STUDY

Lubricant or engine oil is used for lubrication in internal combustion engine system. It creates a separating film between surfaces of moving parts to minimize direct contact from one part to another part. It will reduce the friction coefficient and wear reduction from forming, thus protect the engine.

Over a past few decades, nanotechnologists did some great research on nanoparticles because of their special physical and chemical properties. So, they have made an investigation on the mixture between nanoparticles with conventional diesel engine oil. The mixture showed a lot of improvements happen especially on properties of the engine oil which are under extreme pressure, wear resistance and friction reduction properties. The size of nanoparticles play main role in improvement of lubricant properties. Because of their small size, it allows them enter into the contact interface for load bearing and lubricating easily. Besides that, there are a lot of types of nanoparticles that are used in the improvement of engine oil properties. For example, CuO as addictive in the engine oil.

The reduction of friction coefficient and anti-wear are important in lubricant because it can affect the effects of tribological performance of engine oil. The performance of engine oil is better when the friction coefficient is low and the worn surface that formed on bearing is small.

1.1 PROBLEM STATEMENT

Friction and wear are the important aspect in the engine oil performance. Existing engine oil is only effective at high load, speed and temperature. So, nanoparticles are decided to mix with the engine oil to improve the performance of engine right after startup.

Hence, Taguchi method is the method that will be used while doing the research because of the variance reduction for the experiment with optimum setting of control parameters.

1.2 OBJECTIVES

The objectives of this project are as follows:

1. To determine the optimal parameters for friction and wear reduction for SK11 ball bearing in the mixture of hexagonal boron nitride (hBN) and engine oil at low load, speed and temperature.
2. To propose mathematical model for determining wear and friction of SK11 ball bearing in the mixture of hexagonal boron nitride (hBN) and engine oil in Minitab software by using Taguchi method.

1.3 SCOPE OF PROJECT

This research is carried out to study the prediction for friction and wear of SK11 in nanoparticles-enhanced engine oil at low load, speed and temperature. The Four-Ball Tester experiment will be conducting for this research. The Minitab software and the Design of Experiment (DOE) under the Taguchi method will be used to set up the parameter for this research. The parameters that are going to be used in this study are load, speed and temperature. The Analysis of Variance (ANOVA) will be used to analyze the friction and wear of SK11 ball bearing in nanoparticles-enhanced engine oil.

CHAPTER 2

LITERATURE REVIEW

2.1 NANOPARTICLES AS ADDICTIVES IN ENGINE OIL

Over the past few decades, scientists and technologists have been carried out on the tribological properties of lubricants with different nanoparticles added in the engine oil. Nanoparticles are added into the engine oil because it can improve the properties of engine oil which can reduce coefficient of friction and wear. There are several chemical composition that can be used as addictive in engine oil. For example, metal sulfides such as MoS_2 is one of the chemical composition. Sulfur played an important role in the interaction between particles and molecules of lubricant because of the laminar structure. A tribofilm are formed on the friction surface after the tribochemical reaction take place between particles and the environment under the heat generated by friction and high pressure contact. The tribofilm has unique properties which are hardness, adhesion and roughness. For example, from Figure 2.1, adsorption film was formed after nano-MoS_2 reacted with lubricants (Wei Dai et al., 2016).

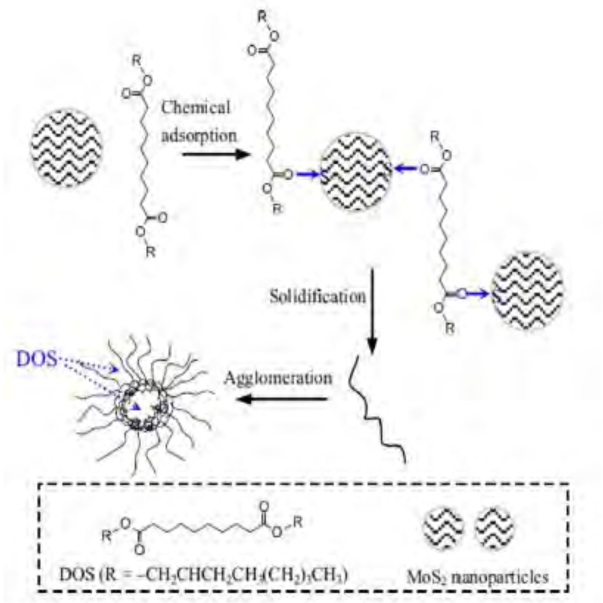


Figure 2.1 The formation of adsorption layer using MoS_2 nanoparticles (Wei Dai et al., 2016)

Next, MoS_2 is also most commonly used solid lubricant to improve performance of the process because it offers very low friction coefficient, high wear resistance and can withstand the heavy load (Gunda et al., 2016).

2.2 NANOPARTICLES AS FRICTION IMPROVER AND WEAR REDUCTION

Nanoparticles are used in the improvement of engine oil because by adding nanoparticles in engine oil, the coefficient of friction and wear will reduce. The properties of lubricant itself is reduced the friction between two surfaces and as anti-wear. The friction coefficient is lowest and wear is reduced on the friction surface that strong solid lubricating film formed during whole test because of the addictive compound effects, S-P addictive. As shown in the Figure 2.2, the coefficient of friction for HD 80w/90 type of engine oil is low because of addictive and Figure 2.3 for anti-wear comparison (Jiyuan et al., 2001). Besides that, normal lubricant (SAE grade 40) combined with amine phosphate and palm oil shows better results especially on reducing friction coefficient, reducing WSD, increasing FTP and reducing TAN value, besides also reducing the viscosity within the operating range. As shown in Figure 2.4, the different COF value between normal lubricant and lubricant with different types of addictive and Figure 2.5, for WSD vs percentage (%), e.g. sample D is normal lubricant with 0.5% Amine phosphate with 1% to

5% waste palm oil (WVO) with base lubricant, sample E is normal lubricant 0.5% Octylated/butylated diphenylamine addictive with 1% to 5% waste palm oil (WVO) with base lubricant (Kalam et al., 2011).

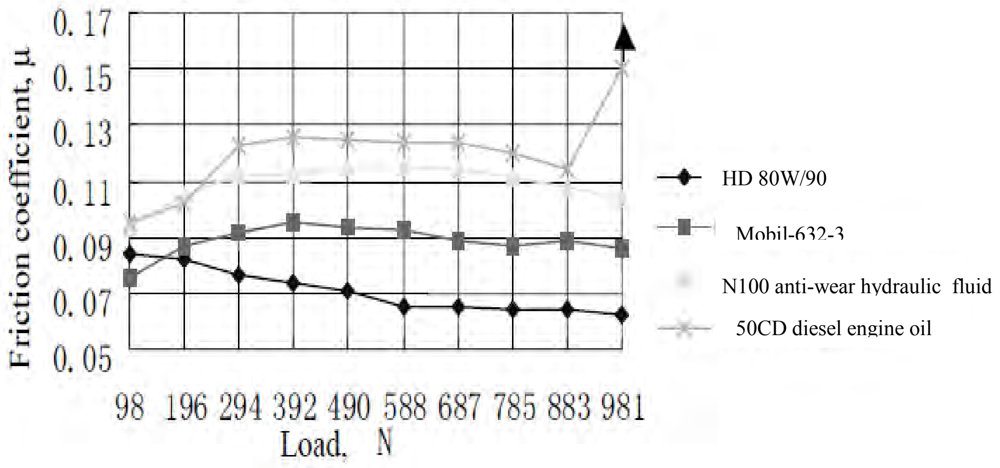


Figure 2.2 The load-friction coefficient curve of 4 oils (Jiyuan et al., 2001)

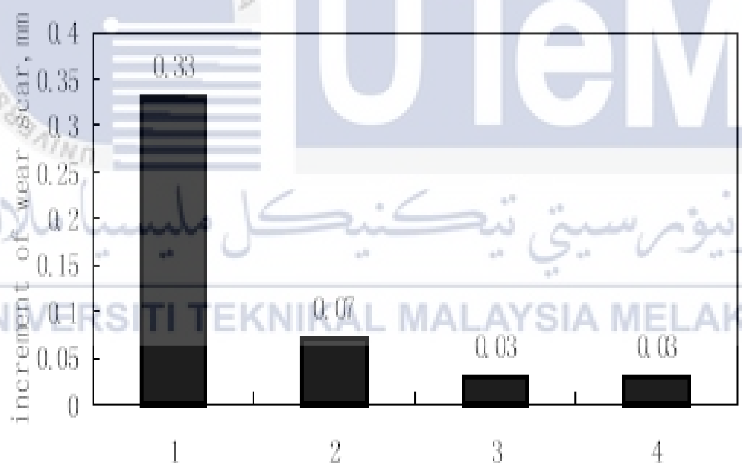


Figure 2.3 Comparison of anti-wear in 4 types of oil. 1. 50CD diesel engine oil, 2. N100 anti-wear hydraulic fluid, 3. mobil-632, 4. HD 80w/90 (Jiyuan et al., 2001)

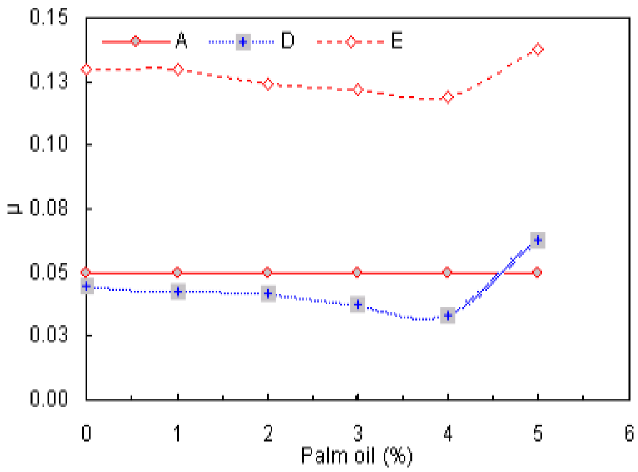


Figure 2.4 COF (μ) vs percentage (%) of palm oil in sample D (normal lubricant with 0.5% Amine phosphate with 1% to 5% waste palm oil (WVO) with base lubricant) and sample E (normal lubricant 0.5% Octylated/butylated diphenylamine addictive with 1% to 5% waste palm oil (WVO) with base lubricant) (Kalam et al., 2011)

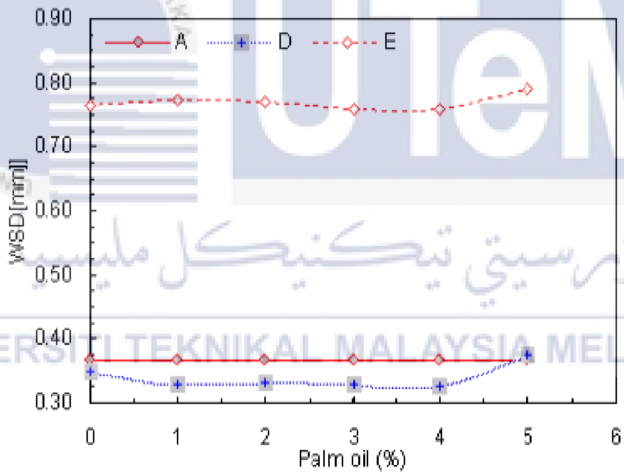


Figure 2.5 WSD vs percentage (%) (Kalam et al., 2011)

Suspension of 3% of CuO nanoparticle content with modified produced COF of 0.13 which is the best COF. It shows that the higher the concentration of CuO, the better the tribological properties and surface modification. It can be approved in the Figure 2.6 (Asrul et al, 2013). Besides that, the tribological properties is improved when nanoparticles was added into base oil especially for friction and wear reduction. In addition, CuO nanoparticles that added into the base oil reduced the COF value from 24% to 53% at 0.5% CuO concentration during the friction reduction test compared to the oil without nanoparticles (Pisal & Chavan, 2014).

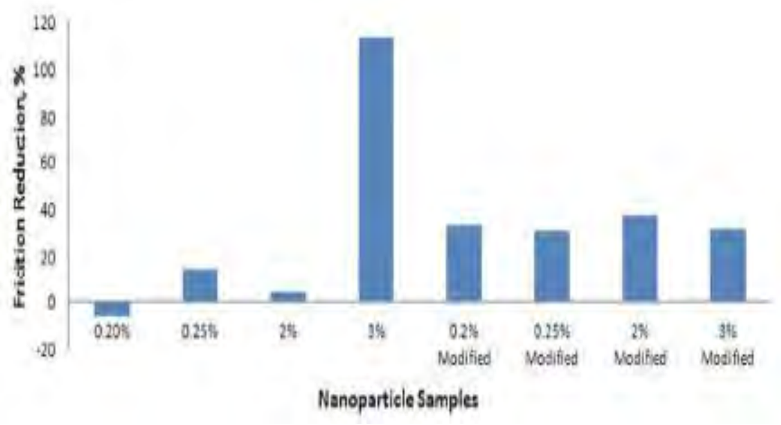


Figure 2.6 Friction reduction vs Nanoparticles samples (Asrul et al., 2013)

The friction coefficient value of the base oil is higher compared to the friction coefficient value of nano-BN oil during the test occur. Furthermore, the increase the concentration of BN nanoparticle addictive, the increase the value of the COF. The concentration nano-BN that are using in the test are 0.1wt.%, 0.5wt.% and 1.0wt.%. The result of the test can be seen in the Figure 2.7. Next, nano-BN also improve the anti-wear properties of base oil which has been confirmed from SEM, AFM and EDS about the worn surface. Figure 2.8 shown the worn surface before test while Figure 2.9 shown the worn surface after the surface was tested by using sample BN01 which contain 0.1wt% of BN (Wan et al., 2015).

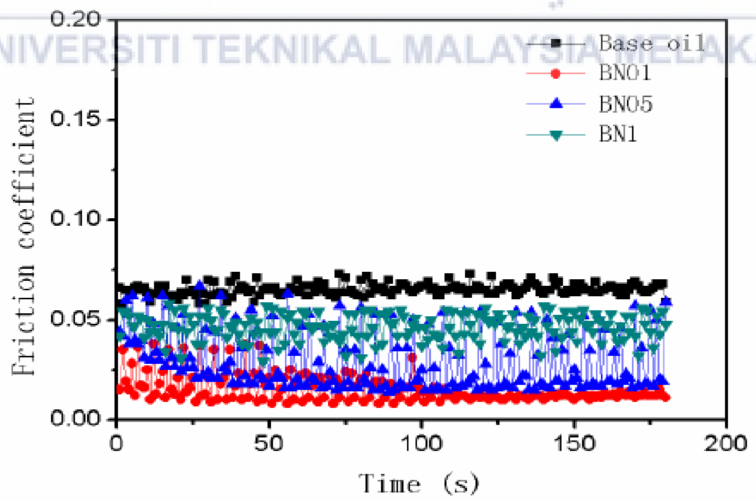


Figure 2.7 Friction coefficients of base oil and nano-BN vs time (Wan et al., 2015)

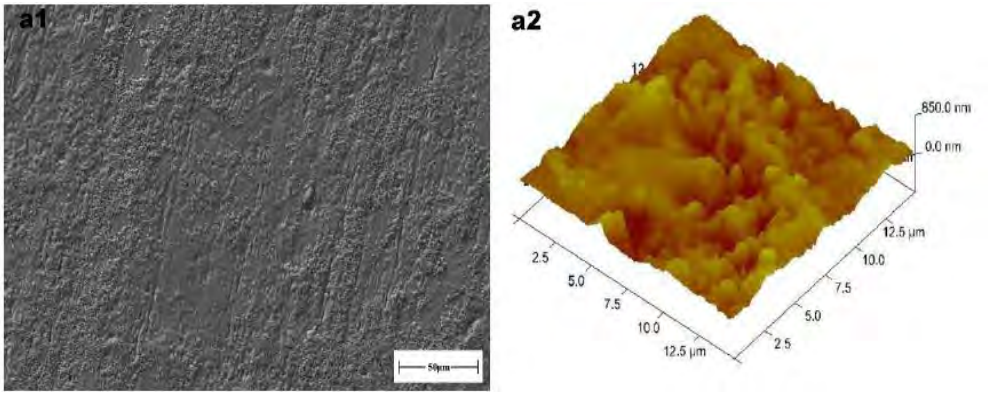


Figure 2.8 Example of worn surface before test with BN01 by using SEM and AFM (Wan et al., 2015)

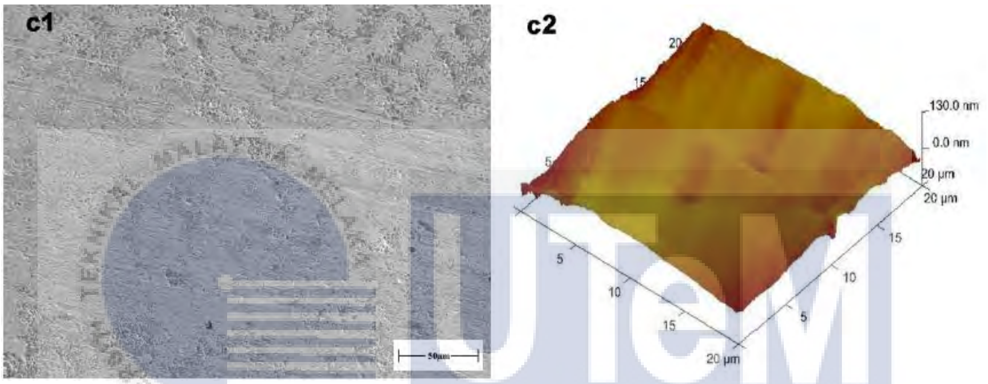


Figure 2.9 Example of worn surface after test with BN01 by using SEM and AFM (Wan et al., 2015)

For a few past decades, nanoparticles as addictive in the lubricant shows the effective decreasing in friction and wear. Metal, metal oxide, metal sulfide, carbonate, borate, carbon material and rare-earth compound have been one of the best addictive in improving the lubricant properties (Shahnazar et al., 2016).

2.3 FOUR BALL TESTER MACHINE

Four ball tester machine is specifically used to determine the friction coefficient and also the wear-preventing properties of various lubricant such as motor oil, cutting oil, hydraulic oil, greases and solid lubricant. Furthermore, it also can be used to determine the friction and wear characteristics of bearing materials. Besides that, it is also important to differentiate between the Four-Ball EP Tester and the Four-Ball Wear Tester. It is because the Four-Ball EP Tester is designed specifically for high test load. The Four-Ball Tester is automatic and can be controlled by using graphical interface $M4B^{TM}$ software (Garcia-Bustos et al., 2013). This machine used four balls which are three balls at the bottom and one ball on the top which is attached to the collate as shown in Figure 2.10 (Syahrullai et al., 2013)

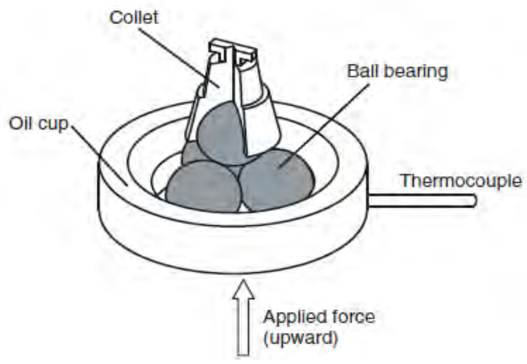


Figure 2.10 Schematic diagram for Four-Ball Tester (Syahrullai et al., 2013)

2.4 TAGUCHI METHOD

Taguchi method is developed by Dr. Taguchi Of Nippon Telephones and Telegraph Company which is based on Orthogonal Array (OA) experiments. This method gives much reduced variance for the experiment with optimum setting of control parameters. The combination between Design of Experiments (DOE) with optimization of control parameter to gain the best result is achieved in Taguchi method. OA provide a set of well balanced and Signal-to-Noise ratios (S/N), which are log functions of desired output. this is served as objective functions for optimization which is help in data analysis and optimum results prediction. This method has divided into three categories of quality characteristic in the S/N ratio which are the-lower-better, the-higher-the-better and the-nominal-the-best (Kapsiz et al., 2011).

DOE is a method that is denoted by "$L_a b_c$". L_a is the orthogonal arrays of variables, b is the levels of variables while c is variables numbers (Kondapalli et al., 2013). (Rao & Padmanabhan, 2012) says that the function of Taguchi method is to determine the optimum settings of input parameters and neglect the variation that has been caused by noise factor.

S/N ratio for COF was computed to quantify the optimal value to each design parameter which mean the greater the value of S/N ratio, the better the performance that will produce. Figure 2.11 is about the interaction plot of COF against three different parameter which are applied load (N), sliding speed (rpm) and sliding distance (km).

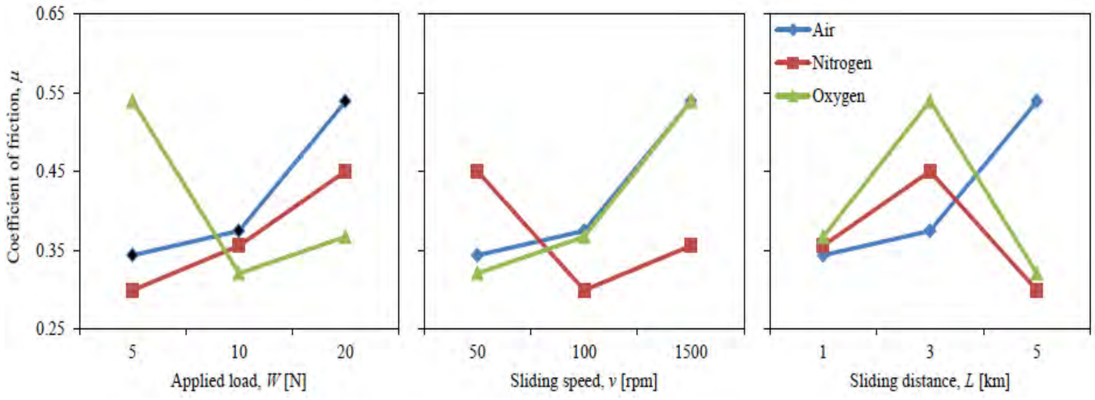


Figure 2.11 Interaction plot for friction coefficient (Rao & Padmanabhan, 2012)

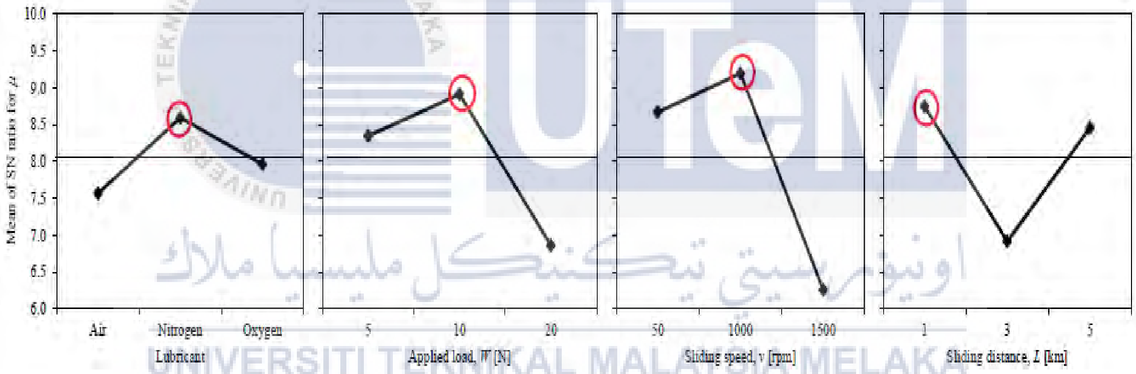


Figure 2.12 Mean of COF (Abdollah et al., 2013)

There red circle in the Figure 2.12 are shown the optimal design parameter after analysis by using S/N ratio (Abdollah et al., 2013). Next, other analysis can be obtained from Taguchi method is Analysis of Variance (ANOVA). (Julie et al., 2007) said that the function ANOVA is to determine the percentage contribution of each parameter against a stated level of confidence for a result of experiment. Besides that, ANOVA also helps in testing of importance of all main factors and their interactions. It can be done by comparing the mean square against an estimate of the experimental errors at specific confidence level. Calculate the total sum of squared deviation SS_T from the total mean S/N ratio n_m as follows:

$$SS_T = -\sum_{i=1}^{n} (n_i - n_m)^2$$

Where;

n_i is the number of experiments in orthogonal array

n_m is the mean S/N ratio for the experiment

Next, the percentage of contribution P can be calculated as follows:

$$P = \frac{SS_d}{SS_T}$$

Where SS_d is the sum of the squared deviations. The ANOVA result as shown in Table 2.0.

Table 2.1 Example for ANOVA

Source of Variation	DOF	Sum of squares (SS)	Variance (V)	F-ratio (F)	P-value (P)	Contribution %
Alumina	2	9.2577	4.6289	3.77	0.209	62.79
hBN	2	2.6553	1.3276	1.08	0.480	18.01
Surfactant	2	0.3778	0.1889	0.15	0.867	2.56
Residual error	2	2.4530	1.2265			
Total	8	14.7439				

2.5 HEXAGONAL BORON NITRIDE (hBN)

Hexagonal Boron Nitride (hBN) is one of nanoparticle type that are used as addictive. Several scientists report that friction coefficient and anti-wear behaviour of nanoparticles depends on characteristics of nanoparticle itself such as size and shape of that nanoparticle. The hBN is in solid form or powder form. The size of hBN is 70 nm with optimal composition which is dispersed into the diesel engine oil by using ultrasonic homogenizer which is the technique is called sonication (M. I. H. C. Abdullah, Abdollah, et al., 2014). Besides that, the structure of hBN is more likely to graphite because of the crystal structure and has been called “white graphite” (Abdullah et al., 2015).

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter is about the guideline to complete this project. It briefly covers the explanation of methodology that will used in this project to ensure smooth flow. Besides that, this is also help to complete the project during the given time. In addition, the methods that are used in this project help to achieve the objective of this project. So, the methodology use for this project is following several steps as shown in Figure.

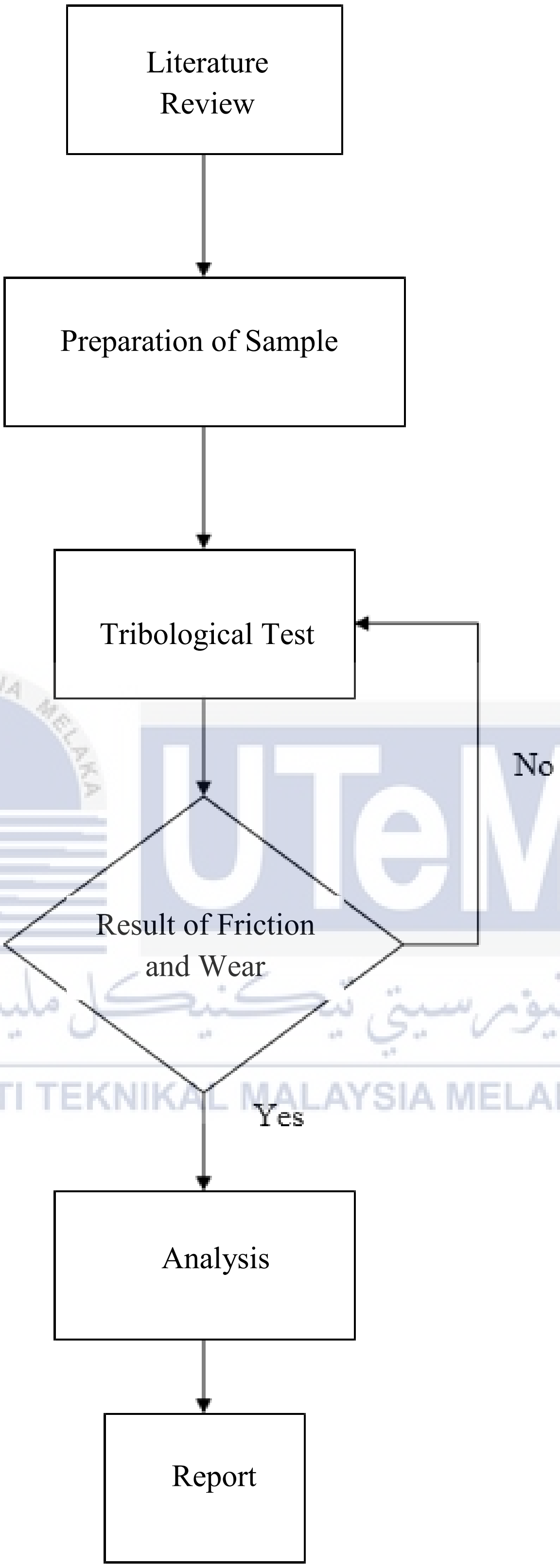


Figure 3.1 Project flow chart

3.2 OPTIMIZATION OF PARAMETER

For this method, Minitab software is used to set the parameter that are going to use for the experiment. Design of Experiment (DOE) is one of the method under Taguchi method. For this experiment, the Taguchi method which is consisting of L_9 orthogonal array is used with nine rows and three columns at three levels. Three design parameters are determined (i.e., load, speed and temperature) as shown in Table 3.0. For Table 3.1, it shows the DOE with L_9 orthogonal arrays using Minitab statistical software.

Table 3.1 Design parameter at different level

Level	Load (N)	Speed (rpm)	Temperature (°C)
1	100	100	27
2	300	300	50
3	500	500	100

Table 3.2 DOE with L_9 (3^3) orthogonal arrays

Test	Load (N)	Speed (rpm)	Temperature (°C)
1	100	100	27
2	100	300	50
3	100	500	100
4	300	100	50
5	300	300	100
6	300	500	27
7	500	100	100
8	500	300	27
9	500	500	50

3.3 SAMPLE PREPARATION

3.3.1 THE MIXTURE OF NANOPARTICLES AND ENGINE OIL

Based on the Table 3.2, nano-oil samples are prepared by dispersing 0.5 vol. % concentrations of 70 nm sized hBN in the conventional diesel engine oil (SAE 15W40) which the engine oil can be a noise factor. Figure 3.2 shows the hBN powder that has been used in this experiment. To stabilize the samples of nanoparticles-enhanced engine oil, the appropriate amount of surfactant which is oleic acid. After that, the solid particles of hBN that has been adding into the diesel engine oil is homogenized by using ultrasonic homogenizer (Sartorius Labsonic P) for 20 minutes with 50% amplitude and 0.5 active time interval.

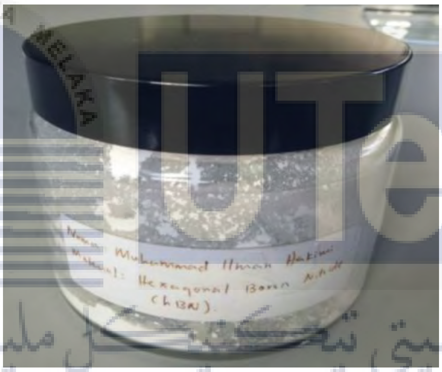


Figure 3.2 The hBN powder

Before adding the hBN into the engine oil, the 0.5 vol.% of hBN need to convert to the unit gram. By using density equation, ρ, the mass of solid particles of hBN can be calculated. The general density of hBN is 2.3 g/cm³.

$$\rho = \frac{m}{v} \tag{1}$$

$2.3\ g/cm^3 = \frac{m}{0.5\ cm^3}$

$m = 1.15\ g$ of hBN nanoparticles

The mass of this hBN is used for 100 ml of solution mixture which is 99.5 ml of the mixture is from diesel engine oil while 0.5 ml is from 1.15 grams of hBN.

3.3.2 PROCEDURES OF MIXING HBN WITH LUBRICANT

1. The weight of hBN was measured before put it into the diesel engine oil by using analytical balance scale.
2. The hBN was put into the diesel engine oil.
3. The Ultrasonic Homogenizer was set up before the beaker that contain hBN and engine oil was put. The amplitude was set at 50% and 0.5 for active time interval.
4. The beaker was put in the container that filled with water to avoid the beaker from break into the pieces during the homogenize process occur.
5. The homogenizer probe was inserted. Next, place the container on the base and make sure the probe immerses in the solution.
6. Lastly, the glass door of the machine was closed. Then, the machine was switched on and the process was run for 20 minutes.

3.3.3 PREPARATION OF SK11 BALL BEARING

For the sample of tribological test, the SK11 ball bearing, with 12.7 mm diameter is used. The surface roughness of this ball is 0.1 μm. Before tribological test is run, four ball bearings were soaking into the acetone. It is because acetone can be used as disturbance absorber by using ultrasonic bath machine.

3.4 TRIBOLOGICAL TEST

By depending on Table 4.2, the tribological test is carried out by using the Four-Ball Tester machine (ASTM D4172). This test needs four ball bearing in each test. The unique sample configuration of one top ball and three bottom balls make a very stable and a repeatable contact in-turn which is this condition allow the test to be very repeatable. The machine is set up by following the speed for first data. After that, temperature also need to be set up before running the test. The test is more preferably start with the lowest temperature to avoid the error from happen. For more accurate data, make sure that the parameter precision shall be only ±2. Average time for each test is 60 minutes.

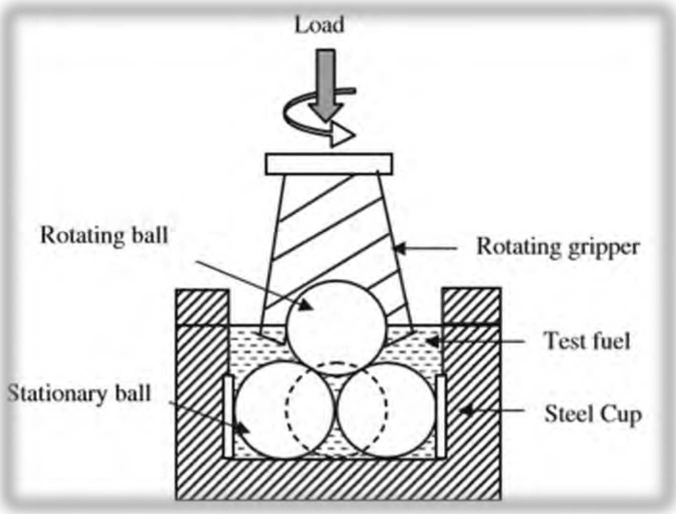


Figure 3.3 Schematic diagram of Four-Ball Tester

3.4.1 PROCEDURE OF FOUR-BALL TESTER EXPERIMENT

1. One of the test ball was inserted into the collate by using the spatula.
2. First, the machine was run to set up the speed. Then, the machine was stopped and the collate was put into the spindle of the machine.
3. Then, other three test ball were put into the steel cup. The ball cup was placed on the steel cup and then the locknut was locked by using hand tightening into the ball cup.
4. The engine oil that has been mixed with hBN was put into the steel cup by using syringe until it reached the top level of the locknut.
5. Then, the steel cup was put into the test machine. Before the machine is started, make sure that the surface between upper ball with lower ball was contacted to each other and make sure that there was no shock during the test load was applying.
6. Next, make sure that the temperature sensor was attached to the ball cup.
7. The time for running the experiment was set up at 60 minutes after the setting up of load, speed and temperature. Next, the experiment was started.

8. After 60 minutes, the steel cup was removed from the machine. Make sure that the temperature sensor was took off from steel cup. Then, the collate was removed from the spindle.
9. All the ball bearing that are used in the experiment were put into the zip plastic bag with small amount of oil. It can prevent rust from form on the ball bearing surface.
10. Each step was repeated for every test with different parameter.

3.4.2 WEAR SCAR DIAMETER EXPERIMENT

After the SK11 bearing tested by using the Four-Ball Tester experiment, it will be go through wear scar diameter experiment by using the Portable Microscope as shown in Figure 3.4. The purpose of this machine is to measure the diameter of wear scar that form on the worn surfaces of specimen.

Figure 3.4 Portable microscope

The procedures to conduct this is experiment is as follows:

1. The software MPS-3080 digital microscope was installed into the computer.
2. The apparatus was set up.
3. Connected the USB wire of the microscope into the computer.
4. Under the microscope, the first ball was put into the ball bearing holder.

5. The magnifying glass was controlled to get the clear image of the wear as shown in the computer.
6. The magnifying range was key in and the image of the wear was then captured after wear on the ball bearing was identified.
7. The image that has been captured was clicked, then obtained the diameter of wear scar by 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 9 samples.

3.5 ANALYSIS

3.5.1 COEFFICIENT OF FRICTION AND WEAR SCAR DIAMETER

Firstly, the coefficient of friction result for the experiment will be analysed. The coefficient of friction is measured in real time by using test equipment during the running of the experiment. The analysis of coefficient of friction can be calculated by using formula:

$$\mu = \frac{\sqrt{6}T}{3Wr} \qquad (2)$$

Where;

μ is the coefficient of friction,

T is the frictional torque [kg.mm],

W is the normal load applied [kg],

r is the rotational radius from the rotation axis.

The rotational radius is fixed as 3.67 mm by the test equipment manufacturer. The average coefficient of friction value is take after run the experiment for three times by using same parameter. Next, analyse the wear scar diameter. There are two parameters that need to be study which are volume and wear rate. This wear scar diameter can be calculated by using the formula as follows:

$$V = (\pi h^2/3)(3R - h) \quad (3)$$

$$h = R - \sqrt{R^2 - a^2} \quad (4)$$

where V is the wear volume in mm³/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. In addition, the wear rate can be calculated by using equation as follows:

$$k = V/t \quad (5)$$

where k is the wear rate in mm³/s and t is representing the time of sliding in second.

3.5.2 SIGNAL TO RATIO (S/N) ANALYSIS

This analysis is carried out in order to achieve the optimization of the operating parameters. The quality with the concept of the-larger-the-better is considered for the metal removal and S/N ratio for the concept the-larger-the-better is as follows:

$$\frac{S}{N} = -10log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \quad (6)$$

where n represented the number of the measurements in a row and y is the measured value in run/row. The greater value of S/N gives a better performance even though without consider the performance characteristic category.

3.5.3 ANALYSIS OF VARIANCE (ANOVA).

ANOVA is uses to investigate the percentage contribution of parameter against a stated level of confident for a result of this experiment. Firstly, calculate the total sum of squared deviation, SS_T from the total mean S/N ratio, n_m by using the equation as follows:

$$SS_T = \sum_{i=1}^{n}(n_1 - n_m)^2 \quad (7)$$

where n is the experiment number in the orthogonal array and n_i is the S/N ratio mean for the experiment. Besides that, it also can be used in the experiment in order to determine the different factors such as variance of the factor, sum of factors square and factor ratio, F. These factors can be calculated by using equation as follows

$$V_{factor} = \frac{SS_{factor}}{DOF_{factor}} \quad (8)$$

$$DOF_{total} = N - 1 \quad (9)$$

$$F_{factor} = \frac{V_{factor}}{V_{error}} \quad (10)$$

$$P_{factor} = \frac{SS_T}{SS_d} \quad (11)$$

F_{factor} is calculated in order to compare which design parameters have significant effect on the quality characteristics while P_{factor} is used to report the level of significance either the value is suitable or not suitable.

CHAPTER 4

RESULT AND DISCUSSION

4.1 TAGUCHI ANALYSIS

The tribological experiments for coefficient of friction and wear rate are conducted as per the orthogonal array based design of experiments given in Table 3.2. The analysis of the data is carried out by using Minitab 17 statistical software. Next, S/N ratio for COF and wear rate are calculated based on smaller-the-better criterion.

4.1.1 EFFECT OF THE FACTORS ON COF

Before any attempt is made, the possible interactions between the control factors must be considered. The experimental lay out and results with calculated S/N ratios for coefficient of friction of SK11 in nanoparticles-enhanced engine oil is shown in Table 4.1.

Table 4.1 The experimental lay out and results with calculated S/N ratios for coefficient of friction of SK11 in nanoparticles-enhanced engine oil

Load (N)	Speed (rpm)	Temperature (°C)	Coefficient of Friction	S/N ratios COF
100	100	27	0.089406	20.9727
100	300	50	0.079696	21.9713
100	500	100	0.111092	19.0863
300	100	50	0.112050	19.0118
300	300	100	0.123573	18.1615
300	500	27	0.130380	17.6958
500	100	100	0.086574	21.2523
500	300	27	0.087519	21.1580
500	500	50	0.092483	20.6788

The S/N response table is used to analyse the influence of each control factor on the coefficient of friction. Table 4.2 shows the S/N response table of coefficient of friction. From the table given, it shows that the applied load is the strongest influence on the coefficient of friction. Then, it is followed by speed and temperature.

Table 4.2 The S/N response table of coefficient of friction

Level	Load	Speed	Temperature
1	20.68	20.21	19.51
2	18.29	20.00	20.55
3	20.60	19.15	19.50
Delta	2.39	1.26	1.05
Rank	1	2	3

The main effects plot for mean S/N ratios for coefficient of friction is shown in the Figure 4.1. The significance of each parameter is determined from the inclination of the main plot graph. The most significant parameter is the parameter that has the higher inclination of line. It is clear from the main effect plot for S/N ratio for coefficient of friction from Figure 4.1 that applied load is most significant parameter. Besides, from the graph, optimal process conditions of control factors can be easily decided. The optimum process parameter is 500 N of applied load at 300 rpm of speed and at temperature of 50°C for this experiment. This can be summarised that the optimal process parameters for coefficient of friction are at level 3 of applied load, at level 2 of speed and at level 2 at temperature.

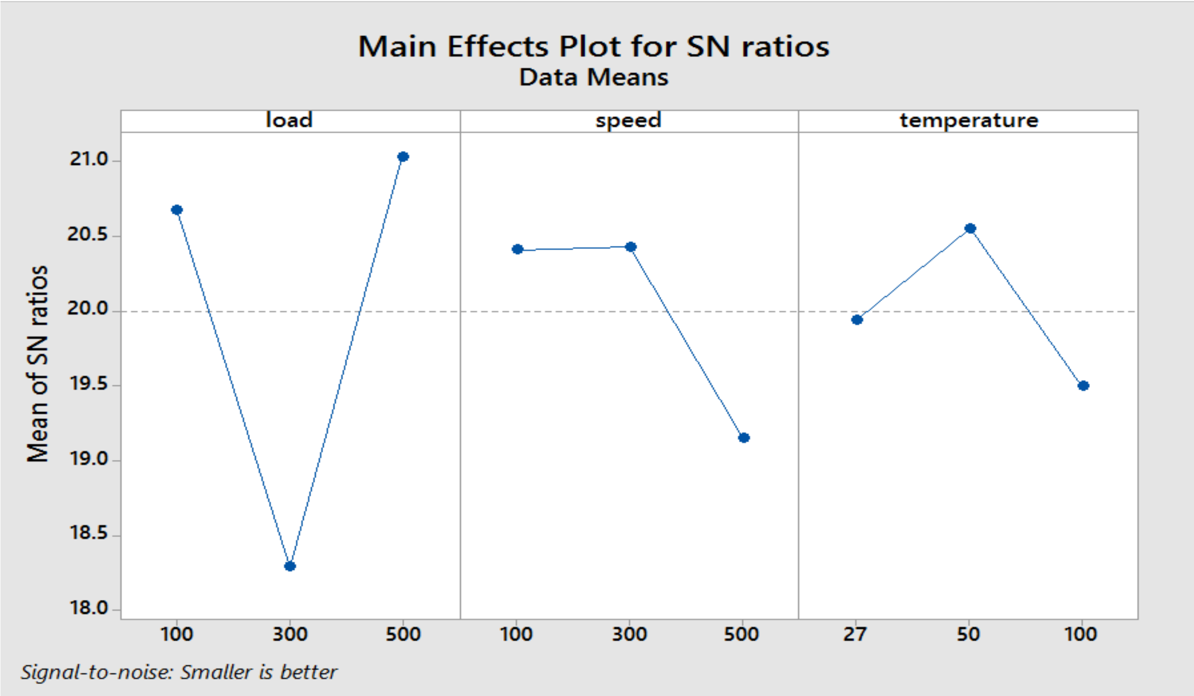


Figure 4.1 Main effects plot for S/N ratios of COF

4.1.2 EFFECT OF THE FACTORS ON WEAR RATE

The experimental lay out and results with calculated S/N ratios for wear rate of SK11 in nanoparticles-enhanced engine oil is shown in Table 4.3. The value of the radius of wear scar, a is the average for three ball bearings.

Table 4.3 The experimental lay out and results with calculated S/N ratios for wear rates of SK11 in nanoparticles-enhanced engine oil

Load, N	Speed, rpm	Temp, °C	Radius, a (mm)	Wear scar diameter, d (mm)	Height (mm) h x 10^{-3}	Volume (mm^3) V x 10^{-5}	Wear rate (mm^3/s) k x 10^{-8}	S/N ratios wear rates
100	100	27	0.103	0.206	5.430	0.937	0.260	168.253
100	300	50	0.111	0.222	7.077	1.709	0.475	165.652
100	500	100	0.122	0.244	9.417	3.311	0.920	162.371
300	100	50	0.155	0.310	19.354	17.481	4.886	154.054
300	300	100	0.180	0.360	31.007	51.246	14.235	148.852
300	500	27	0.174	0.348	28.223	41.188	11.441	150.037
500	100	100	0.222	0.444	62.100	243.880	67.744	141.567
500	300	27	0.200	0.400	43.875	112.108	31.141	145.196
500	500	50	0.253	0.487	99.351	520.596	144.610	137.028

The calculation of height of wear scar, wear volume and wear rate are shown at the example of calculation below by using equation (3)-(5).

Sample data for load = 100N, speed = 100rpm and temperature = 27°C

R = 6.35 mm, a = 0.103 mm, t = 3600 s

$h = 6.35 - \sqrt{(6.35)^2 - (0.103)^2}$

$= 5.430 \times 10^{-3}$mm

$V = \frac{(\pi(5.430\times10^{-3})^2)}{3}(3(6.35) - 5.430\times10^{-3})$

$V = 0.937\times10^{-5}\ mm^3$

$k = 0.937 \times10^{-5} / 3600$

$k = 0.260\times10^{-8}\ mm^3/s$

Influences of each design parameters (Load, Speed, Temperature) on wear rate is obtained from the response table of mean S/N ratio. Table 4.4 presents the S/N response table of wear rate. From the table given, it is showed that applied load is the dominant parameter on the wear rate. Then, it is followed by speed and temperature.

Table 4.4 The S/N response table of wear rate

Level	Load	Speed	Temperature
1	165.4	154.6	154.5
2	151.0	153.2	152.2
3	141.3	149.8	150.9
Delta	24.2	4.8	3.6
Rank	1	2	3

The main effects plot for S/N ratios for wear rate is shown in the Figure 4.2. The significance of each parameter is determined from the inclination of the main plot graph. The most significant parameter is the parameter that has the higher inclination of line. It is clearly show from the main effect plot for S/N ratio for wear rate from Figure 4.2 that applied load is most significant parameter. In addition, optimal process conditions of control factors can be easily decided from the graph below. The optimum process parameter is 100 N of applied load at 100 rpm of speed and at temperature of 27°C for this experiment. This can be summarised that the optimal process parameters for coefficient of friction are at level 1 of applied load, at level 1 of speed and at level 1 at temperature.

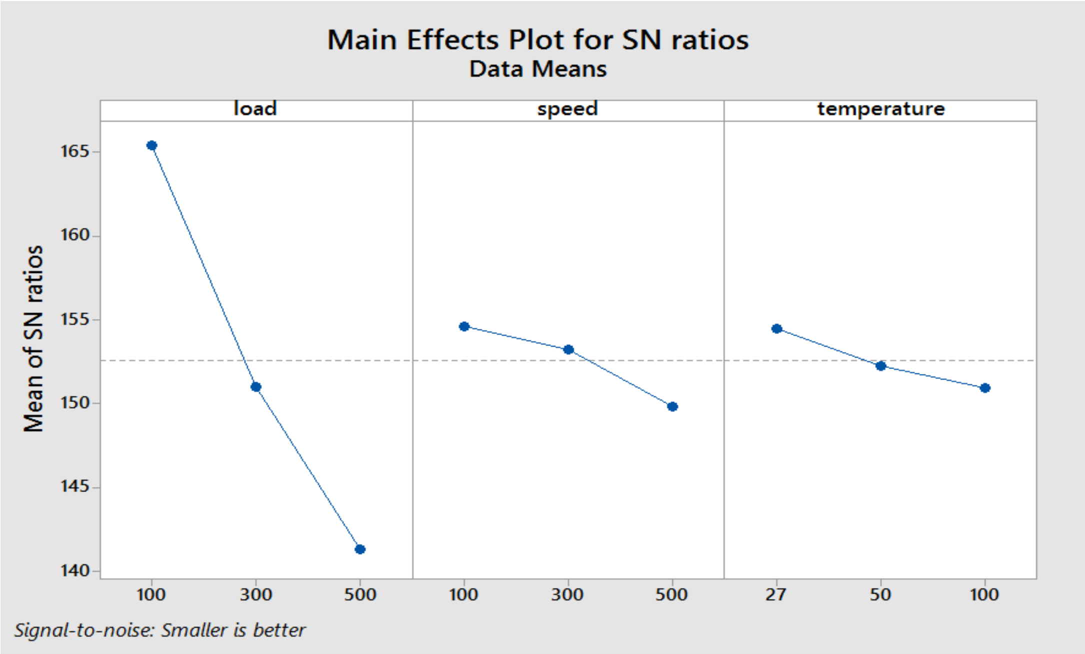


Figure 4.2 Main effects plot for S/N ratios of wear rate

Figure 4.3 shows the wear scar that formed on the ball bearing. From the Figure 4.3, the wear scar diameter become bigger as the load and speed were increased.

(a)

(b)

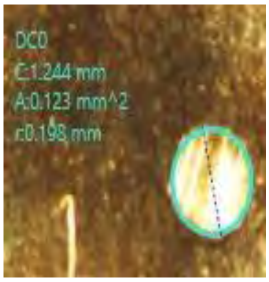
(c)

(d)

(e)

(f)

(g)



(h)

(i)

Figure 4.3 Sample of wear scar diameter of (a)100N 100rpm 27°C (b) 100N 300rpm 50°C (c)100N 500rpm 100°C (d)300N 100rpm 50°C (e)300N 300rpm 100°C (f) 300N 500rpm 27°C (g)500N 100rpm 100°C (h)500N 300rpm 27°C (e)500N 500rpm 50°C

4.2 ANOVA

The percentage contribution for each control factor is employed to measure the corresponding effect on the quality characteristic. By performing the analysis of variance, the dominant factor and the percentage contribution of that particular independent variable can be decided. The analysis is carried out for the confidence level of 95% and to have a statistically significant contribution to the performance measures, sources with P value must less than 0.05. In addition, F-test also can be used to determine the significant parameter that effect on the quality characteristics. The larger the value of the F value, the higher the significant effect on the performance.

4.2.1 COF

The last column of ANOVA table shows the P value of each factor on the total variation, indicating the degree of influence on the result as shown in Table 4.5. The influence of control factor can be observed and it shows that the applied load (P = 0.035) is the greater influencer for coefficient of friction. Besides, the F value is also dominant for the applied load. The result for ANOVA can be calculated using Eqs. (7)-(11) .

Table 4.5 The ANOVA for COF

Source	DF	Sum of squares	Mean squares	F	P
Applied Load	2	13.3301	6.6651	27.90	0.035
Speed	2	3.2142	1.6071	6.73	0.129
Temperature	2	1.6805	0.8403	3.52	0.221
Error	2	0.4779	0.2390		
Total	8	18.7027			

Figure 4.4 Estimated Model Coefficients for S/N ratio

```
Term            Coef  SE Coef        T      P
Constant     19.9987   0.1629  122.740  0.000
load 100      0.6781   0.2304    2.943  0.099
load 300     -1.7090   0.2304   -7.417  0.018
speed 100     0.4135   0.2304    1.795  0.215
speed 300     0.4316   0.2304    1.873  0.202
temperat 27  -0.0566   0.2304   -0.246  0.829
temperat 50   0.5552   0.2304    2.410  0.138

S = 0.4888   R-Sq = 97.4%   R-Sq(adj) = 89.8%
```

The ANOVA analysis was significant because the confidence level is 97.4% as shown in Figure 4.4.

4.2.2 WEAR RATE

The last column of ANOVA table shows the P value of each factor on the total variation, indicating the degree of influence on the result as shown in Table 4.6. The influence of control factor can be observed and it shows that the applied load (P = 0.011) is the greater influencer for coefficient of friction. Besides, the F value (F = 94.04) is also dominant for the applied load. The result for ANOVA can be calculated using Eqs. (7)-(11) .

Table 4.6 The ANOVA for wear rate

Source	DF	Sum of squares	Mean squares	F	P
Applied Load	2	886.831	443.416	94.04	0.011
Speed	2	36.802	18.401	3.90	0.204
Temperature	2	19.500	9.75	2.07	0.326
Error	2	9.431	4.716		
Total	8	952.563			

Figure 4.5: Estimated Model Wear Rate for S/N ratio

```
Term            Coef  SE Coef        T      P
Constant     152.557   0.7238  210.765  0.000
load 100      12.869   1.0236   12.571  0.006
load 300      -1.576   1.0236   -1.539  0.264
speed 100      2.068   1.0236    2.020  0.181
speed 300      0.677   1.0236    0.661  0.577
temperat 27    1.938   1.0236    1.894  0.199
temperat 50   -0.312   1.0236   -0.305  0.789

S = 2.171   R-Sq = 99.0%   R-Sq(adj) = 96.0%
```

The ANOVA analysis was significant because the confidence level is 99.0% as shown in Figure 4.5.

4.3 MULTIPLE LINEAR REGRESSION MODEL

By using Minitab 17 statistical software, a multiple linear regression model is developed. By fitting a linear equation to observe data, a multiple linear regression gives the relationship between an independent or predicted variable and a response variable.

4.3.1 LINEAR REGRESSION MODEL OF COF

The regression equation developed for engine oil and 0.5.vol % hBN of friction coefficient is as follows:

$$\text{Coefficient of Friction} = 0.0878 - 0.000011 \text{ load (N)} + 0.000038 \text{ speed (rpm)} + 0.000093 \text{ temperature (°C)} \qquad (12)$$

From Eq (12), it is observed that load play a major role on coefficient of friction. Besides, it is also a greater influencer in friction coefficient.

4.3.2 LINEAR REGRESSION MODEL OF WEAR RATE

The regression equation developed for engine oil and 0.5.vol % hBN of wear rate is as follows:

$$\text{Wear Rate (mm}^3\text{/s)} = -0.000000 + 0.000000 \text{ load (N)} + 0.000000 \text{ speed (rpm)} + 0.000000 \text{ temperature (°C)} \qquad (13)$$

It is observed that load play a dominant role on wear rate due to the Table 4.6 and it is also a greater influencer in friction coefficient. The model cannot be determined since the wear rate value is small. Thus, the regression model in Minitab 17 statistical software cannot be defined.

4.4 CONFIRMATION TEST

The confirmation test is a final step in the design of experiment. This test is used to predict and verify the improvement of the response by using the optimal levels of design parameter from the Taguchi analysis. The improvements of S/N ratios from initial to optimal levels is about 15.6% for COF.

Table 4.7 Confirmation test for coefficient of friction

Load (N)	Speed (rpm)	Temperature (°C)	Coefficient of friction		Percentage error %
			Experimental	Regression	
500	300	50	0.1165	0.0984	15.6

Table 4.8 Confirmation test for wear rate

Load (N)	Speed (rpm)	Temperature (°C)	Wear rate, K (mm^3/s)		Percentage error %
			Experimental	Regression	
100	100	27	0.00000000260	0.0000	100

The regression value of COF and wear rate can be calculated using equation (11) and (12) as follow:

COF = 0.0878 – 0.000011(500) – 0.000038(300) + 0.000093(50)

= 0.0984 mm^3/s

Wear Rate = -0.000000 + 0.000000(100) +0.000000(100) + 0.000000(27)

= 0.0000 mm^3/s

The percentage error of wear rate cannot be defined because the regression value is too small.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

As a conclusion, the optimal parameter for coefficient of friction is at 500N, 300rpm and 50ºC. Next, the optimal parameter for wear rate is at 100N, 100rpm and 27ºC. Besides, the additional of hBN into the engine oil gave a positive effect in reducing the COF and wear scar diameter of ball bearing from the start up. This was because this nanoparticles can change the sliding friction into rolling friction between the ball bearings. In addition, the applied load had the highest influence on COF and wear rate followed by speed and temperature by using Taguchi method. The confidence level for COF and wear rate were significant due to ANOVA which are 97.4% for COF and 99.0% for wear rate. The mathematical model for coefficient is equal to 0.0878 - 0.000011 load (N) + 0.000038 speed (rpm) + 0.000093 temperature (°C) while for wear rate, the model is equal to -0.000000 + 0.000000 load (N) + 0.000000 speed (rpm) + 0.000000 temperature (°C). The objectives are achieved.

As a recommendation, use other types of nanoparticles to make sure that nanoparticles can reduce the friction coefficient and wear scar on the ball bearing. Besides, use various type of lubricant to test the behaviour of ball bearing.

REFERENCES

Abdollah, M. F. Bin, Mazlan, M. A. A., Amiruddin, H., & Tamaldin, N. (2013). Frictional Behavior of Bearing Material under Gas Lubricated Conditions. *Procedia Engineering*, *68*, 688–693. https://doi.org/10.1016/j.proeng.2013.12.240

Abdullah, M. A., Saleman, S. A., Tamaldin, N., & Suhaimi, M. S. (2013). Reducing wear and friction by means of lubricants mixtures. *Procedia Engineering*, *68*, 338–344. https://doi.org/10.1016/j.proeng.2013.12.189

Abdullah, M. I. H. C., Abdollah, M. F. Bin, Amiruddin, H., Tamaldin, N., Nuri, N. R. M., Hassan, M., & Rafeq, S. A. (2014). Improving engine oil properties by dispersion of hBN/Al2O3 nanoparticles. *Applied Mechanics and Materials*, *607*(July), 70–73. https://doi.org/10.4028/www.scientific.net/AMM.607.70

Abdullah, M. I. H. C., Fadzli Abdollah, M., Amiruddin, H., Tamaldin, N., & Mat Nuri, N. R. (2014). Effect of hBN/Al2O3 nanoparticle additives on the tribological performance of engine oil. *Jurnal Teknologi (Sciences and Engineering)*, *66*(3), 1–6. https://doi.org/10.11113/jt.v66.2685

Abdullah, M. I. H. C., Bin Abdollah, M. F., Amiruddin, H., Tamaldin, N., & Nuri, N. R. M. (2015). The potential of hBN nanoparticles as friction modifier and antiwear additive in engine oil. *Mechanics & Industry*, *17*(1), 104. https://doi.org/10.1051/meca/2015037

Abdullah, M. I. H. C., Bin Abdollah, M. F., Tamaldin, N., Amiruddin, H. and Nuri, N. R. M. (2016). Effect of hexagonal boron nitride nanoparticles as an additive on the extreme pressure properties of engine oil. *Industrial Lubrication and Tribology*. https://doi.org/10.1108/ILT-10-2015-0157

Asrul, M., Zulkifli, N. W. M., Masjuki, H. H., & Kalam, M. A. (2013). Tribological properties and lubricant mechanism of nanoparticle in engine oil. *Procedia Engineering*, *68*, 320–325. https://doi.org/10.1016/j.proeng.2013.12.186

Balki, M. K., Sayin, C., & Sarikaya, M. (2016). Optimization of the operating parameters based on Taguchi method in an SI engine used pure gasoline, ethanol and methanol. *Fuel*, *180*, 630–637. https://doi.org/10.1016/j.fuel.2016.04.098

Dai, W., Kheireddin, B., Gao, H., & Liang, H. (2016). Roles of nanoparticles in oil lubrication. *Tribology International*, *102*, 88–98. https://doi.org/10.1016/j.triboint.2016.05.020

Fawzi, M., Tukiman, M. M., & Mustaffa, N. (2016). Small engine lubricant oil friction tester, *11*(18), 11192–11197.

Fazal, M. A., Haseeb, A. S. M. A., & Masjuki, H. H. (2013). Investigation of friction and wear characteristics of palm biodiesel. *Energy Conversion and Management*, *67*, 251–256. https://doi.org/10.1016/j.enconman.2012.12.002

Garcia-Bustos, E., Figueroa-Guadarrama, M. A., Rodríguez-Castro, G. A., Gómez-Vargas, O. A., Gallardo-Hernández, E. A., & Campos-Silva, I. (2013). The wear resistance of boride layers measured by the four-ball test. *Surface and Coatings Technology*, *215*, 241–246. https://doi.org/10.1016/j.surfcoat.2012.08.090

Golshokouh, I., Syahrullail, S., & Ani, F. N. (2014). Influence of normal load and temperature on tribological properties of jatropha oil. *Jurnal Teknologi*, *71*(2), 145–150.

Gunda, R. K., Kumar, S., & Narala, R. (2016). Surface & Coatings Technology Tribological studies to analyze the effect of solid lubricant particle size on friction and wear behaviour of Ti-6Al-4V alloy. *Surface & Coatings Technology*, *308*, 203–212. https://doi.org/10.1016/j.surfcoat.2016.06.092

Jiyuan, C. a I., Quan, G. a N., & Lixia, D. a I. (2001). Investigation on tribology behavior of lubricants using the coefficient of friction test method, *44*(August).

Jung, H., Kittelson, D. B., & Zachariah, M. R. (2003). The Influence of Engine Lubricating Oil on Diesel Nanoparticle Emissions and Kinetics of Oxidation. *SAE Technical Paper*, *2003-01–31*. https://doi.org/10.4271/2003-01-3179

Kalam, M. A., Masjuki, H. H., Varman, M., & Liaquat, A. M. (2011). Friction and Wear Characteristics of Waste Vegetable Oil Contaminated Lubricants. *International Journal of Mechanical and Materials Engineering (IJMME)*, *6*(3), 431–436.

Kapsiz, M., Durat, M., & Ficici, F. (2011). Friction and wear studies between cylinder liner and piston ring pair using Taguchi design method. *Advances in Engineering Software*, *42*(8), 595–603. https://doi.org/10.1016/j.advengsoft.2011.04.008

Kondapalli, S. P., Chalamalasetti, S. R., & Damera, N. R. (2013). Application of Taguchi based Design of Experiments to Fusion Arc Weld Processes : A Review. *International Journal of Technology and Management*, *2*(1), 1–8.

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

Leśniewski, T., & Krawiec, S. (2008). The effect of ball hardness on four-ball wear test results. *Wear*, *264*(7–8), 662–670. https://doi.org/10.1016/j.wear.2007.06.001

Mohammed, F. M., & Mohammed, Muwadfaq, M. A. (2012). Effect of temperature on lubricating oil and poly (methyl methacrylate) additive. *Diyala Journal of Engineering Sciences*, *5*(1), 205–220.

Nachimowicz, J., & Jałbrzykowski, M. (2012). Performance Evaluation of Rolling Element Bearings Based on Tribological Behaviour.

Pisal, A. S., & Chavan, D. S. (2014). Experimental Investigation of Tribological Properties of Engine oil with CuO nanoparticles, (2), 34–38.

Rao, S. R., & Padmanabhan, G. (2012). of Taguchi methods and ANOVA in optimization of process parameters for metal removal rate in electrochemical machining of Al/5% SiC composites. *International Journal of Engineering Research and …*, *2*(3), 192–197. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Application+of+Taguchi+methods+and+ANOVA+in+optimization+of+process+parameters+for+metal+removal+rate+in+electrochemical+machining+of+Al+/+5+%25+SiC+composites#0

Shahnazar, S., Bagheri, S., & Abd Hamid, S. B. (2016). Enhancing lubricant properties by nanoparticle additives. *International Journal of Hydrogen Energy*, *41*(4), 3153–3170. https://doi.org/10.1016/j.ijhydene.2015.12.040

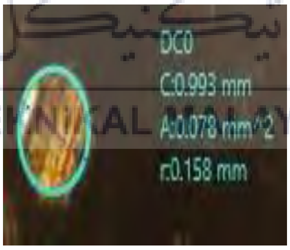
Syahrullail, S., Wira, J. Y., Nik, W. B. W., & Fawwaz, W. N. (2013). Friction Characteristics of RBD Palm Olein using Four-Ball Tribotester, *315*, 936–940. https://doi.org/10.4028/www.scientific.net/AMM.315.936

Truhan, J. J., Qu, J., & Blau, P. J. (2005). A rig test to measure friction and wear of heavy duty diesel engine piston rings and cylinder liners using realistic lubricants. *Tribology International*, *38*(3), 211–218. https://doi.org/10.1016/j.triboint.2004.08.003

Wan, Q., Jin, Y., Sun, P., & Ding, Y. (2015). Tribological behaviour of a lubricant oil containing boron nitride nanoparticles. *Procedia Engineering*, *102*, 1038–1045. https://doi.org/10.1016/j.proeng.2015.01.226

Wu, Y. Y., Tsui, W. C., & Liu, T. C. (2007). Experimental analysis of tribological properties of lubricating oils with nanoparticle additives. *Wear*, *262*(7–8), 819–825. https://doi.org/10.1016/j.wear.2006.08.021

APPENDICES

	
100N, 100rpm, 27°C	
	
100N, 300rpm, 50°C	
	
300N, 100rpm, 50°C	
	
300N, 300rpm, 100°C	

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