A STATISTICAL MODEL FOR DETERMINING FRICTION AND WEAR OF SK11 IN ENGINE OIL

NOR HIDAYU BINTI MOHD ARIF

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

A STATISTICAL MODEL FOR DETERIMINING FRICTION AND WEAR OF SK 11 IN ENGINE OIL

NOR HIDAYU BINTI MOHD ARIF

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

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

DECLARATION

I declare that this project report entitled "A Statistical Model for Detremining Friction and Wear of SK11 Ball Bearing in 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 parents and my friends

ABSTRACT

In this project, several tools have been used during running the experiment. Firstly, it has been stand by the material that using such as lubricant with engine types of SAE 15W-40 an SK11 ball bearing. From these material, it has several parameters that will be followed before starting the experiment. Secondly, the experiment has been running by a Four-Ball Tester machine. The machine has been setup with several parameters before running the experiment such as value of load, speed and temperature. The result of the experiment will be cover the friction and wear rate of the SK11 ball bearing. Next, the result of friction and wear will be analyze into the S/N ratio and ANOVA in Taguchi method to get a proper statistical model result. Based on the analysis, the optimal parameter and model has been developed. Value for wear rate and coefficient of friction analyzed from Taguchi method observes that the result were significant.

ABSTRAK

Dalam projek ini, terdapat beberapa kaedah dan alatan yang digunakan semasa menjalankan eksperimen. Pertama, ia terdiri daripada balan pelincir seperti minyak engine jenidd SAE 15W-40 dan bola SK11. Daripada bahan-bahan ini, terdapat beberapa parameter yang perlu diikuti sebelum menjalankan eksperimen. Yang kedua, eksperimen ini dijalankan mengunakan mesin Four-Ball. Beberapa parameter perlu di set pasa mesin sebelum menjalan eksperimen seperti nilai beban, kelajuan dan suhu. Nilai geseran dan kadar calar bola yang dihasilkan akan digunakan sebagai data hasil dari eksperimen ini. Seterusnya, hasil tersebut akan dianalisi ke dalam nisbah S/N dan ANOVA dengan mengunakan kaedah Taguchi untuk mendapatkan model statistic yang sepatutnya. Merujuk pada analisis, optimum parameter untuk kadar calar pada bola dan kadar geseran telah ditentukan. Melihat dari kedua-dua nilai tersebut, data yang didapati untuk kedua-dua analysis dapat disahkan signifikan melalui kaedah Taguchi.

ACKNOWLEDGEMENT

I would like to express my deepest appreciation to my supervisor, Prof. Madya. Dr Mohd Fadzli bin Abdollah for giving me this opportunity to do final year project with him. He never hesitated to give me advice and guidance whenever I confronted problems. I am thankful for his patience and advice while leading me in this project.

Secondly, I would like to thank a seniors for spending their time to guide me. They would share their knowledge in the field of tribology with me and guide me to do experiment. Also, I would like to thank laboratory assistant for his kindness in suggesting me the suitable time to use laboratory equipment for his action saved me a lot of time.

I would like to thank my course mates for giving me their support, patience and encouragement. Finally, I would like to thank my family for their support.

TABLE OF CONTENTS

LIST OF FIGURE

LIST OF TABLE

LIST OF ABBREVIATIONS

DOE	Design of Parameters
ANOVA	Analysis of Variance
OA	Orthogonal Array
WSD	Wear Scar Diameter
SK11	Carbon Chrome Steel
S/N	Signal to Noise
COF	Coefficient of Friction

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

The focus for the project is about wear and friction. Lubricant are usually liquid, solid and gases or any combination of solids, liquids and gases. Lubrication used in an engine is important to separate surfaces in relative movement, flushing away particles, cooling the engine and reducing wear and friction. In order to reduce wear and friction, lubrication oil will be the main issued. Lubricant usually consists of two main components which are 90% base oil and 10% additives. Besides, consumption of lubricant oil increase with 1.5 % to 2% annually, thus by eliminating or reducing them is now impossible (Golshokouh, et al, 2014).In other hand, lubricants are an integral part of industrial application and in automobile engine.

Wear is a surface damage that occur due to the removal of material during sliding contact of two surfaces. Wear can occur as a result of several mechanism which includes abrasion and adhesion (Les Girard, et al, 2015). (Girard. L. et al) run a wear test that show the scar size of bearing lubricated with engine oil was a lot smaller compared with the scar size of bearing lubricated with mineral oil.

Other test run showed that the worn surface of a ball bearing 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, et al , 2013)

1.2 PROBLEM STATEMENT

Friction and wear are the important aspect in the engine oil performance. Existing engine oil is only at high temperature, speed and load. So, in this project low value of load, speed and temperature with engine oil will be test to improve the performance of engine right after engine start up. 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.

1.3 OBJECTIVE OF PROJECT

The objectives of this project are as follows:

i. To define the optimal parameters for friction and wear reduction of SK 11 ball bearing in engine oil type of SAE 15W-40.
ii. To determine statistical model for friction and wear of SK 11 ball bearing in engine oil using L_9 Taguchi orthogonal arrays method.

1.4 SCOPE OF PROJECT

This research is carried out to study the prediction for friction and wear of SK11 in engine oil. The Four-Ball Tester experiment will be conducting for this research. The design of experiment under Taguchi method will be uses to set up the parameter for this research by using Minitab software. The parameter that are going to be used in this experiment are load, speed and temperature. The analysis of variance (ANOVA) and S/N ratio is used to analyse the friction and wear of SK11 ball bearing in engine oil.

CHAPTER 2

LITERATURE REVIEW

2.1 LUBRICANT REGIMES

Based on the friction experiment of bearing, Stribeck curve will expressed which part that the lubricant occurs. In the diagram, friction coefficient, f plotted as a function of the

Stribeck number, ηU/P where η is the dynamic viscosity of the oil, U is the relative speed between lubricated surfaces and P is pressure or load between the surfaces. Lubricating friction are divided into three regimes such as boundary, mixed or elastohydrodynamic and hydrodynamic lubrication.

$$lubricant\ regimes \equiv \frac{squeezed\ film\ thickness, h}{average\ surface\ roughness, R_a} \qquad (1)$$

From the equation (1) (Les Girard, et al, 2015), if $h < R_a$, the direct contact occurs between high asperities of bearing surfaces. This lubricant called boundary lubrication and the regime will result in high friction and high wear. At this regimes, the friction coefficient is a constant and relatively large value of approximately 0.1 (Coy, 1998). Mixed lubrication where $h \approx R_a$ is characterized of intermittent contact between sliding surfaces at moderates speed and loads. During the mixed lubrication, the friction coefficient drops drastically to a minimum on the order of 0.001 to 0.002. The majority of the normal load between surfaces are supported by the pressurized lubricant and only a few sharp surfaces are brought into contact (Les Girard, et al, 2015). Last lubricant regimes is hydrodynamic lubrication where $h \gg R_a$. This lubrication condition occurs with high relative speeds or load. As the pressure in the oil produced by speed and viscosity overcomes load, the two surfaces in this regimes are completely separated by a film of lubricant. Friction and wear do not occur in this regime.

These three lubrication regimes can be visualized in the Stribeck curve as shown in figure 2.1.

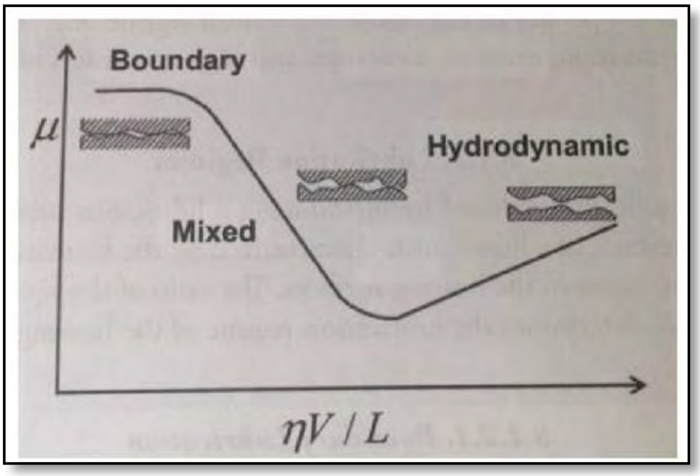


Figure 2.1: Stribeck curve showing three lubrication regimes. (Les Girard, et al, 2015)

2.2 LUBRICANT COEFFICIENT FRICTION

Determination of lubricants friction coefficient is a kind of oiliness test in the friction and wear test. Based on the changing of experimental parameters, contact resistance curves can be obtained. From the specific test method, the relationship between the friction coefficient and the contact resistance show that the friction coefficient increase rapidly with time to a saturated value. Generally, the value of contact resistance decreases with increasing normal load, but the friction coefficient increase as the normal load increase. Then, for standard test method it shown that the start of the test contact resistance quickly increase to a maximum value. It is because the initial lubricant condition between sliding and stationary ball is one of direct contact, so the contact resistance will present at lower value at the beginning of the test (Kuo, Chiou, & Lee, 1996). The different of both test are shown in Figure 2.2 and Figure 2.3.

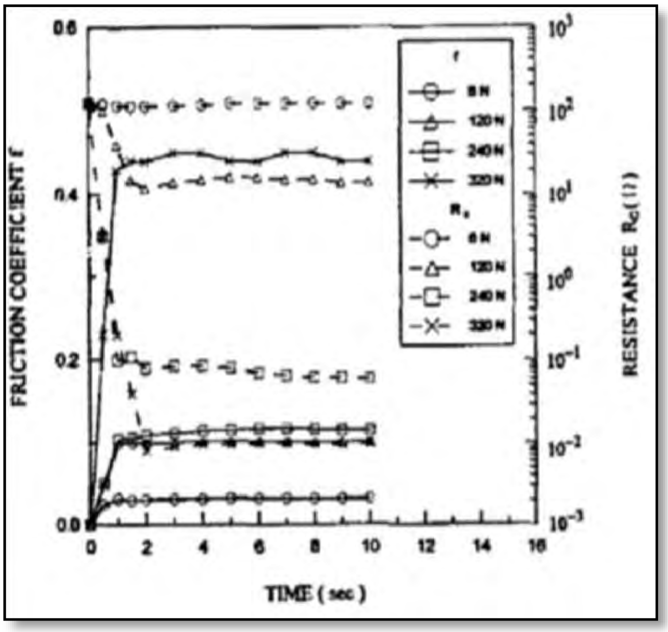


Figure 2.2: The Friction Coefficient and Contact Resistance Curve for the Specific Test Method. (Kuo et al., 1996)

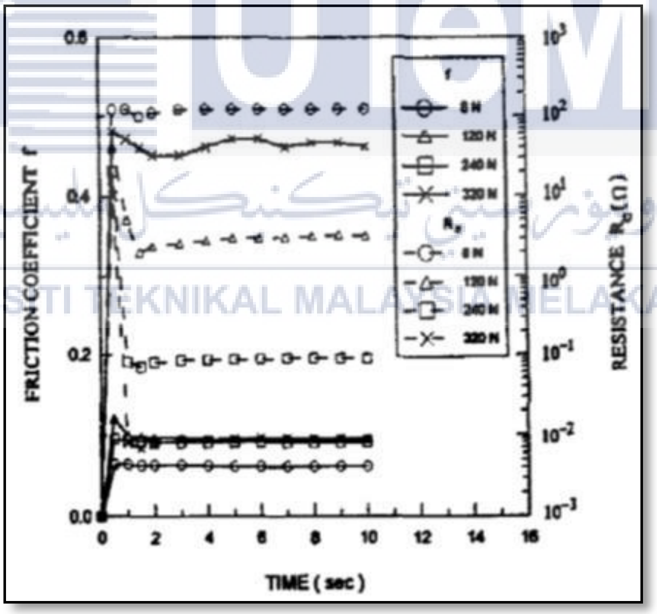


Figure 2.3: The Friction of Coefficient and Contact Resistance curves for the Standard Test Method. (Kuo et al., 1996)

In the past, there are only determining lubricant friction coefficient at certain load and cycles by using oiliness testing machine and Falex Ring-Block Test Machine. As the result, the differential ability of those test is very limited. It only provide the result for certain load condition.

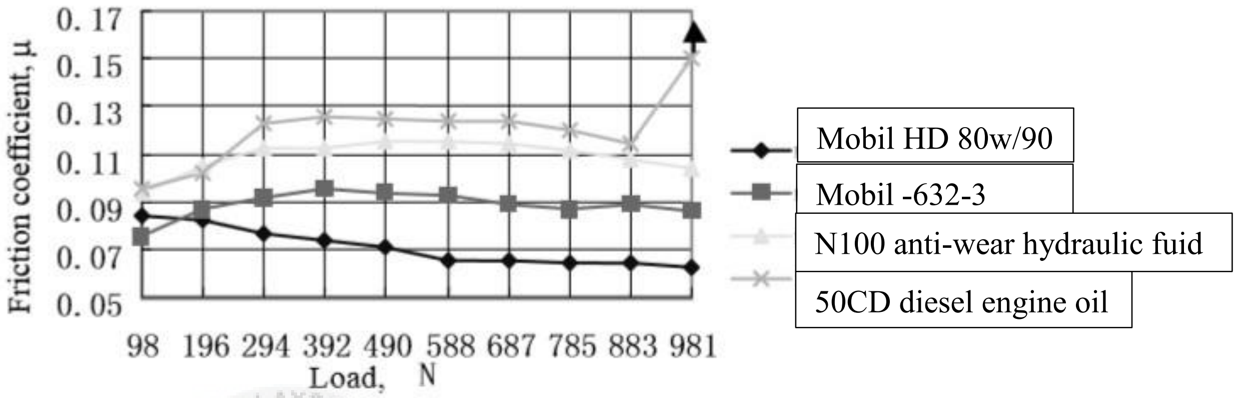


Figure 2.4: The load vs friction curve of 4 oil. (Jiyuan et al., 2001)

From the graph above, it shown that friction coefficient tends to decrease as the load is increase. It show the better improvement of friction reduction and the test state in boundary lubrication. If the friction coefficient is between 0.05-0.1, it is occur in boundary lubricating state. As a result, it can reduce friction coefficient, decrease wear rate, increase load-carrying capacity and improve boundary lubricating effect (Jiyuan, Quan, & Lixia, 2001). According to Figure 2.5, there are no significant changes show in coefficient of friction of Jatropha oil and hydraulic with increasing of temperature (Golshokouh et al., 2014).

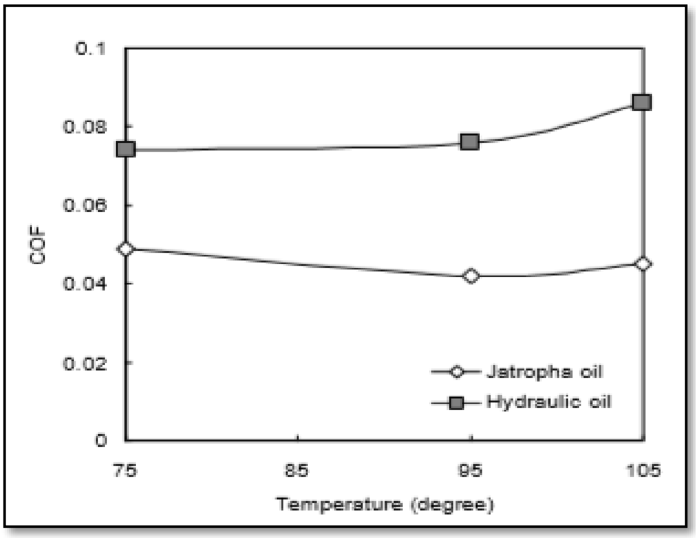


Figure 2.5: Effect of temperature on coefficient of friction for Jatropha and hydraulic oil. (Golshokouh et al., 2014).

2.3 WEAR TESTING

Wear is defined as surface damaged due to the removal of material during contact between two surfaces. The process of wears can be analysed in term of four mechanism which is adhesion, abrasion, tribo-fatigue and tribo-chemical reaction. In case of relationship between wear scar diameter and contact resistance, the specific speed method has larger contact resistance than the standard test method because it possess a better initial lubricant conditions. Based on the test between specific speed method and standard test method, it shown that there are no wear scars occurs at the contact surface under light load. But, small wear scar occurs in standard test method under same operation. It is believed that standard test method are mainly caused the wear scar occurs by initial direct contact (Kuo et al., 1996). The result as shown in the Figure 2.6 and Figure 2.7. In general, the higher the value of wear scar diameter, the more severe the wear (Kapsiz, Durat, & Ficici, 2011).

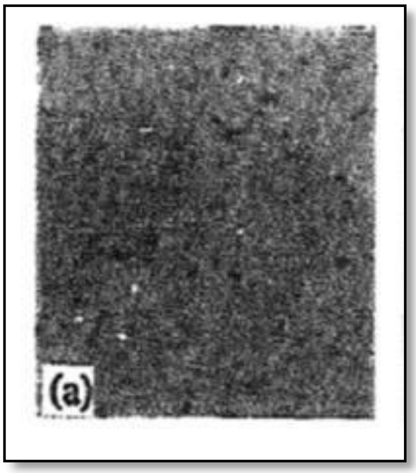


Figure 2.6: Specific Speed Method Sear Scar Result.(Kuo et al., 1996)

Figure 2.7: Standard Test Method Wear Scar Result.(Kuo et al., 1996)

Wear testing is important in engineering from two aspect. Firstly, from a material aspect which is it important to understand the wear properties of material in order to determine whether it suitable to use or not. Secondly, this testing also used to review surface treatment and conditions in order to find the most optimized setup. As a result, wear will occurs in several mechanism, including abrasion and adhesion. Abrasion is the removal of surface material, while adhesion is another mechanism of wear which is result in the transfer of material from surface to another. Based on the test with lubricant type and normal load, the diameter of surface scar in the high-wear test are larger than low-wear test as shown in Figure 2.7 and Figure 2.8. This improved that the higher load correspond to bigger wear (Les Girard, Naomi Kibrya, 2015).

Figure 2.8: Bottom (left) and top (right) ball bearing from low-wear test using engine oil. (Les Girard, Naomi Kibrya, 2015)

Figure 2.9: Bottom (left) and top (right) ball bearing from high wear test using engine oil. (Les Girard, Naomi Kibrya, 2015)

Based on effect of temperature and normal load, it shown that wear scar on the ball surface increase with increasing the temperature. Same way to the normal load, where the wear scar has direct relationship with the increase of loads (Syahrullail, et al, 2013). An experiment was carried to improve the result. Figure 2.10 shows the wear scar on ball specimen at different temperature while Figure 2.11 shows the wear scar on ball specimen with different load.

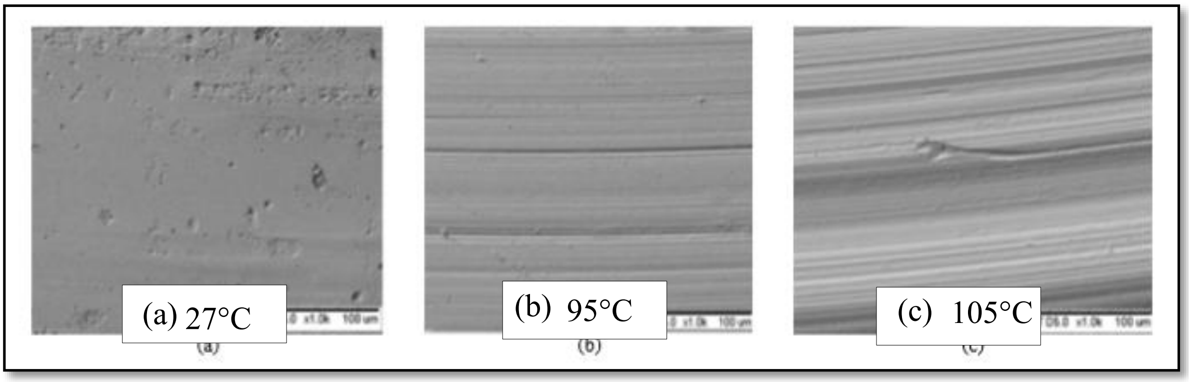


Figure 2.10: Wear scar on the balls specimen with different temperature (Syahrullail et al., 2013)

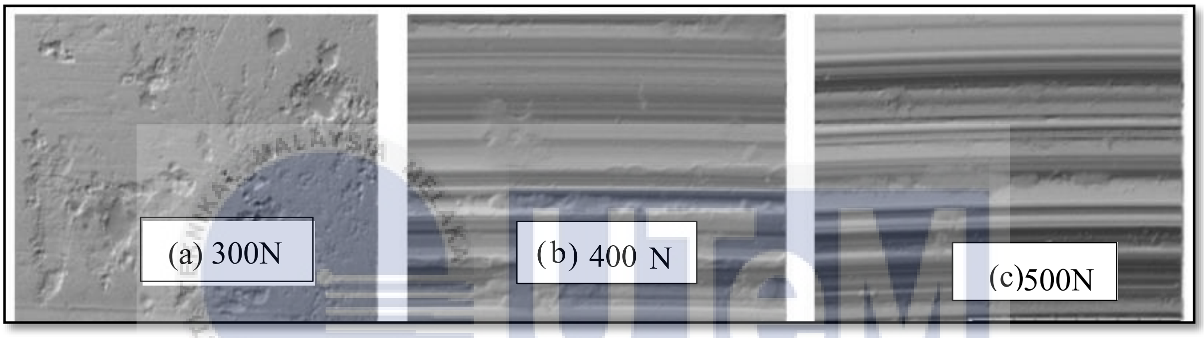


Figure 2.11: Wear scar on the balls specimens at different load.(Syahrullail et al., 2013)

These figure shown the ball surface at temperature 75°C is covered with small pits where it appear due to material transfer between contact parts. Also, from the figure for normal load 300N, several micro cutting observed on the balls. Micro cutting appeared when the adhesive wear occurs between surfaces and the lubricating film was broken down.

In term of rotational speed, it showed that the wear scar diameter increase as the rotating speed increases. It is shown in the Figure 2.12. It is observed that higher speed will cause the higher wear scar diameter. The increased wear with increase of speed may be related to the generation of higher heat between the contact surface as a consequence of higher speed (Fazal, Haseeb, & Masjuki, 2013)

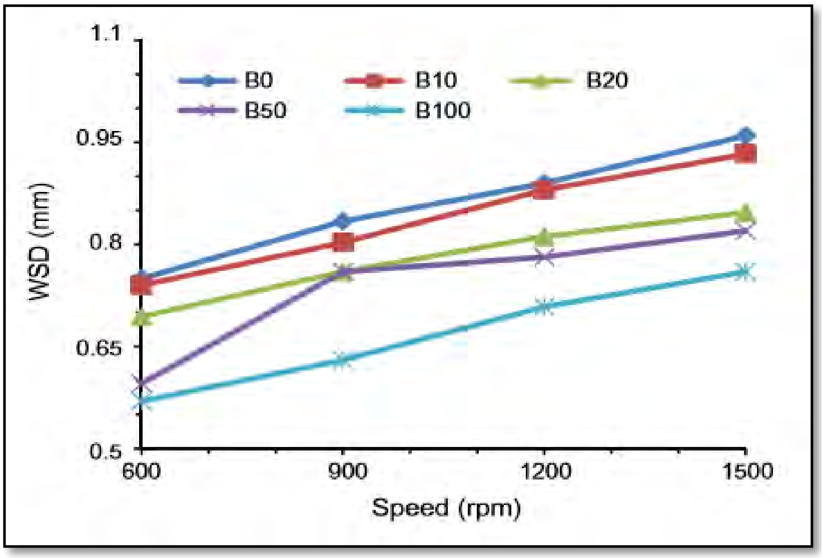


Figure 2.12: Effect of speed on wear scar diameter. (Fazal et al., 2013)

2.4 OPTIMIZATION PARAMETER.

Taguchi has placed great impact on the importance of minimizing variation of the primary means of improving quality. Taguchi method was purposed to determine statistically the optimal parameters. In this method, the result from experiment will be converted into a signal-to-noise (S/N) ratio. The quality characteristic in the S/N ratio in Taguchi method is divided into three categories which is the-lower-the-better, the-higher-the-better and the-nominal-the-better (Kapsiz et al., 2011). The use of this S/N ratio is to justify on the basic that it encompasses both the mean (signal) and the variation (noise) in one parameter.

The characteristic as well were calculate as:

$$\frac{S}{N} = -10log\frac{1}{n}(\sum y^2) \qquad (2)$$

Where 'n' is the number of observations, and y the observed data. For the higher the better type, it will cause the quality performance characteristic is continuous and nonnegative. In this type, the value of y must be larger. So, to find the S/N. ratio, this type have to turn into lower the better by using the reciprocal of performance characteristic (Dieter, at al, 2013). The value can be defined by

$$\frac{S}{N} = -\log\left[\frac{1}{n}\sum\frac{1}{y^2}\right] \tag{3}$$

The highest S/N ratio gives the optimum levels for operating parameters in the S/N ratio graphics (Balki, Sayin, & Sarikaya, 2016). For example, in the experiment for optimize three different fuel that shown in the figure 2.13.

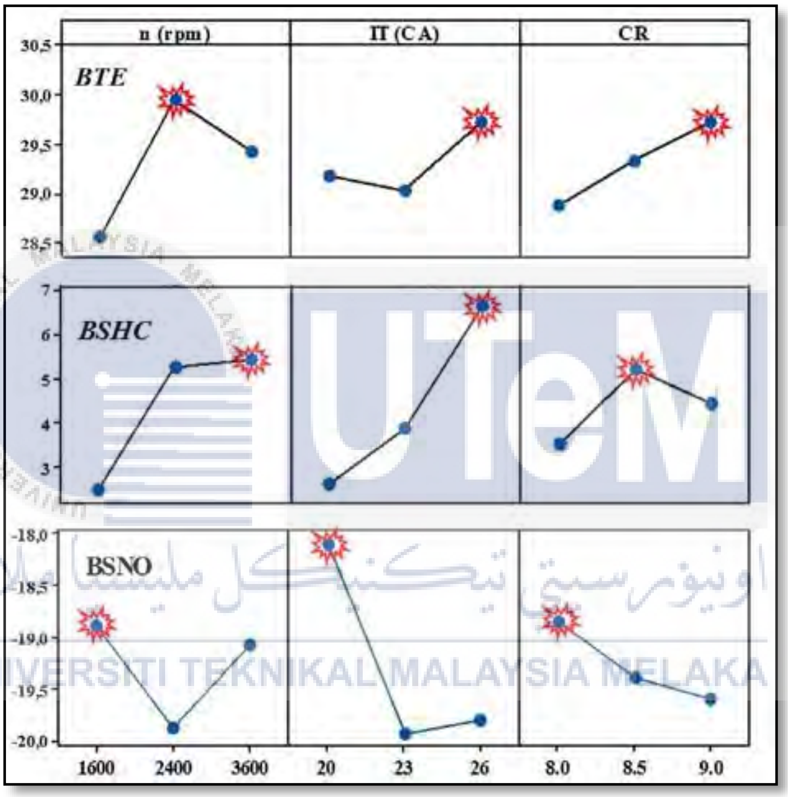


Figure 2.13: S/N ration for gasoline.

From the Figure 2.13, the optimum operating combination parameters in term of engine performance for BHSC and BSNO is A3-B3-C2 and A1-B1-C1. Based on the figure, the best combination can be summarized as A2-B3-C2.

Next, Taguchi method also known as an orthogonal array design to conventional experimental design by adds a new dimension. There are two type of method that used in Taguchi which is Design of Experiment (DOE) and Analysis of Variance (ANOVA). The

Taguchi's DOE are marked by 'L_ab_c' where 'L_a' is the orthogonal array of variable or design matrix, 'b' is the levels of variables and 'c' is numbers of variables (Kondapalli, Chalamalasetti, & Damera, 2013). The step that include in this method are: selecting the suitable orthogonal array (OA) according to the number of factors which the parameters. Next, the experiment test based on the OA. Then, analysing data, and lastly conducting confirmation test with the optimal levels of all the parameters (Zhang, Chen, & Kirby, 2007). Table 2.1 and Table 2 (Abdollah, et al, 2013) show the example for DOE in Taguchi where there are four design parameter (lubricant, applied load, sliding speed and sliding diameter) and three level for each parameter. So, when the parameter and level completely determined, there are only nine test will be running.

Table 2.1: Design parameters at three different levels.

Level	Design Parameters			
	Lubricant	Applied Load(W), N	Sliding Speed (v), rpm	Sliding Distance (L),km
1	Air	5	50	1
2	N_2-gas	10	1000	3
3	O_2-gas	20	1500	5

Table 2.2: Taguchi L_9 (3^3) orthogonal arrays.

Test	Design parameters			
	Lubricant	Applied Load (W), N	Sliding Speed (v), rpm	Sliding distance (L),km
1	Air	5	500	1
2	Air	10	1000	3
3	Air	20	1500	5
4	N_2-gas	5	500	5
5	N_2-gas	10	1000	1
6	N_2-gas	20	1500	3
7	O_2-gas	5	500	3
8	O_2-gas	10	1000	5
9	O_2-gas	20	1500	1

ANOVA is a statistical design method used to separate the individual effect from all control factor (Kapsiz et al., 2011). In the Taguchi, suggestion for two different routes were carried out to complete the analysis. Firstly, in the standard approach where the result of the single run are processed through the main effect and ANOVA (raw data analysis). Secondly, that are strongly suggest for multiple run to use the Signal-to-Noise (S/N) ratio for the same step in the analysis (Kondapalli et al., 2013). ANOVA assist in formally testing the significance of all main factors and their interaction by comparing the mean square against an estimate of the experimental errors at specific confidence levels (Rao & Padmanabhan, 2012). The total sum of squared derivations SS_T from the total mean S/N ratio can be calculated as:

$$SS_T = \sum_{i=1}^{n}(n_1 - n_m)^2 \tag{4}$$

Where n is the number of the experiments in the orthogonal array and η_i is the mean S/N ratio. In ANOVA, there are other tool called F test where it can be used to see which design parameters have a significant effect on the quality characteristic. Besides, percent (%) is defined as the significance rate of the process parameters on the metal removal rate. The percentage contribution P can be calculated as:

$$P = \frac{SS_d}{SS_T} \quad (5)$$

Where SS_d is the sum of the squared deviations.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter describes the methodology used in this project to obtain the data. The project was carried out based on the flow chart. This project involves two main process which is Four Ball Tester experiment and Wear Scar Diameter (WSD). Before carry on with the procedure, revision of some journal or others article have be reviewed first to study the past project that have been done according to this project by other persons. The result will show the coefficient of friction and the wear scar diameter of ball bearing in engine oil.

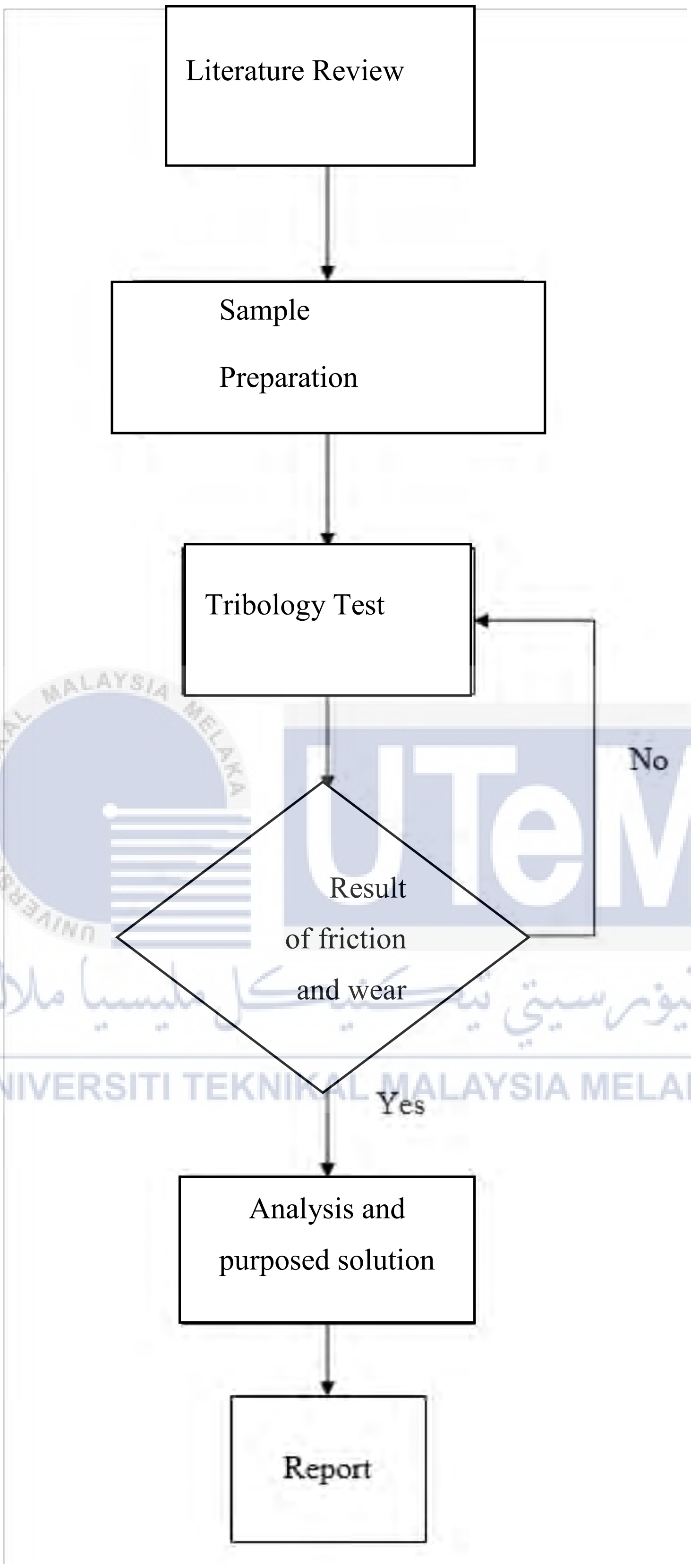


Figure 3.1: Flow Chart of the General Project.

3.2 DESIGN OF PARAMETER.

For this method, the parameters that have been decided was converted into DOE's Taguchi design. In DOE, three design parameters was determined such as applied load, speed, and temperature. For the level of design parameters, three level were selected for each parameter. The design parameter and level are shown in Table 3.1.

Table 3.1: Design parameters at three different level.

Level	Design Parameter		
	Applied Load (W), N	Speed (*v*), rpm	Temperature (T), °C
1	100	100	27
2	300	300	50
3	500	500	100

Then, Taguchi L_9 (3^3) orthogonal arrays were selected using Minitab statistical software. The data from the orthogonal array were shown in Table 3.2. As the Taguchi L_9 orthogonal array was selected, there are nine experiments that need to be test. Each test repeated three times to get the average value in order to reduce experimental errors.

Table 3.2: Taguchi $L_{9}(3^3)$ orthogonal array.

Level	Design Parameter		
	Applied Load (W), N	Speed (v), rpm	Temperature (T), °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 PREPARING OF SAMPLE

The sample used in this experiment is Engine Oil with grade SAE 15W-40 as a lubricant oil. Then, the test ball is Carbon-Chrome Steel (SKF), 12.7 mm in diameter with a surface roughness of 0.1 µm. Before start the experiment, all the test ball should be soap in Acetone. Volume of the Acetone depends on the ball where the ball should submerged in the beaker. Then, the beaker with ball are placed in the ultrasonic bath to absorb disturbance at the ball surface.

3.4 TRIBOLOGICAL TEST

Test machine used in this experiment is Standard Four Ball Tester (ASTM D-4172). To setup the machine, firstly, the drive of the test machine have to be set in order to obtain a spindle speed at 100 rpm for the first data. Besides, the temperature also was set up before running the experiment, preferably start with lower temperature which is at room temperature. The loading mechanism must be balanced to a zero reading with all the parts and test grease in place. Precision for the value of the parameters should be only ± 2. This experiment takes 60 minutes for each test.

3.4.1 FOUR BALL TESTER EXPERIMENT

The procedure for Four Ball Tester experiment were carried out as follow:

1. One of the test clean test ball was inserted into the ball chuck using spatula. Then, the ball chuck was inserted into spindle of the test machine.
2. The other three test ball was placed into the steel cup and ball cup. Then, the ball cup was locked in position by hand tightening the locknut into the ball cup using the wrench supplied by the equipment manufacturer.
3. Next, the test balls located in the ball chuck and the ball cup was coated completely with engine oil level off with the top surface of the locknut.

4. The ball cup assembly containing the three test ball and engine oil was placed on the test machine. Make sure there are no shock when applying the test load and the temperature sensor was attached with the ball cup.
5. The experiment was started for 60 minutes since the temperature and speed was already set up when turn on the test machine.
6. After 60 minutes, the three test ball was removed from the test machine. Make sure to take off temperature sensor attached before remove it. Also, the test ball that attached in the chuck was removed using equipment that have been prepared in the lab.
7. The test ball then placed into the plastic with small amount of engine oil to prevent rust.
8. The other test was repeated with the same procedure.

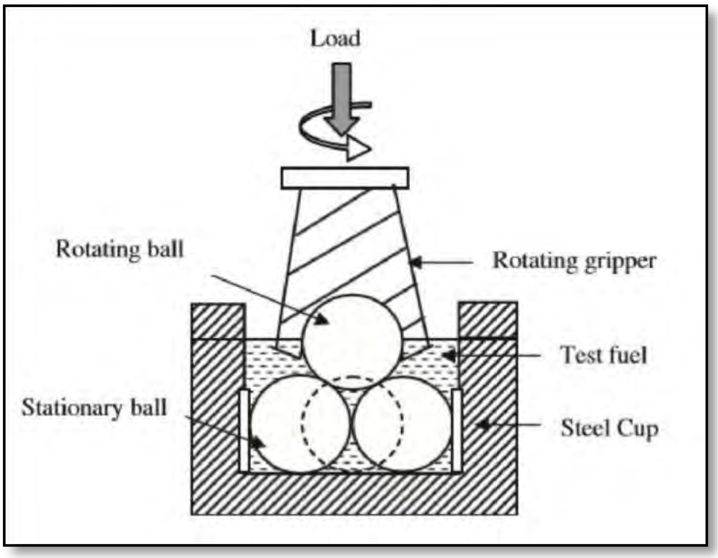


Figure 3.2: Schematic diagram for Four Ball Tester.

3.4.2 WEAR SCAR DIAMETER EXPERIMENT

This experiment was carried out after determine the Four Ball Tester experiment. Machine used in this experiment is Inverted Microscope. This experiment were purposed to measure the wear scar that occurs on the ball surface. There are several step to obtain the data for wear scar as:

1. The test ball was cleaned with a tissue.
2. Then, the clean test ball was placed on the specimen stages. Make sure the scar of the test ball is snug within the circular groove.
3. The bright-field microscopy power switch was turn on.
4. Adjusted filter cube and selector slide to get the great position for the test ball until the image of scar can be seen and sent to the computer.
5. Once the image begin to focus, the adjustment stage knob was used to move upward and downward also left and right. So the image can be clearly seen.

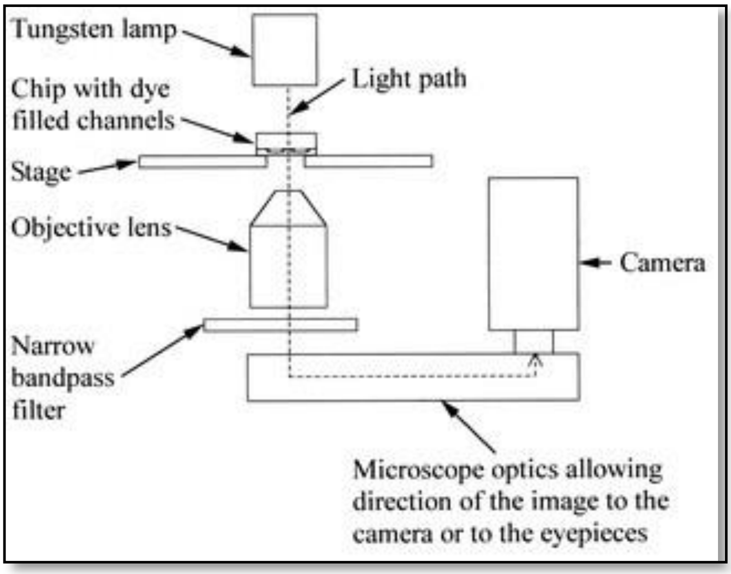


Figure 3.3: Schematic diagram for portable microscope.

3.5 ANALYSIS AND PURPOSED SOLUTION.

In this part, analysis will cover the result for coefficient of friction, wear scar diameter and analysis based on Taguchi method into S/N ratio and ANOVA.

3.4.1 COEFFICIENT OF FRICTION AND WEAR RATE.

In this part, result of the experiment will be analysed. First analysis was by calculate the coefficient of friction. During the experiment, the coefficient of friction was measured in the real time by using test equipment. The equation was calculate using formula:

$$\mu = \frac{\sqrt{6T}}{3Wr} \tag{6}$$

where μ is the coefficient of friction, T is the frictional torque in kg.mm, W represented the normal load applied in kg and r is the rotational radius from the rotation axis which is defined as 3.67 mm by the test equipment manufacturer. The value of coefficient friction was take at the average value where the experiment has to be test three time.

Next is calculate the value of wear scar diameter. Wear scar diameter of each ball was measured using portable microscope. There are two parameters that need to calculate such as volume and wear rate.

The value of these parameters was calculated by using the following equation:

$$V = (\pi h^r/3)(3R - h) \tag{7}$$

$$h = R - \sqrt{R^2 - a^2} \tag{8}$$

Where V is the wear volume in mm^3, R represented the radius of ball in mm, *a* is the radius of the wear scar in mm and *h* represented the height of wear scar in mm. By using the following equation:

$$\mathrm{K} = V/t \tag{9}$$

Where, K is the wear rate in mm^3/s and *t* is sliding time in seconds, the wear rate then calculated.

3.5.2 SIGNAL TO RATIO (S/N) ANALYSIS

This analysis was carried out to achieve the optimization of the operating parameters. The metal removal considered as the quality with the concept of the –larger-the –better. The S/N ration for this concept is:

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

Where n represented the number of the measurements in a row and y is the measured value in run/row. A greater S/N values correspond to a better performance without considering the category of the performance characteristic (Rao & Padmanabhan, 2012).

3.5.3 ANALYSIS OF VARIANCE (ANOVA).

ANOVA is a statistical design method used to separate the individual effect from all control factors. Firstly, the total sum of squared deviations SS_T from the total mean S/N ratio, n_m was calculated using equation:

$$SS_T = \sum_{i=1}^{n}(n_1 - n_m)^2 \tag{11}$$

Where n is the number of experiments in the orthogonal array and n_i is the mean of S/N ratio for the experiment. This analysis also used to determine the different factors including variance of the factor, sum of squares of the factor and F ratio of the factor. These factors can be calculated using equation:

$$V_{factor} = \frac{SS_{factor}}{DOF_{factor}} \tag{12}$$

$$DOF_{total} = N - 1 \tag{13}$$

$$F_{factor} = \frac{V_{factor}}{V_{error}} \tag{14}$$

$$P_{factor} = \frac{SS_T}{SS_d} \tag{15}$$

In the equation (14), F_{factor} was calculated to see which design parameters have a significant effect on the quality characteristic and P_{factor} reports the significance level which the value is suitable and unsuitable.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 RESULT FOR ANALYSIS OF COEFFICIENT OF FRICTION

4.1.1 SIGNAL TO NOISE (S/N) ANALYSIS OF COF

The analysis was done using MINITAB 17. The possible interaction between the controls factors must be considered before any attempt is made. Table 4.1 shows the experimental array and result with calculated S/N ratios for measuring the quality characteristic of coefficient of friction on SK11 ball bearing. The value of the COF was calculated using equations (1).

Table 4.1: Experimental lay out and results with calculated S/N ratios for coefficient of friction of SK11.

Applied Load (W), N	Speed (*v*), rpm	Temperature (T), °C	Coefficient of friction (μ)	S/N ratios COF
100	100	27	0.09573	20.3790
100	300	50	0.10420	19.6426
100	500	100	0.12381	18.1449
300	100	50	0.08127	21.8014
300	300	100	0.06397	23.8805
300	500	27	0.06381	23.9022
500	100	100	0.10975	19.1919
500	300	27	0.07965	21.9763
500	500	50	0.09528	20.4200

Analysis of the influence of each controls factor such as load, speed and temperature on the coefficient of friction was carried out with the S/N ratio response table. The ranking of factors using signal to noise ratios were obtained for different factor levels for coefficient of friction are shown in table 4.2. It is observed from the table that the applied load is the dominant factors on the coefficient of friction followed by temperature and speed.

Table 4.2: S/N responses table for coefficient of friction of SK11.

Level	Load	Speed	Temperature
1	19.39	20.46	22.09
2	23.19	21.83	20.62
3	20.53	20.82	20.41
Delta	3.81	1.38	1.68
Rank	1	3	2

In Figure 4.1, the main effect plots for S/N ratio are shown. S/N ratios from Taguchi method were used to obtain the optimization of operating parameters. The ratio used is "smaller the better" to minimize the friction. Optimal process conditions of these control factors could be easily decided from this graph. From the graph, the highest S/N ratio gives the optimum levels for operating parameters. It could be seen that the optimum operating parameters is provided at 300N of applied load, 300 rpm of speed and 27°C of temperature. This can be summarized as A2-B2-C1 (300N, 200rpm, 27°C). That it, the optimal process parameters for COF are the applied load at level 2, the speed at level 2, and the temperature at level 1.

Taguchi's method uses the statistical measure of performance called signal–to-noise ratios (S/N), which is logarithmic function of desired output to serve as objective function for optimization. The ratio "smaller the better" was used for minimizing the wear.

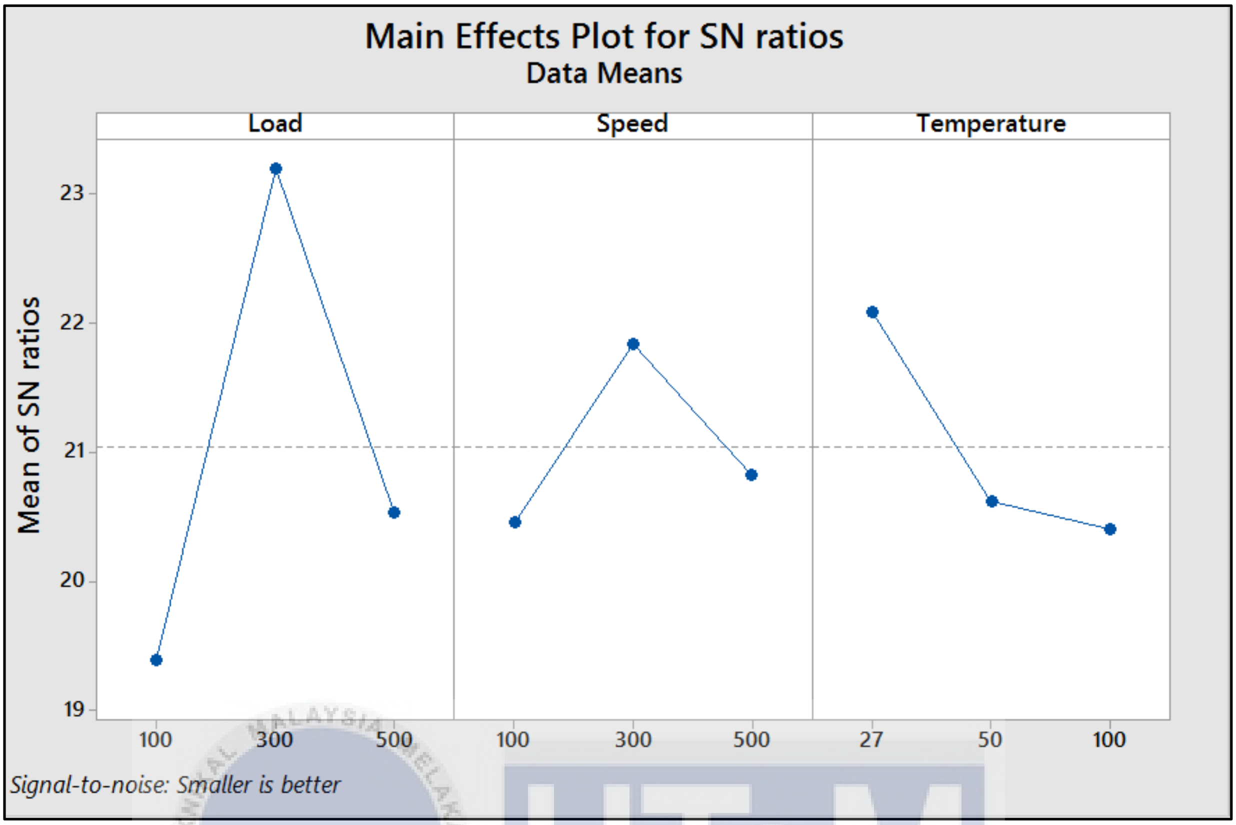


Figure 4.1: S/N ratios for Coefficient of Friction.

4.1.2 ANALYSIS OF VARIANCE (ANOVA) OF COF

ANOVA is a statistical design method used to separate the individual effect from all control factors. The last column of the ANOVA table show the percentage of contribution (P) of each factor on total variation. The percentage contribution can be used to determine the significant parameters that affects the performance characteristic. From Table 4.3, it shown that the percentage of contribution of applied load is 70.89%. So, from the calculation it shown that load have great influence on the friction loss. These result are calculated using equation (12) – (15) from previous chapter.

Table 4.3: The ANOVA for the coefficient friction loss.

Source	DF	SDQ	SS_{Factor}	Variance	F_{test}	P (%)
Load	2	22.889	22.889	11.4446	17.11	70.89
Speed	2	3.047	3.047	1.5237	2.28	9.51
Temperature	2	5.014	5.014	2.5070	3.75	15.52
Residual Error	2	1.338	1.338	0.6688		
Total	8	32.288				

Besides, F-test also can be used to determine the parameter that have significant effect on the quality characteristic based on the 95% confidence level. From the test, it shown that analysis was performed with 95.9% which is it more that the value for confidence level. The analysis can be referred in Figure 4.2. Thus, from the figure it shown that the P-value for applied was less than 0.05 for both 100 N and 300 N. So, the value prove that the P-value is significant with the test.


```
Estimated Model Coefficients for SN ratios

Term           Coef  SE Coef       T      P
Constant    21.0376   0.2726  77.176  0.000
Load 100    -1.6488   0.3855  -4.277  0.051
Load 300     2.1571   0.3855   5.595  0.030
Speed 100   -0.5802   0.3855  -1.505  0.271
Speed 300    0.7955   0.3855   2.064  0.175
Temperat 27  1.0482   0.3855   2.719  0.113
Temperat 50 -0.4163   0.3855  -1.080  0.393

S = 0.8178   R-Sq = 95.9%   R-Sq(adj) = 83.4%
```

Figure 4.2: Estimated Model Coefficient for S/N ratios table.

4.1.3 MULTIPLE LINEAR REGRESSION MODEL FOR COF

This model will be obtained by using the statistical software “MINITAB 17”. Relationship between an independent or predicted variable and response variable will be obtain in this model by fitting a linear equation to observe data (Rana, et al, 2014). The correlations between the factors and the measured parameter were obtained by multiple linear regression. The regression equation developed for the coefficient of friction is as follows:

$$COF = 0.0873 - 0.000033*Load - 0.000003*Speed + 0.000241*Temperature \quad (16)$$

From the equation (16), it is observed that applied load play a dominant role on coefficient of friction and it is highly effected by load and temperature.

4.2 RESULT FOR ANALYSIS OF WEAR RATE

4.2.1 SIGNAL TO NOISE (S/N) ANALYSIS OF WEAR RATE

This analysis also done by using the same software which is MINITAB 17. Table 4.4 shows the pattern of experiment array and the result with calculated S/N ratios for measuring the wear rate that have been obtain from surface of SK11 ball bearing.

Table 4.4: Result with calculated S/N ratio for wear rate.

Load (N)	Speed (RPM)	Temp (°C)	Area, A (mm^2)	Height (mm)	Volume (mm^3)	Wear rate (mm^3/s)	S/N ratio wear rate
100	100	27	0.102	8.1927×10^{-4}	1.3389×10^{-5}	3.7192×10^{-9}	168.591
	300	50	0.113	1.0055×10^{-3}	2.0168×10^{-5}	5.6022×10^{-9}	165.033
	500	100	0.115	1.0414×10^{-3}	2.1653×10^{-5}	6.0147×10^{-9}	164.416
300	100	50	0.156	1.9165×10^{-3}	6.3265×10^{-5}	2.0351×10^{-8}	153.828
	300	100	0.167	2.1964×10^{-3}	9.6227×10^{-5}	2.6730×10^{-8}	151.460
	500	27	0.172	2.3299×10^{-3}	1.0828×10^{-4}	3.0078×10^{-8}	150.435
500	100	100	0.201	3.1820×10^{-3}	2.0195×10^{-4}	5.6097×10^{-8}	145.021
	300	27	0.215	3.6408×10^{-3}	2.6438×10^{-4}	7.3439×10^{-8}	142.681
	500	50	0.210	3.4734×10^{-3}	2.4063×10^{-4}	6.6842×10^{-8}	143.499

The result from the table obtained from the equation (7) – (9) as shown below where the value for radius of ball, R is 3.67mm.

$$height, h = 3.67 - \sqrt{(3.67)^2 - (0.102)^2}$$

$$= 8.1974 \times 10^{-4} mm$$

$$Volume, V = (\frac{\pi(8.1974 \times 10^{-4})^2}{3})(3(3.67) - (8.1974 \times 10^{-4}))$$

$$= 1.3389 \times 10^{-5} mm^3$$

$$Wear\ rate, k = \frac{1.3389 \times 10^{-5}}{3600}$$

$$= 3.7192 \times 10^{-9}$$

Analysis of the influence of each controls factor such as load, speed and temperature on the coefficient of friction also was carried out with the S/N ratio response table. The ranking of factors using signal to noise ratios were obtained for different factor levels for coefficient of friction are shown in Table 4.5. It is observed from the table that the applied load is the dominant factors on the coefficient of friction followed by speed and temperature.

Table 4.5: S/N responses table for wear rate of SK11.

Level	Load	Speed	Temperature
1	166.0	155.8	153.9
2	151.9	153.1	154.1
3	143.7	152.8	153.6
Delta	22.3	3.0	0.5
Rank	1	2	3

In Figure 4.3, the main effect plots for S/N ratio are shown. From this graph, optimal process condition of these control will be easy to obtain. From the graph, the highest S/N ratio gives the optimum levels for operating parameters. It could be seen that the optimum operating parameters is provided at 100N of applied load, 100 rpm of speed and 50°C of temperature. This can be summarized as A1-B1-C2 (100N, 100rpm, 50°C). That it, the optimal process parameters for COF are the applied load at level 1, the speed at level 1, and the temperature at level 2.

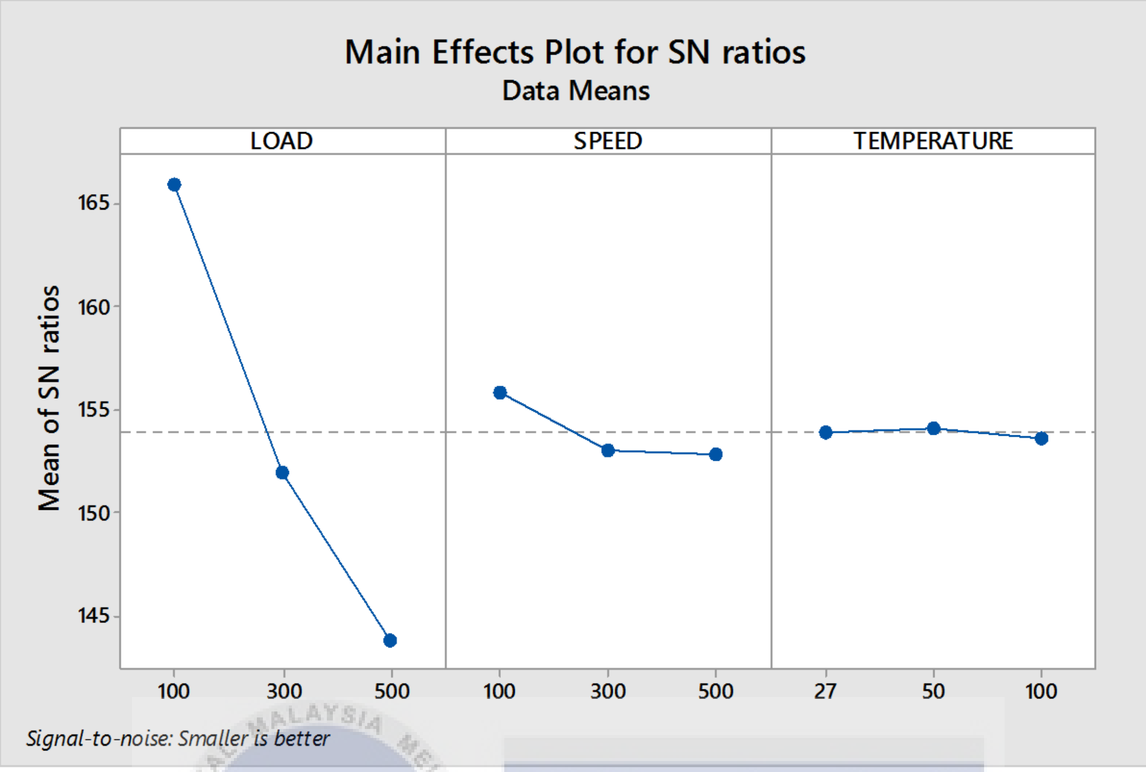


Figure 4.3: S/N ratio for Wear Rate.

Figure 4.4: wear diameter (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 (i) 500N, 500rpm, 50°C

4.2.2 ANALYSIS OF VARIANCE (ANOVA) FOR WEAR RATE

It is method where the process parameter and their interaction was predicted which is it significantly affect the quality characteristics. (Sudeepan, et al, 2014). The contribution of applied load in determine the value for wear rate also shown the strong influence in the test with 97.6%. The result calculated using equation (12) - (15).

Table 4.6: The ANOVA for the wear rate.

Source	DF	SDQ	SS_{Factor}	Variance	F_{test}	P (%)
Load	2	762.142	762.142	11.4446	417.02	97.6
Speed	2	16.850	16.850	1.5237	9.22	2.16
Temperature	2	0.358	0.358	2.5070	0.20	0.05
Residual Error	2	1.828	1.828	0.6688		
Total	8	781.178				

Moreover, F-test show from the figure that the significant effect of the quality characteristic based on confident level is 99.8%. Thus, the result of the analysis was significant hence its value higher than 95%. It also shown that the P-test is significant with the factor based on their value is lower than 0.05 for both load and speed at 100rpm. These both result can be referred to the Figure 4.6.

Estimated Model Coefficients for SN ratios

Term	Coef	SE Coef	T	P
Constant	153.885	0.3186	482.938	0.000
LOAD 100	12.128	0.4506	26.914	0.001
LOAD 300	-1.977	0.4506	-4.388	0.048
SPEED 100	1.929	0.4506	4.280	0.050
SPEED 300	-0.827	0.4506	-1.835	0.208
TEMPERAT 27	0.018	0.4506	0.039	0.972
TEMPERAT 50	0.235	0.4506	0.522	0.654

S = 0.9559   R-Sq = 99.8%   R-Sq(adj) = 99.1%

Figure 4.5: Estimated model wear rate for S/N ratio table.

4.2.3 MULTIPLE LINEAR REGRESSION MODEL FOR WEAR RATE VALUE

The equation 12 show multiple regression model obtain for wear rate of SK11 ball bearing. This model also obtain by using the statistical software " MINITAB 17".The positive sign in the equation indicates the increase of response with increase of the related variable while the negative sign of term shows the response decrease with increase of the variable (Banker, et al, 2016).

$$\text{Wear} = -0.000000 + 0.000000{*}\text{Load} + 0.000000{*}\text{Speed} - 0.000000{*}\text{Temperature} \quad (17)$$

From the equation, it is observed that the values for all parameter in order to determine the strong role in the test was small. Thus, the wear regression model for wear rate cannot be decided.

4.3 CONFIRMATION TEST

The analysis value for optimal level of design parameter for both COF and wear rate were carried in this test. In Taguchi method, this is the final step to predict and verify the enhancement of the response using the optimal level of process parameter. This test are carried out in order to validate the experimental result and to evaluate the accuracy of the analysis. It is necessary to carried out this test. In order to validate the model of regression, the experiments for both optimal parameter were carried out with the conditions. Then, the result will be compared with the predicted model result. The result are shown in Table 4.7.

Table 4.7: Confirmation test for estimated and actual COF

Load (N)	Speed (rpm)	Temperature (°C)	Coefficient of friction		Percentage error %
			Experimental	Regression	
300	300	27	0.1042	0.0839	19.5

The value for regression can be calculated using equation (16) as follow:

COF = 0.0873 – 0.000033(300) – 0.000003(300) + 0.000241*(27)

= 0.0839

In this test, the predicted values and experimental value are adhering close to each other. The error percentage error should be lower than 20% for reliable statistical analysis (Manivel & Gandhinathan, 2016). As the result in Table 4.8, the percentage of error calculated for coefficient of friction is 19.5%. The result test obtained from the confirmation test indicates the successful optimization since the value are within the acceptable range. In case of regression model of wear rate, it cannot be determine because the result obtain from the regression model calculated are smaller. Thus, the confirmation test for wear rate cannot be calculated.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Based on the result that have been obtained, it shows that the applied load plays a dominant roles in determining the optimal value for coefficient of friction and wear rate. According to result on S/N ratio using “smaller is better2 approach, the optimal level of parameters for coefficient of friction were A2B2C1 with load = 300N, speed = 300rpm, temperature = 27°C and wear rate were A1B1C2 with load = 100N, speed = 100rpm, temperature = 50°C. Based on result of ANOVA analysis, the main contributing factor affecting the coefficient of friction and wear rate of SK11 ball bearing with 70.89% and 97.6% respectively. The significant contributions of speed and temperature on coefficient of friction were found to be 9.51% and 15.52% respectively and on wear rate were found to be 2.16% and 0.05% respectively. Generally, it was observed that the interactions between the control factors do not have significant influence on the speed and temperature of coefficient of friction and wear rate.

As a recommendation, in future hopefully more research and study about the friction and wear rate effect in the lubrication. Besides, the other factors could be considered like different ball bearing coating, different analysis methods and type of lubricant used such as grease, all these factors would effect on the coefficient of friction and wear rate.

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. I. H. C., Abdollah, M. F. B., Amiruddin, H., & Nuri, N. R. M. (2013). Optimized Nanolubricant for Friction Reduction, (March), 2013.

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

Banker, V. J., Mistry, J. M., Thakor, M. R., & Upadhyay, B. H. (2016). Wear Behavior in Dry Sliding of Inconel 600 Alloy using Taguchi Method and Regression Analysis, *23*, 383–390. https://doi.org/10.1016/j.protcy.2016.03.041

Coy, R. C. (1998). Practical applications of lubrication models in engines. *Tribology International*, *31*(10), 563–571. https://doi.org/10.1016/S0301-679X(98)00077-2

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

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.

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).

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.

Kuo, W., Chiou, Y., & Lee, R. (1996). A study on lubrication mechanism and wear scar in sliding circular contacts. *Wear*, *201*(1–2), 217–226. https://doi.org/10.1016/S0043-1648(96)07247-X

Les Girard, Naomi Kibrya, K. H. and W. W. (2015). Wear Testing. *Wear Testing*.

Manivel, D., & Gandhinathan, R. (2016). Optimization of surface roughness and tool wear in hard turning of austempered ductile iron (grade 3) using Taguchi method. *Measurement*, *93*, 108–116. https://doi.org/10.1016/j.measurement.2016.06.055

Rana, R. S., Purohit, R., Sharma, A. kumar, & Rana, S. (2014). Optimization of Wear Performance of Aa 5083/10 Wt. % Sicp Composites Using Taguchi Method. *Procedia Materials Science*, *6*(Icmpc), 503–511. https://doi.org/10.1016/j.mspro.2014.07.064

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

Sudeepan, J., Kumar, K., Barman, T. K., & Sahoo, P. (2014). Study of Friction and Wear of ABS/Zno Polymer Composite Using Taguchi Technique. *Procedia Materials Science*, *6*(Icmpc), 391–400. https://doi.org/10.1016/j.mspro.2014.07.050

Syahrullail, S., Wira, J. Y., Nik, W. B. W., & Tiong, C. I. (2013). The effect of sliding speed on friction and wear of RBD palm olein. *Applied Mechanics and Materials*, *315*, 951–955. https://doi.org/10.4028/www.scientific.net/AMM.315.951

Zhang, J. Z., Chen, J. C., & Kirby, E. D. (2007). Surface roughness optimization in an end-milling operation using the Taguchi design method. *Journal of Materials Processing Technology*, *184*(1–3), 233–239. https://doi.org/10.1016/j.jmatprotec.2006.11.029

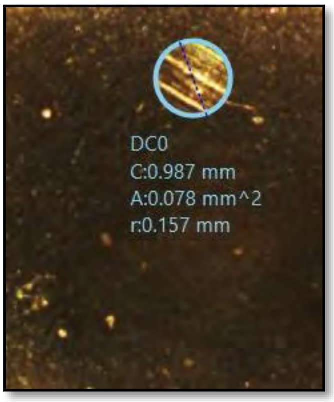
APPENDIX

(a) 100N, 100rpm, 27°C

(b) 100N, rpm, 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

(i) 500N, 500rpm, 50°C