ANALYSIS OF ROLLING CONTACT

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Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

MUHAMMAD ABDUL QAHHAR BIN ABDUL MALIK
Date: 07/06/2017

STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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STATEMENT 2

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MUHAMMAD ABDUL QAHHAR BIN ABDUL MALIK

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Nomenclature

Ra	:	Average roughness (µm)
P_{max}	:	Maximum pressure (MPa)
Rq	:	Root mean square roughness (µm)
L	:	Surface testing length
F	:	Applied force (N)
l	:	Length of contact
E_1 & E_2	:	Modulus of elasticity for material 1 and 2

ANALISA SENTUHAN GOLEKAN

Abstrak

Dalam bidang kejuruteraan mekanikal dan tribology, hubungan tekanan Hertzian adalah penerangan tentang tekanan pada bahagian bahan uji yang permukaannya bersentuhan. Tekanan ini selalunya tidak ketara pada kebanyakan masa, tetapi boleh menyebabkan masalah yang serius jika tidak diambil kira dalam beberapa kes. Bearing ideal adalah bearing yang permukaannya licin dan mempunyai calar yang agak dalam untuk menakung dan mengalirkan minyak pelincir. Purata aritmetik nilai mutlak (R_a) dan luas lekuk bearing (BAC) telah diiktiraf sebagai cara yang lebih baik untuk mengklasifikasi permukaan bahan 304SS. Perubahan bentuk pada permukaan bahan uji kaji boleh dikurangkan dengan menggunakan pelincir yang mempunyai kelikatan rendah. Nilai kekasaran akan meningkat apabila bilangan putaran meningkat. Uji kaji ini telah dijalankan dalam dua keadaan (kering dan berpelincir) dan menjalani seratus putaran setiap satu. Kedua-dua parameter permukaan dengan nilai tertinggi adalah kekasaran purata R_a (0.7101μm) dan luas lekuk bearing (16,2656). Kedua-dua hasil adalah daripada keadaan kering.

ANALYSIS OF ROLLING CONTACT

Abstract

In mechanical engineering and tribology, Hertzian contact stress is a description of the stress within mating parts. This kind of stress may not be significant most of the time, but may cause serious problems if not take it into account in some cases. An ideal bearing surface is the one with smooth surface and having relatively deep scratches to hold and distribute lubricant. The arithmetic average of the absolute value (Ra) and bearing area curve (BAC) had been recognise as better way to characterise 304SS roller surface. Deformation on the rolling surface can be reduced by applied low viscosity lubricant. Roughness value will increase as the number of cycles increase. The test have been conducted in two conditions (dry and lubricated) and endure one hundred cycles each. The two surface parameters with the highest value are average roughness Ra (0.7101µm) and bearing area curve (16.2656µm). Both results from dry condition

Chapter 1

Introduction

1.1 Introduction

Friction and wear are controlled by the interactions that take place at the interface. Friction and wear are system properties which are dependant on the materials used and on the operational (contact) conditions. Forces are transmitted, mechanical energy is converted during the interactions, physical of the materials that interact are altered. The essence of tribology is based on the nature of the interactions and solving the technological problems associated with the interfacial phenomena. Rolling contacts is one solution to control friction and wear of a load carrying interface in which two bodies are separated by rolling elements.(Jamari, 2006)

Contact modelling of two surface under normal approach and with relative motion is carried out to predict real area of contact. The surface and subsurface stresses affecting friction and wear of an interface. When two macroscopically flat bodies with micro-roughness in contact, the contact occurs at multiple asperities of arbitrary shapes, varying sizes and height. The asperity contacts deformation can be either elastic or elastic-plastic. At the interface if a thin liquid film is present, attractive meniscus forces may affect friction and wear. To predict contact parameters, models have been used and these generally require many assumptions about asperity geometry and height distributions. Numerical contact models of 3-D surfaces have been developed with the advanced computer technology and it can simulate digitized rough surfaces with no assumption concerning the roughness distribution. (Bhushan, 1998)

1.2 Problem Statement

When the surfaces of two rollers are loaded and rolling on one another, changes generally occur at both surfaces. The changes which occur between start-up and steady state are associated with running-in (also called breaking-in or wearing-in). Although in terms of conservation, wear is always undesirable, running-in wear is encouraged rather than avoided. In this study, the surface of one of the roller in the contact pair is monitored using the roughness measurement system. The wear of a line contact is monitor after each successive rolling motion to determine the effect of rolling on the surface roughness.

1.3 Objective

1. To study the deformation of asperities of a cylinder in a rolling contact under dry and lubricated surface.

1.4 Thesis Outline

The thesis of this project is divided into five chapters which comprises:

- Chapter 1 (Introduction), explains about the overview structure of the project, the objectives that need to be achieved, the problem statement of the project and thesis outline.
- Chapter 2 (Literature Review), presents the literatures regarding the theory of contact, roughness, wear of specimen surface, effect of lubricant and the summary of the literatures.
- Chapter 3 (Project methodology), focuses on the preparation of specimen, frame to support load, Arduino and experiment configuration.
- Chapter 4 (Results and discussion), presents the results of the graph Ra, BAC height and analysis of the wear surfaces. A thorough discussion is made relating to the deformation behaviour of the 304SS and how it effects the overall performance of the material in engineering applications.
- Chapter 5 (Conclusion), summarizes the outcomes of the project and the recommendation of the possible future works.

Chapter 2

Literature Review

Palmgren (1945) recanted his doubts about the validity of Hertz theory and incorporated the Hertz contact stress equation in his book. In one of their paper, Lundberg and Palmgren (1947) state, “Hertz theory is valid under the assumptions that the contact area is small compared to the dimensions of the bodies and that the frictional forces in the contact areas can be neglected. For ball bearings, with close conformity between rolling elements and raceways, these conditions are only approximately true. For line contact the limit of validity of the theory is exceeded whenever edge pressure occurs.” Lundberg and Palmgren exhibited a great deal of insight into the other variables modifying the resultant shear stresses calculated from Hertz theory. They state “No one yet knows much about how the material reacts to the complicated and varying succession of (shear) stresses which then occur, nor is much known concerning the effect of residual hardening stresses or how the lubricant affects the stress distribution within the pressure area. Hertz theory also does not treat the influence of those static stresses which are set up by the expansion or compression of the rings when they are mounted with tight fits.” These effects are now better understood, and life factors are currently being used to account for them to more accurately predict bearing life and reliability.(Zaretsky, 2013)

Bearing curves parameters are found to closely correlate with feed rate and other surface texture parameters and to follow asymmetrical distributions over milled surfaces. Roughness of engineering surfaces is expressed by various parameters, arithmetic and statistical. One of the latter is bearing area or Abbott curve; it provides representation of the existing material in various heights of the surface profile and corresponds to cumulative probability of profile amplitude distribution. It is evident that there is a satisfactory agreement between experimental and calculated data. In this way, bearing curves of face milled surfaces may be described for ranges of cutting conditions by appropriate controlling of the relevant statistical distributions parameters. Variation of the bearing ratio parameters over face milled surfaces conform to asymmetric statistical distributions modelled by "J" Pearson statistical functions form. (Pandazaras, 2001)

The dynamic behaviour of radially-loaded roller bearings operating at high loads and low speeds with different surface roughness values is investigated. Although it is possible to calculate the film thickness in different lubrication regimes with a good accuracy, reliable prediction of the traction coefficient under severe contact pressures in rolling bearings still remains to be a challenging task. Traction coefficient is also a highly influential parameter in dynamic modelling of rolling bearings, where elastohydrodynamic lubrication (EHL) prevails. At high sliding velocities, considerable errors can occur in the final results of dynamic models. The results of dynamic simulations provide useful insight into the variation of these parameters as the rollers travels in the orbital direction. It is shown that the film thickness and the rate of heat generation between the rollers and the race ways increase at greater surface roughness. (Takabi & Khonsari, 2015)

Paggi and Ciavarella (2010) proposed two new theoretical equations generalizing Greenwood and Williamson (GW) and Bush, Gibson and Thomas (BGT) to take into account interaction effects in an approximate way (GW-I and BGT-I, respectively), which significantly improve the accuracy of original asperity models. Due to the effect of roughness, which promotes linearity of real contact area with load. Today, this effect is being again re-discovered to be the basic factor affecting friction even at the nanoscale, where roughness is now to be interpreted as “molecular roughness”, where asperities are defined even by single atoms. The Greenwood and Williamson contact theory with Nayak parameters (GW-N) is the simplest one, since it assumes a Gaussian distribution of asperity heights, a constant radius of curvature for the asperities, and it neglects asperity interaction effects. Then, the Greenwood and Williamson contact theory with zeroth order asperity interaction (GW-I) removes part of the limitation of GW-N regarding asperity interaction effects, adding the mean pressure effect term. (Paggi & Ciavarella, 2010)

Yusof and Ripin (2016) developed a technique to measure surface asperities plastic deformation in rolling contact. They quantify the flow of material from the peaks to the valleys by measuring the area and volume from the asperity profile difference for each successive profile. A reference profile is used as the baseline for measuring the progressive surface deformation so the same measurement area is obtained after each cycle for profile analysis. The system can quantify minor surface deformation position of the original as the overlapped peaks of a non-contacting roller. The results obtained was only for one particular load and speed. (Yusof & Ripin, 2016)

Measurement of Roughness

Surface roughness plays an important role in determining surface coefficient of friction (COF), wear and release properties. There are many different roughness parameters in use, but **Ra**, the arithmetic average of absolute values of peaks & valleys of the sample length measured, is the most common referred to in the roller manufacturing industry. Another common parameter is **Rz**, the average between the 5 highest peaks & lowest valleys in the sample length being measured. A roller surface with a large **Ra** or **Rz** value will usually have a higher COF, which may wear faster and have poorer release properties. **R_t** is the range of the collected roughness data points. Controlling the roller surface finish is an important factor in roller performance. There are various Ra's that can be achieved for each type of roller covering.

Table 2.0: Line Measurement of Roughness

Parameter	Description	Formula
R_a,[3] R_{aa}, R_{yni}	arithmetic average of absolute values	$R_a = \frac{1}{n}\sum_{i=1}^{n} \lvert y_i \rvert$ [3]
R_q, R_{RMS}[3]	root mean squared	$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} y_i^2}$ [3]
R_v	maximum valley depth	$R_v = \min_i y_i$
R_p	maximum peak height	$R_p = \max_i y_i$
R_t, R_y	Maximum Height of the Profile	$R_t = R_p + R_v$
R_{sk}	skewness	$R_{sk} = \frac{1}{nR_q^3}\sum_{i=1}^{n} y_i^3$
R_{ku}	kurtosis	$R_{ku} = \frac{1}{nR_q^4}\sum_{i=1}^{n} y_i^4$

Measurement of Wear

Topographic image subtraction for wear distribution mapping:

The first technique is suitable mainly for qualitative presentation of the *distribution of wear* over the surface and to indicate the magnitude of the individual wear events. This information is obtained by taking the topographical image of a worn surface and subtracting the previously recorded unworn (or less worn) topographical image of the same surface. This procedure effectively eliminates all unaltered surface features, leaving corresponding areas flat (the `zero wear' level), and exhibits lost material as elevations over this flat surface and gained (plastically displaced) material as depressions. To get a good mapping, the lateral matching of the two images has to be very precise. Contrastingly, the technique does not require a height reference, but only the existence of unaltered parts of the surface that become flat after subtraction and thus indicate the zero wear level.

Roller volume subtraction for local wear volume determination:

The second technique is used to quantitatively determine the volume loss *over* the local studied area. This is achieved by using roller histograms to calculate the volume of material left above the common fixed surface level. The more the surfaces are worn, the less volume of material is left above the common reference level. To obtain the roller volumes from the topographical data each measured point (surface element) of the specified surface area is multiplied by its height over the reference level. The accumulated wear volume is then calculated by subtracting this roller volume by the corresponding volume obtained after the wear test. Note that the roller volumes calculated are directly related to the choice of the reference level. Determination of the common reference level is thus crucial, and roller volumes cannot be directly compared between different locations. In contrast to topographical image subtraction, roller volume subtraction involves no point-to-point comparison and thus does not depend on a precise lateral matching of the two images. A small deviation from perfect matching only affects by giving the studied area a slightly different margin and the following difference in the calculated bearing volume will be small.(Gahlin, 1998)

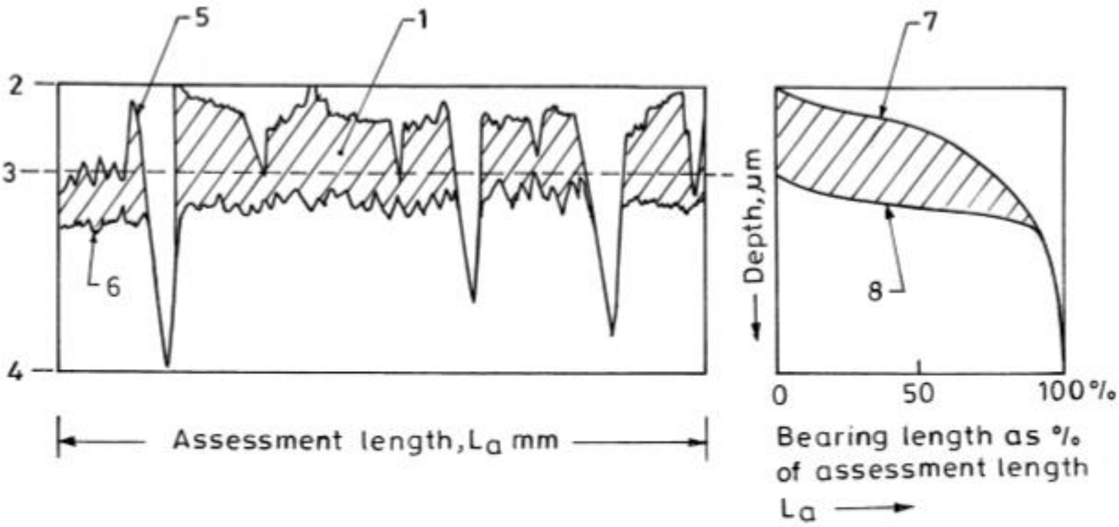

Figure 2.0: Roughness and Wear

Fig. 2.0. Schematic diagram of roughness profiles and corresponding bearing length curves before and after wear. Shaded area in roughness profile = Shaded area in bearing length curve. (1) Worn material; (2) Upper reference line for profile before wear; (3) Upper reference line for profile after wear; (4) Lower reference line for both profile before and after wear; (5) Roughness profile before wear; (6) Roughness profile after wear; (7) Bearing length curve before wear; 8 Bearing length curve after wear. Wear depth determination procedure is considered better than the estimation based on the difference of actual cutting points of two curves on the depth axis as these points are likely to be influenced by some high peaks on the surface. (Kumar, Kumar, Prakash, & Sethuramiah, 2000)

Chapter 3

Research Methodology

3.1 Material

Material chosen for specimen is stainless steel 304SS. This material is chosen because of its wide application in industry. The material tested is in a cylindrical shape. The mechanical properties of chosen material are listed below.

Table 3.1: List of the Stainless Steel 304SS Properties

Properties	**Value**
Density	8000 kg/m^3
Young's Modulus	190 GPa
Tensile Strength	820 GPa
Yield Strength	240 GPa
Shear Modulus	86 GPa
Brinell Hardness	88 HB
Poisson's Ratio	0.29

3.2 Schematic Diagram

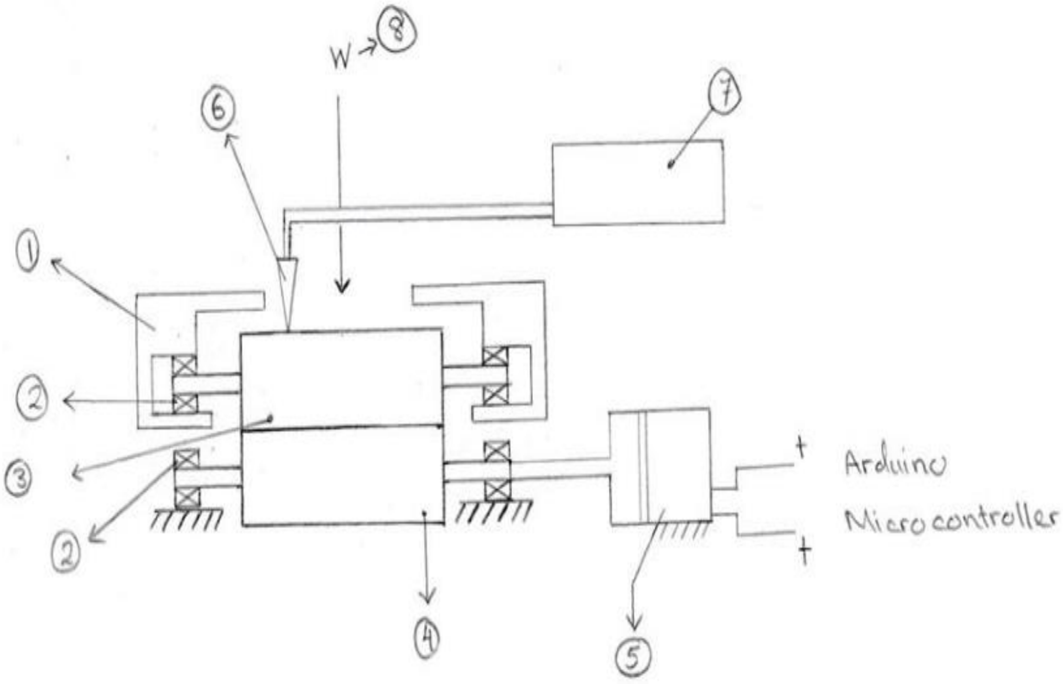

Figure 3.1a: 2D schematic diagram

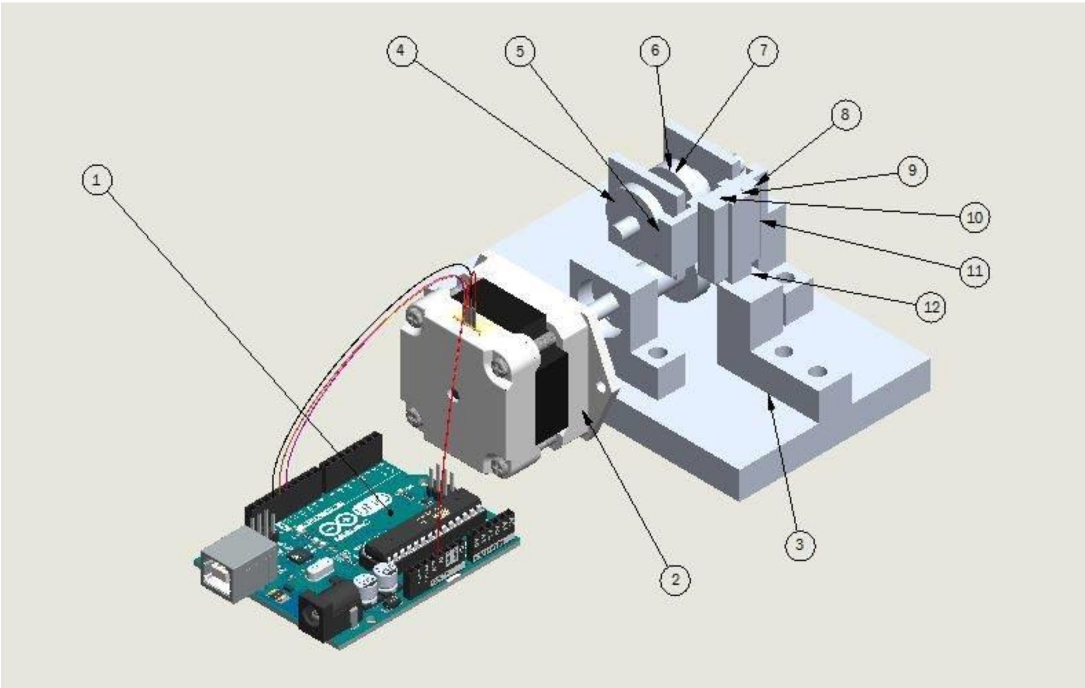

Figure 3.1b: 3D assembly drawing of rolling machine

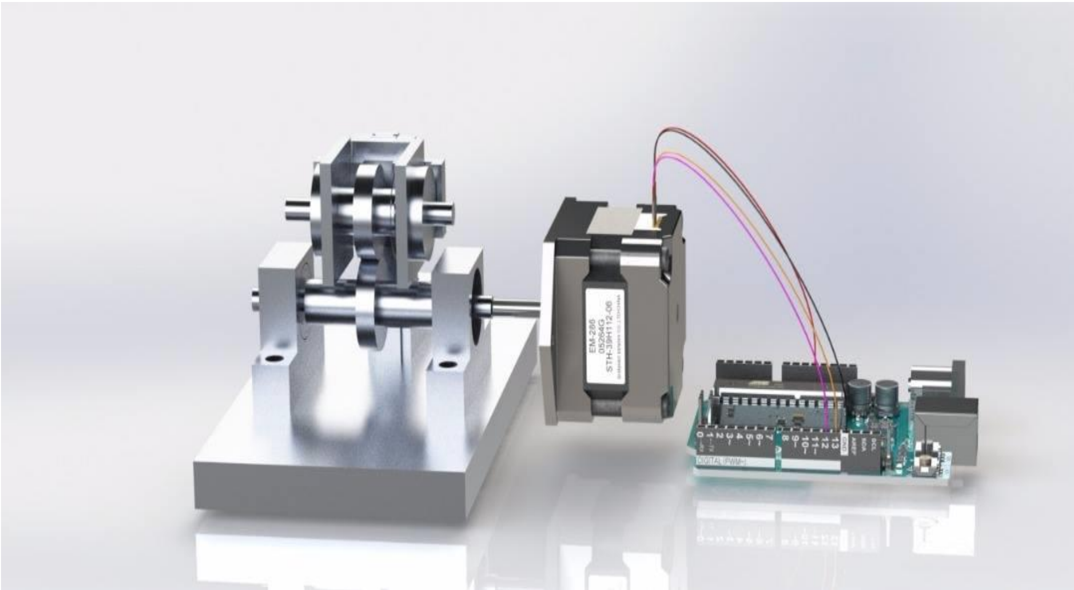

Figure 3.1c: 3D rendering drawing of rolling machine

3.3 Equipment

Table 3.2: List of the Equipment Used

(Numbering refer Figure 3.1a)

Name	Purpose
1. Bearing Holder	Hold bearing, supports roller and load frame
2. Bearing	Mount to roller to allow movement
3. Upper Roller	Specimen of this experiment
4. Lower Roller	Drive the upper roller to rotate
5. Stepper Motor	To controlled the speed of roller
6. Stylus	Scan the surface of specimen
7. Controller Unit	Controlled the elongation of rod that hold stylus
8. Weight	To ensure the roller always in contact

3.3 Testing location of asperities deformation for rolling contact

The testing of physical model was conducted in the metrology laboratory of University Sains Malaysia (USM), Pulau Pinang, Malaysia. The roller test frame was fabricated locally and several improvements were made to make sure that the test frame functions well and in good condition for testing process.

The experiment was set up just like in figure 3.3, 3.4 and 3.5. The components and its functions had been described in table 3.2. As the power supplied to the Arduino which has been coding. The stepper motor moved according to the coding which is 1 rpm. Upper roller (specimen) will be drived by lower roller which connected to the stepper motor. Reading being recorded after each 10 cycles.

The load frame part being milled 2mm in z-axis and 10mm in x-axis enabled the stylus needle reach the studied surface. 53.82 Newton load being applied to the specimen. The load being applied to avoid pure sliding occur. The experiment focuses on pure rolling.

The Arduino Uno - R3 - DEV-11021 with ATmega328 microcontroller, input voltage from 7-14V, 14 digital I/O pins (6 PWM outputs), 6 analog inputs, 32k flash memory and 16 Mhz clock is used there to drive the stepper motor at one rpm for each cycle. For each the surface roughness is measured and recorded using the Mitutoyo Surftest SV-3100. This machine has 0 – 80 mm/s drive speed with measuring speed of 0.02 – 5 mm/s and 0.05 µm resolution.

Ra and BAC height are the crucial parameters in this experiment. Ra is the arithmetic average of the absolute values of the profile height deviations from the mean line, recorded within the evaluation length. Simply put Ra is the average of a set of individual measurements of a surfaces peak and valleys. The Abbott-

Firestone curve or bearing area curve (BAC) describes the surface texture of an object. The curve could be found from a profile trace by drawing lines parallel to the datum and measuring the fraction of the line which lies within the profile.

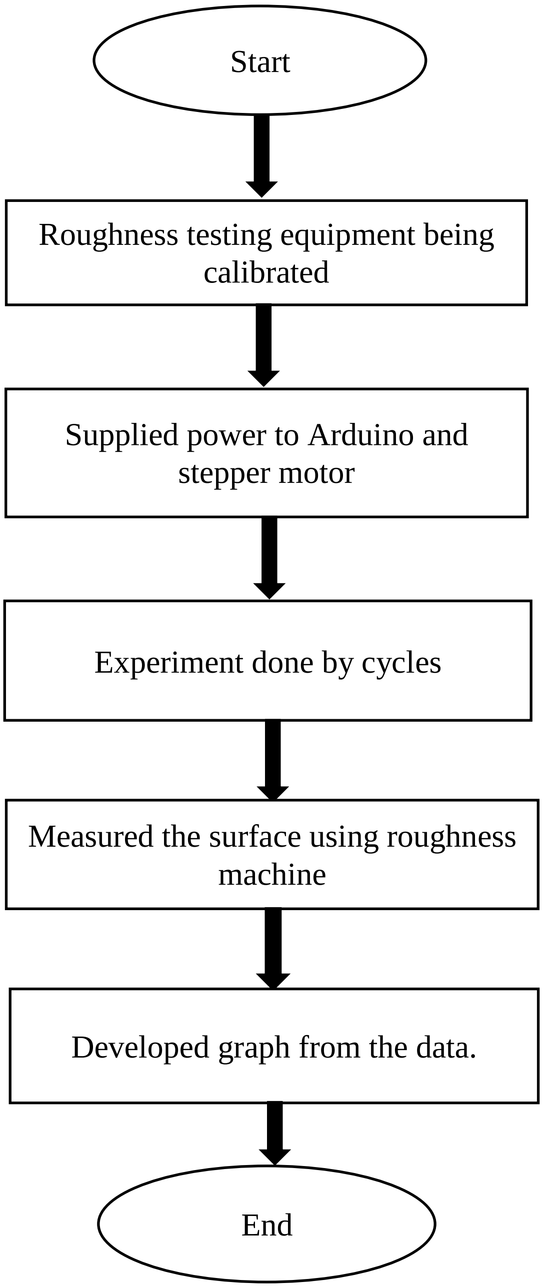

Figure 3.2: Flowchart of Methodology

3.4 Experimental set up

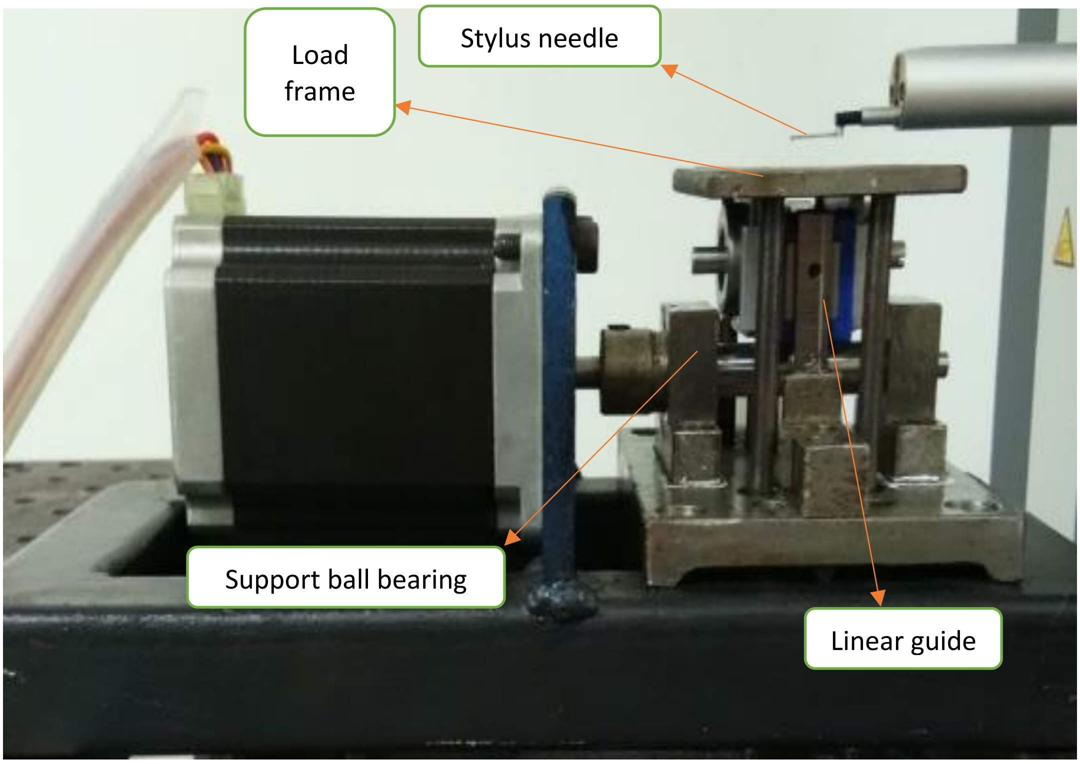

Figure 3.3: Machine Assembly

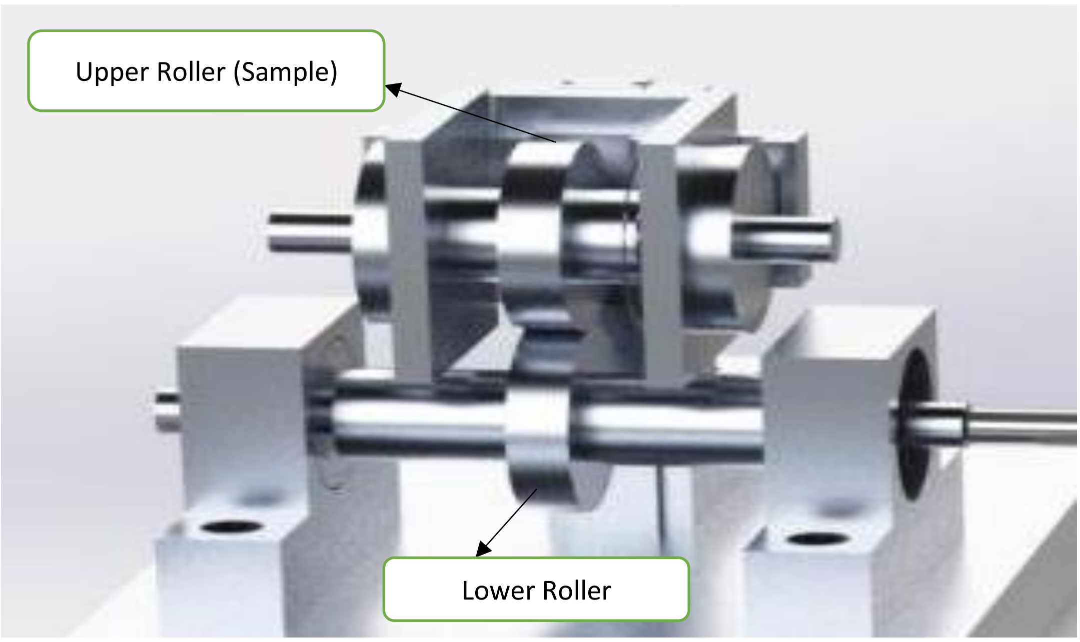

Figure 3.4: Specimen Configuration

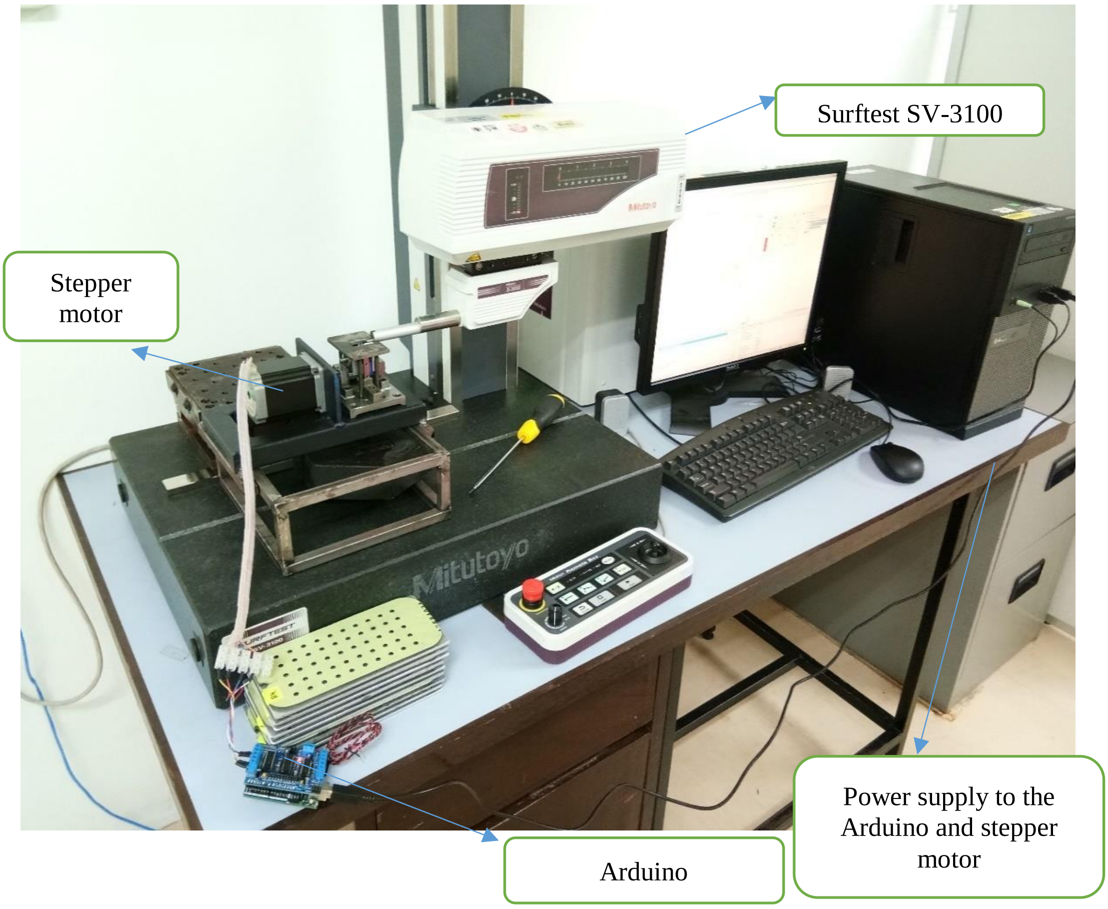

Figure 3.5: The Full Experiment Setup with Test Frame and Roughness Measurement System Surftest SV-3100

3.5 Measurement method

In order to obtain the same line in each measurement, two reference points are used. The reference point is an indentation made using a micro-indenter in order to get a fixed datum for each measurement. The sample is assembled on the test rig and mounted on the Surftest SV-3100 table. The reference point is identified from the scanned image to set the start position before rolling the sample. The changes in the surface geometry are measured from the datum when the rolling motion is stopped after every complete cycle. The scanning is repeated until the final 100 cycles and the results are saved for further analysis.

Related Formula to Rolling Contact

1. Roughness Average, Ra

$$Ra = (1/L) \int_0^L |Z(x)|\, dx$$

2. Half-width b of the rectangular cotact area

$$b = \sqrt{\frac{4F\left[\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}\right]}{\pi l \left(\frac{1}{R_1} + \frac{1}{R_2}\right)}}$$

E_1 and E_2 are moduli of elasticity for cylinders 1 and 2. V_1 and V_2 are Poisson’s ratios. l is the length of contact.

3. Maximum contact pressure

$$P_{max} = \frac{2F}{\pi b L}$$

4. Root mean square roughness, R_{RMS} / R_q

$$R_q = \sqrt{\frac{1}{L} \int_0^L Z^2(x) dx}$$

Chapter 4

Result and Discussion

This chapter presents the experimental results and discussion consisting of two sections. The first section illustrates the experimental results for arithmetic average of the absolute values (Ra). The second section respectively discusses the bearing area of curve (BAC).

4.1 Arithmetic average of the absolute values (Ra)

4.1.1 Ra Dry Surface

From Figure 4.1, it show inverted “L” shape. The minimum roughness (10 cycles) is 0.1371 µm and maximum roughness (100 cycles) is 0.7101 µm. The trend of the graph start to climb high after 80 cycles because micropitting occur on the specimen and drive roller. From figure 4.2b, range between 0.0 and 0.4 had shown the roughness trend of the specimen after 100 cycles. This phenomena affect the roughness values and the waviness scale at y-axis also drastically change from (-0.5 to +0.5) µm to (-10 to +5) µm. As the cycles number of the roller increases, the waviness of the surface increases and the graph line become more compact. After done the experiment, dry surface easily produce more friction during rolling in progress and the consequence it cause a lot of tiny stainless steel dust. Dust that being produced from previous cycles being collected and after 80 cycles it showed the effect of the metal dust on the specimen surface. Figure 4.1 show how stiff the graph after 80 cycles and it cause micropitting obviously produced on the surface of specimen.

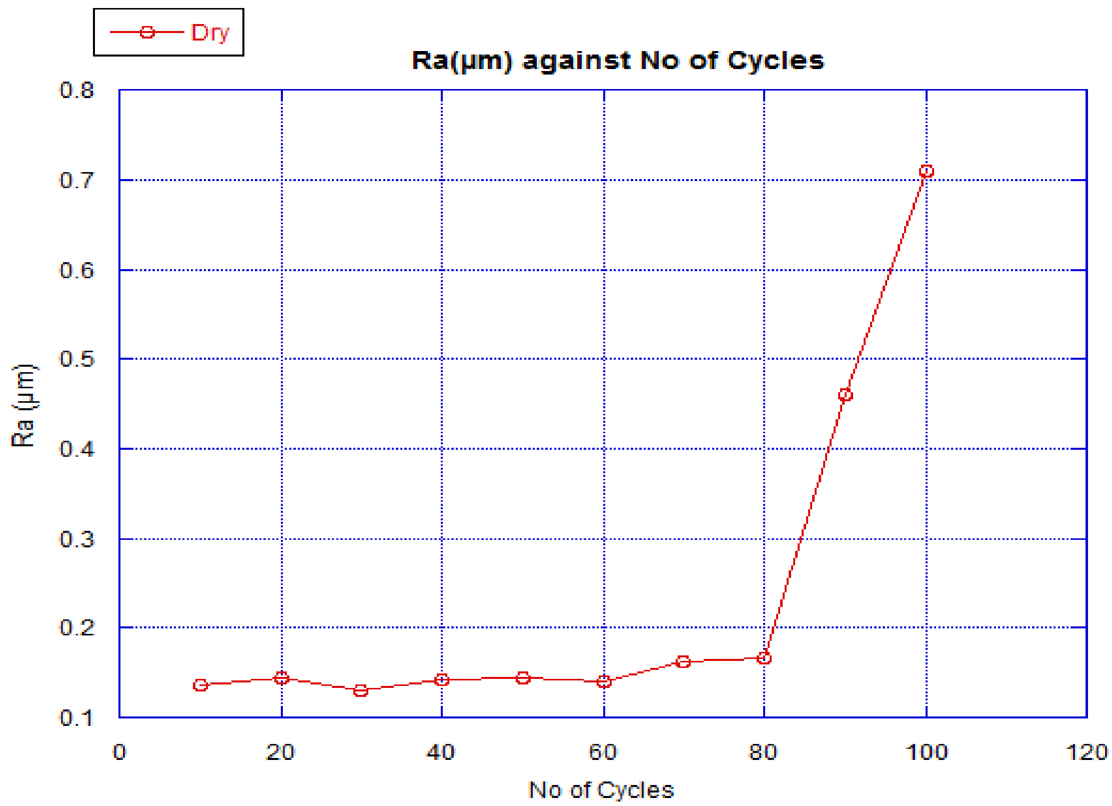

Figure 4.1: Ra against No. of Cycles (Dry)

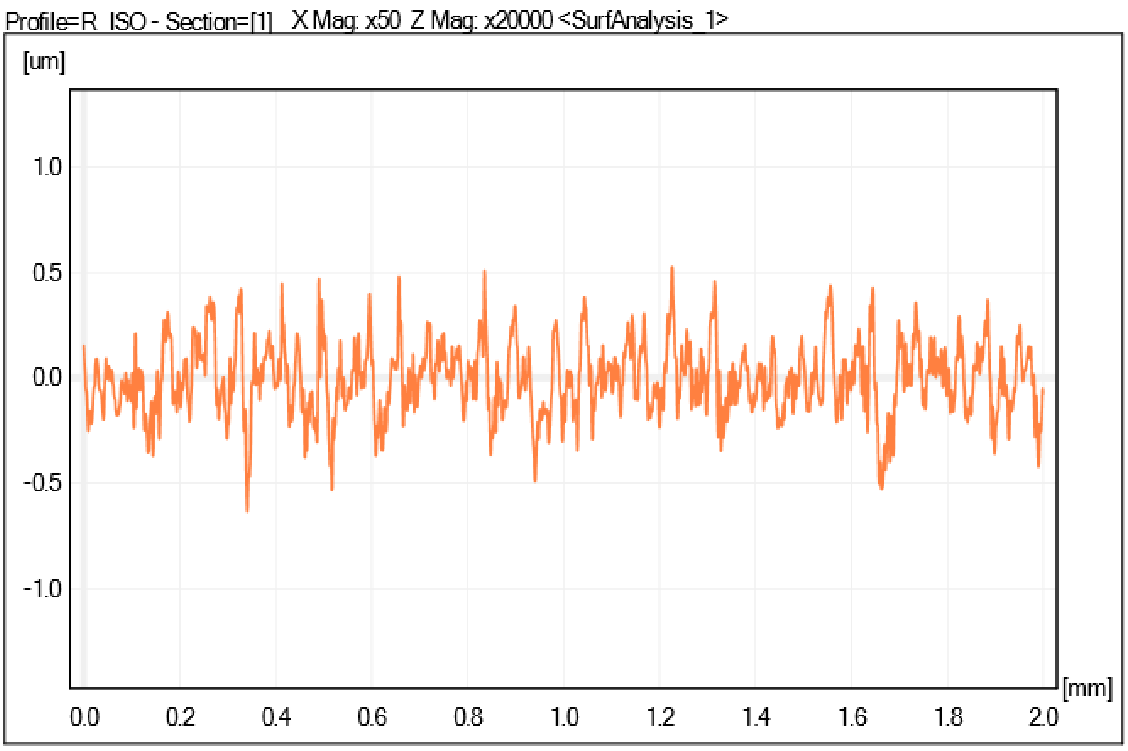

Figure 4.2a: N = 1 (Dry)

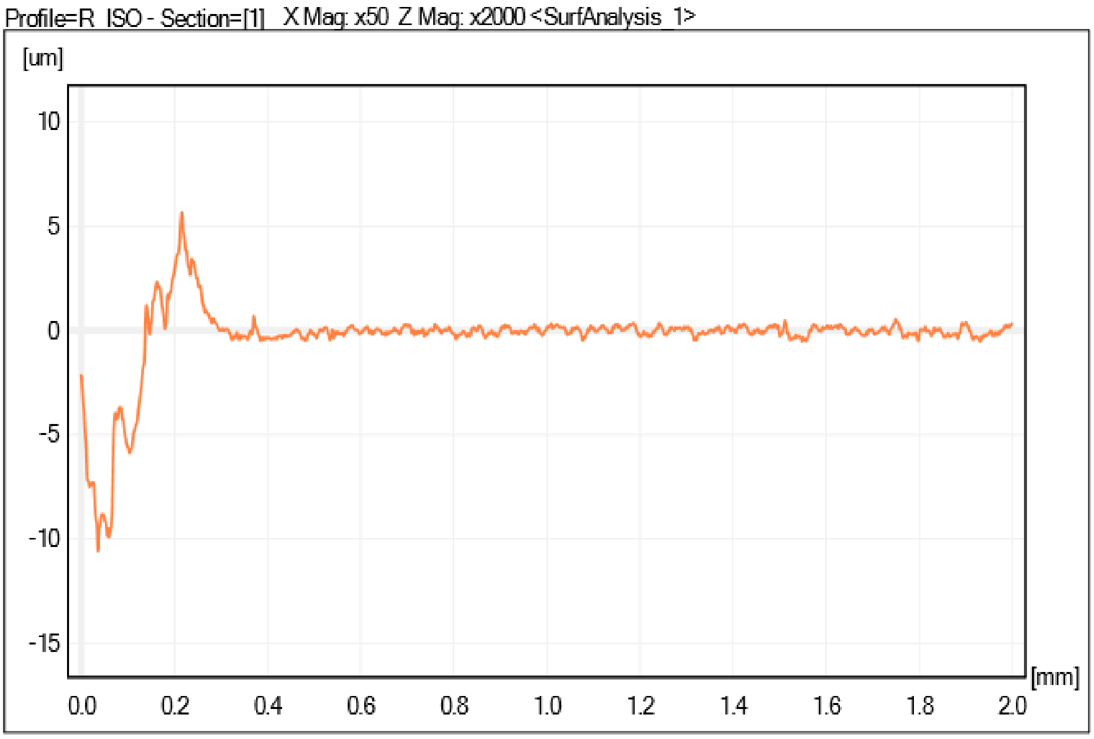

Figure 4.2b: N = 100 (Dry)

4.1.2 Ra Lubricated Surface

From figure 4.3, the Ra of the graph gradually increase from 10 until 40 cycles. After 40 cycles, the pattern of the graph start to fluctuate in the range 0.1593 µm to 0.1706 µm. The range of Ra for both one and hundred cycles are between -0.4 to 0.6 µm as shown in figure 4.4a and 4.4b. Even though the range still the same but the roughness value still increasing and waviness of the specimen surface become more compact. The oil on the specimen and drive roller formed a thin layer of lubrication which affect the contact stress. The lubricated surface also reduces the friction of the contact surface. (Didn't Measure and Focus in This Experiment). This at once prevent micropitting from occur and provide better Ra distribution values in the 100 cycles process. In the three boxes shows the increasing in depth of valley on the specimen and the increment is not as much in dry the condition.

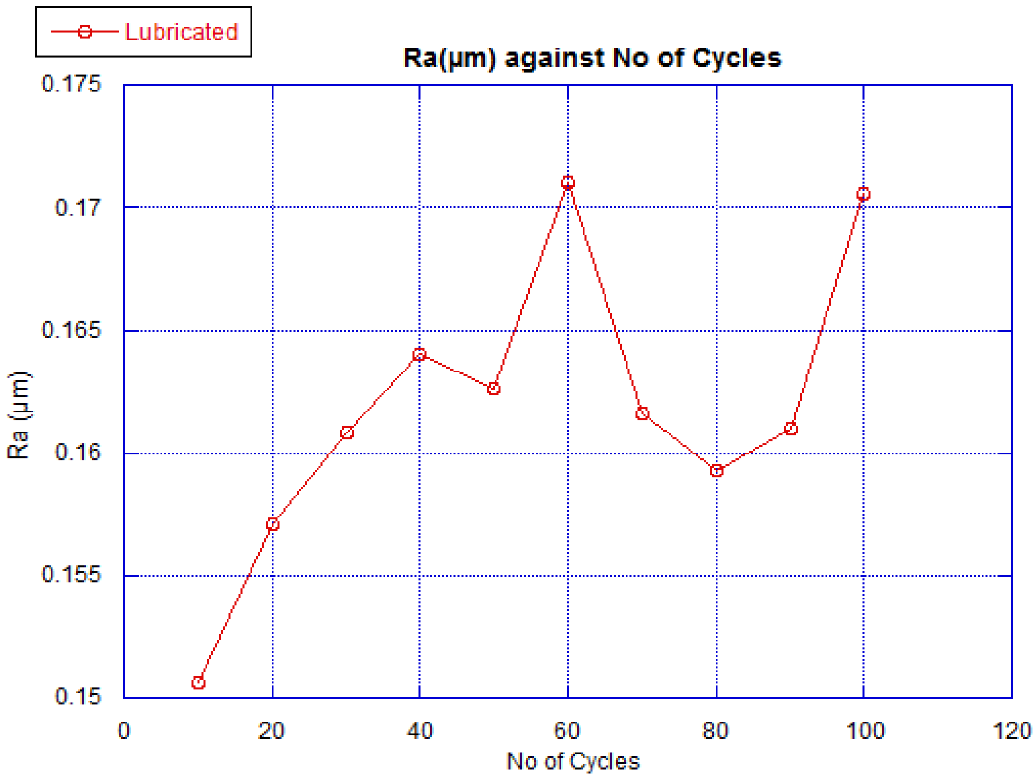

Figure 4.3: Ra against No. of Cycles (Lubricated)

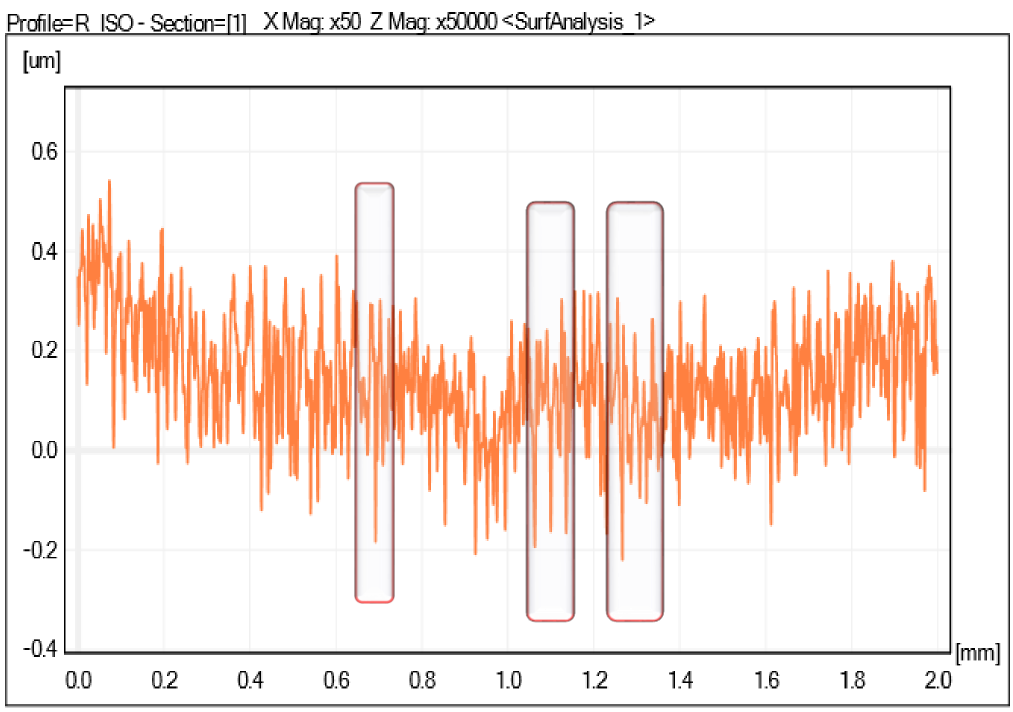

Figure 4.4a: N = 1 (Lubricated)

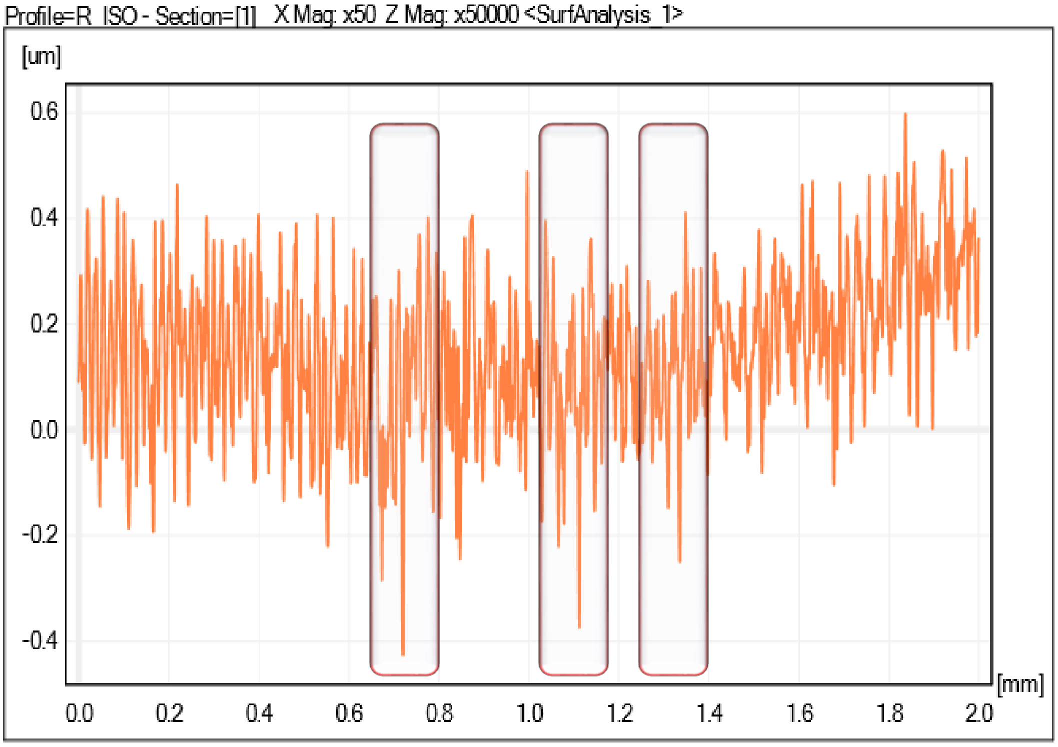

Figure 4.4b: N = 100 (Lubricated)

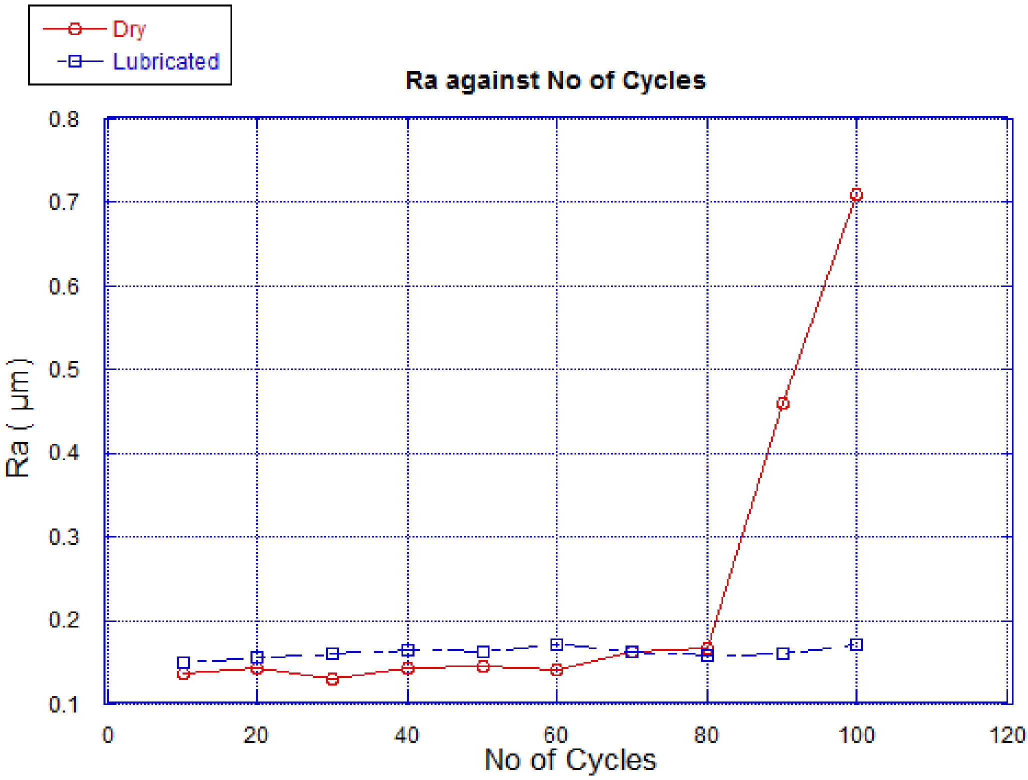

Figure 4.5: Ra against No. of Cycles (Dry and Lubricated)

4.2 Bearing area of curve (BAC)

4.2.1 BAC Height for Dry Surface

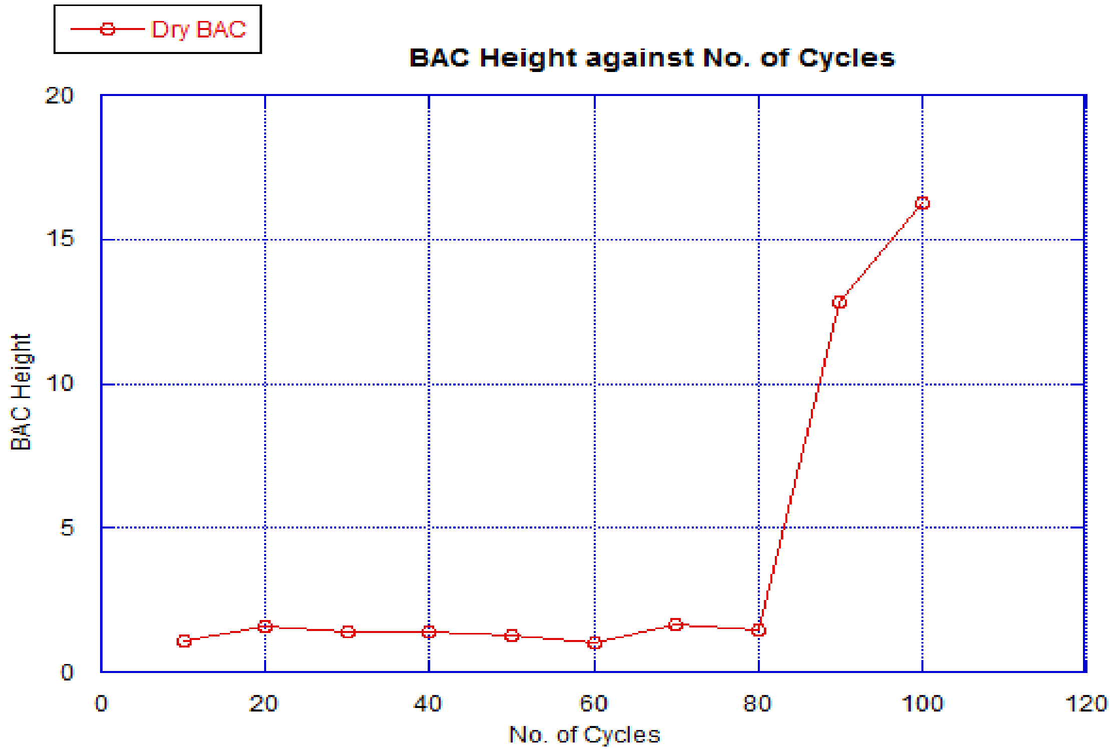

Figure 4.6: BAC Height against No. of Cycles (Dry)

From Figure 4.6, it show inverted "L" shape and Abbott-Firestone graph in figure 4.7 change from S-shape to Z-shape. The minimum BAC height (10 cycles) is 1.1087 µm and maximum BAC height (100 cycles) is 16.2656 µm. The trend of the graph start to climb high after 80 cycles because curving area of the curve surface had change from its normal condition. By looking at figure 4.7a and 4.7b, the Rpk, Rk and Rvk values had change obviously. Reduced peak height (Rpk) had shrink too much while reduced valley height (Rvk) had increase drastically. The main part of the graph is the core roughness depth (Rk) area also mostly shifted above the mean line. The stiffness of the graph decreases because of the 90 and 100 cycles BAC height values increments are too large and causes Rk size also decreases. From the calculation based on figure 4.7, the changes of area at the Rpk site is 363.515 μm^2. After 100 cycles, that's the amount of wear occur at the testing surface under dry condition.

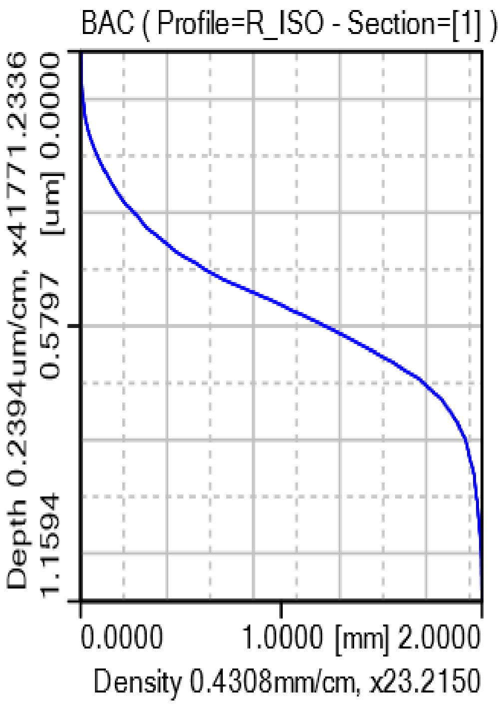

Figure 4.7a: N = 1 (Dry)

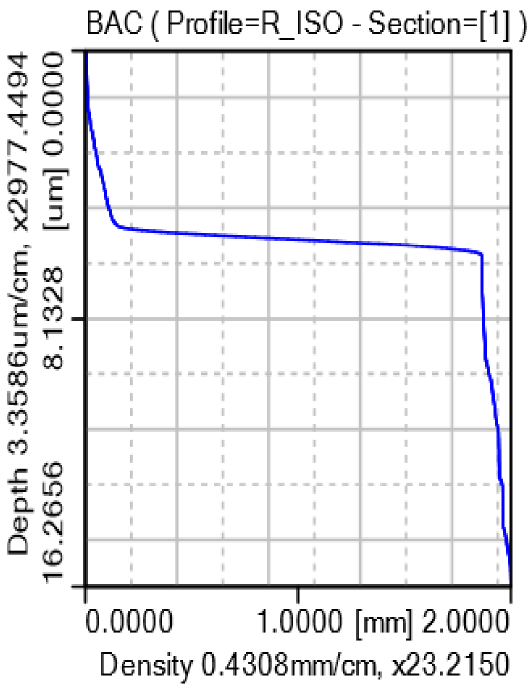

Figure 4.7b: N = 100 (Dry)