THE EFFECTS OF MATERIAL PROPERTIES ON THE ROLLING CONTACT SURFACE DEFORMATION

By:

AMIRUL AKIL BIN ADMAN

(Matrix no: 131135)

Supervisor:

Dr. Nurul Farhana Binti Mohd Yusof

May 2019

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfilment of the requirement to graduate with honor degree in

BACHELOR OF MECHANICAL ENGINEERING

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for other degree in this university or elsewhere

The Effects of Material Properties on The Rolling Contact Surface Deformation

Signature : ……………………………………………………………

Name : ……………………………………………………………

Date : ……………………………………………………………

Supervisor's Declaration

I hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by Universiti Sains Malaysia (USM)

Signature : ……………………………………………………………

Name : ……………………………………………………………

Date : ……………………………………………………………

ACKNOWLEDGEMENT

First of all, I would like to thank to Almighty Allah for giving me strength and ability to finish my thesis in order to qualify my study in Degree of Mechanical Engineering at Universiti Sains Malaysia.

I would like to express my utmost gratitude to my research supervisor Dr. Nurul Farhana Mohd Yusof, lecturer of School of Mechanical Engineering, Univeriti Sains Malaysia for assisting me throughout this final year project. Her willingness to involve on my progress has resulted in the completion of this project. Dr. Farhana always welcome me to her office to ask question regarding my project and thesis. Besides, thanks to Dr Mohamad Ikhwan Zaini Ridzwan for arrange the schedule for final year student to attend the talk and workshop from lecturers and staffs of Universiti Sains Malaysia.

I also extend my thanks to Encik Mohd Ashamuddin Hashim for spending time to assist me in conducting the experiments. Not forgetting, Encik Wan Mohd Amri Wan Mamat Ali, Encik Mohd Syahril Mohd Yusof, and Encik Abdul Halim Che Aat for their help to guide me using machine in mechanical workshop, giving an idea for my project and help me to solve the problem regarding my project.

Deepest thanks and appreciation to my parents, family and friends for their moral support, encouragement and helpful thoughts throughout this final year project. Thank you.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRAK

Sifat bahan adalah penting ketika interaksi permukaan sentuhan berguling kerana ia dapat memberi kesan terhadap geseran dan kehausan. Keadaan sentuhan dapat dikawal dengan pemilihan bahan permukaan berdasarkan tekanan sentuhan yang dihasilkan dan juga kekerasan. Pemilihan bahan yang baik dapat meningkatkan prestasi dan jangka hayat komponen mekanikal. Kehausan dan perubahan bentuk plastik ialah dua mekanisma yang kritikal yang dapat membawa kepada kegagalan permukaan ketika sentuhan berguling. Dalam kerja ini, eksperimen dijalankan secara atas talian yang mana imbsan permukaan dijalankan secara terus di bawah Mikroskop Fokus Tak Terhingga. Empat bahan yang berbeza digunakan untuk fabrikasi specimen pengguling iaitu aluminium, tembaga, keluli lembut dan keluli tahan karat untuk menghasilkan keadaan sentuhan yang berbeza. Profil permukaan menggerutu pada keadaan awal dan akhir telah diplot untuk menilai perubahan bentuk permukaan menggeru . Purata kekasaran R_a dari kitaran 0 hingga 100 diplot dan ditemui dapat digunakan untuk menunjukkan kadar kehausan. Parameter BAC dapat mewakili nisbah puncak permukaan menggerutu yang mana R_{pk} yang tinggi diperolehi jika permukaan menggerutu mempunyai puncak yang tinggi. Penemuan menunjukkan kekerasan bahan mempunyai kesan yang jelas terhadap kadar ubah bentuk berbanding modulus elastik dan tekanan sentuhan. Bahan yang mempunyai kekerasan yang tinggi menunjukkan perubahan yang kurang berbanding bahan yang mempunyai kekerasan lebih rendah.

ABSTRACT

Material properties are crucial during surface interaction in rolling contact as it may affect friction and wear. The contact condition can be controlled by selection of material of the mating surfaces based on the produced contact stress and the hardness. A good selection of materials may increase the performance and the lifetime of any mechanical components. Wear and plastic deformation are two critical mechanisms that may lead to surface failure during rolling contact. In this work, the experiment is carried out using online method where the surface scanning is carried out directly under the Infinite Focus Microscopy (IFM). Four different materials are used to fabricate the roller specimen, there are aluminium, brass, mild steel and stainless steel to produce different contact condition. Surface asperities profile at initial and final condition is plotted to evaluate the surface asperities deformation. The average roughness R_a from 0 cycle until 100 cycle is plotted and found can be used to indicate wear rate. The BAC parameter is sufficient to present the ratio of asperities peak where high R_{pk} is obtained when the surface asperites profile has high peaks. Based on surface roughness parameter and asperities profile, aluminium which has the lowest hardness value has the highest surface deformation followed by brass, mild steel and stainless steel that having lower hardness respectively. The finding shows that material hardness has a significant effect on the deformation rate compared to modulus of elasticity and contact pressure. The material with higher hardness shows less deformation compared to the lower hardness material.

CHAPTER 1 INTRODUCTION

1.1 PROJECT BACKGROUND

The tribology of contact involves the interactions of solid contacting surface in relative motion. The contact can be either in the form of a dry or a lubricated sliding or a rolling contact. In sliding and rolling contacts, wear and plastic deformation are the two critical mechanisms observed that may lead to failure of the contacting components. Contact deformation depends on contact condition, where it is categorized as macro-contact and micro-contact. Changes in macro-geometry may lead to vibration, while change in micro-scale may influence the friction level[1, 2]. When omitting the effect of surface roughness, macroscopic contact can be analysed [3]. However, most engineering surfaces produced in micro-scale are rough. In tribology, asperities are high spots or micro-protrusions on all solid surfaces irrespective of their method of production.

The experimentation and simulation of evolution of surface roughness levels during running-in has been extensively done[1, 2, 4-8]. Surface deformation at the micro-geometry also have been studied[3, 9-12]. For micro-geometry level, a precise measurement technique is required, because the individual asperity is measured in sub-micron units and the relative change of geometry makes it necessary to locate and scan the same particular asperities repeatedly. The on-line method are used which measures the surface sample directly. This method reduces measurement inaccuracy due to sample shifting during remounting and sample damage during dismantling.

The understanding of asperities response towards the applied force or applied load over each rolling cycle can be improve by continuous evaluation. The first phase of rolling contact, which is known as the running-in phase, is generally associated with two main mechanisms which is plastic deformation and wear[13]. During running-in phase, plastic deformation of the cyclically loaded structure with the application of load occurs until the elastic steady state is achieved[14]. In this period, the continuous rolling contact caused plastic deformation of the two contacting surface asperities, resulting in the reduction of the surface roughness is called polishing effect[1, 2, 15]. Halme and Andersson[16] claimed that surface roughness due to surface deformation can increase or decrease depending on the rolling condition and initial surface roughness.

A solid surface that has a complex structure and complex properties dependent upon the nature of solids, the method of surface preparation, and the interaction between the surface and the environment. Properties of solid surfaces are crucial to surface interaction because surface properties affect real area of contact, friction, wear, and lubrication. For example, different surface hardness may results in different surface deformation. Solid surfaces contain irregularities or deviations from the prescribed geometrical form. No machining method, however precise, can produce a molecularly flat surface on conventional materials. Even the smoothest surfaces contain irregularities the heights of surface asperities.

1.2 PROBLEM STATEMENT

A good selection of materials may increase the performance and the lifetime of any mechanical components. In sliding or rolling contacts particularly, the surface condition during the contact is very crucial as it is used to transfer load between the mating components. Wear and plastic deformation are two critical mechanisms that may lead to surface failure during rolling contact. This can be contributed by the contact condition produced by the materials of the mating surfaces such as contact stress and hardness of the material. There are limited literature that focusing on effect of material properties on rolling contact surface deformation. There is a need to identify the effect of material properties on the surface deformation of a rolling contact.

1.3 OBJECTIVE

The objective of this research is:

1. To investigate the effect of material properties on the rolling contact surface deformation.
2. To evaluate surface deformation using surface roughness parameter and the asperities profile.

1.4 SCOPE OF WORK

This project involves fabrication of the roller specimens, experimentation, surface scanning and analysis of results. Four different materials are used to fabricate the roller specimen, there are aluminium, brass, mild steel and stainless steel to produce different contact condition. These materials have different mechanical properties such as modulus of elasticity, tensile strength, elongation, hardness and fatigue limit. The surface deformation is evaluated by surface scanning at progressive cycles. The bottom roller for all tests are made from stainless steel which has adequate hardness to ensure that it will give effect to the top roller which has lower hardness. The average roughness is monitored throughout the 100 cycles and the trend is compared with general wear-time curve. The roughness asperities profiles are plotted and the asperities peak and valley are related to BAC parameter.

CHAPTER 2 LITERATURE REVIEW

2.1 OVERVIEW

In this section, a brief on the surface deformation and wear in rolling contact, surface roughness parameters and the materials properties that may affect surface deformation are presented.

2.2 SURFACE DEFORMATION AND WEAR IN ROLLING CONTACT

Surface measurement is normally carried out to evaluate surface deformation of rolling contact. Wang et al. [4] measure the surface roughness change of two-disk machine by measuring the surface roughness in a real time mode and compared with the experimental data measured in a conventional manner by stopping the wear test at a certain period. They observed that the online roughness measurement showed higher data consistency compared to the offline as shown in Figure 2.1. This is due to the online method reduces the measurement inaccuracy due to the sample shifting or damage during dismantling and remounting during the offline method.

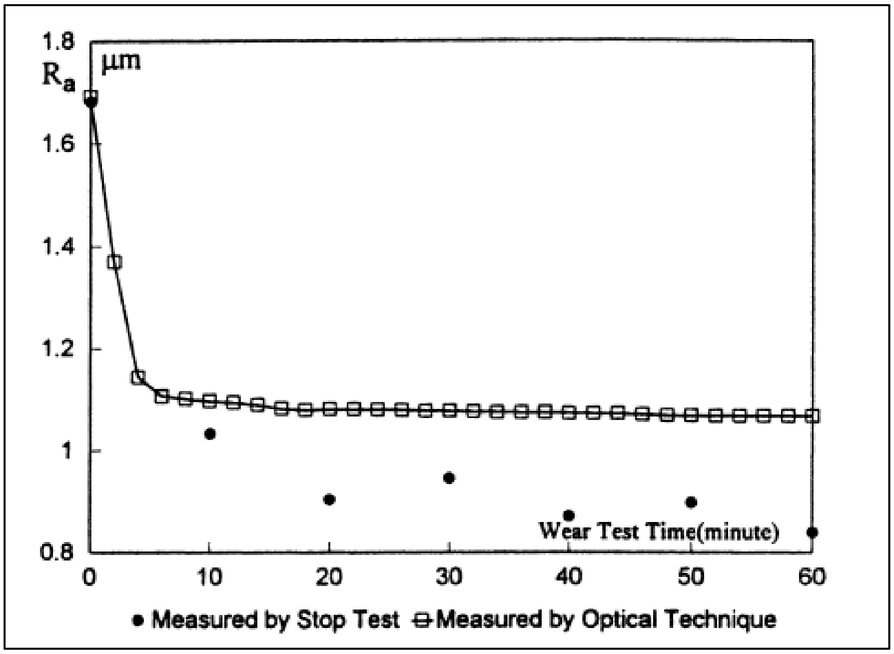


Figure 2.1 Comparison between online and offline measurement effect on surface roughness [4]

The experimental setup used in [4] was further used to investigate the relationship between the average surface roughness and wear volume of a soft rough aluminium disc that were in contact with hard smooth steel [31] .The wear volume was obtained by measuring the weight of aluminium disc before and after the experiment and the surface roughness of the discs was evaluated. The finding showed that the wear volume can be related to the total average roughness change by second order polynomial as shown in Figure 2.2.

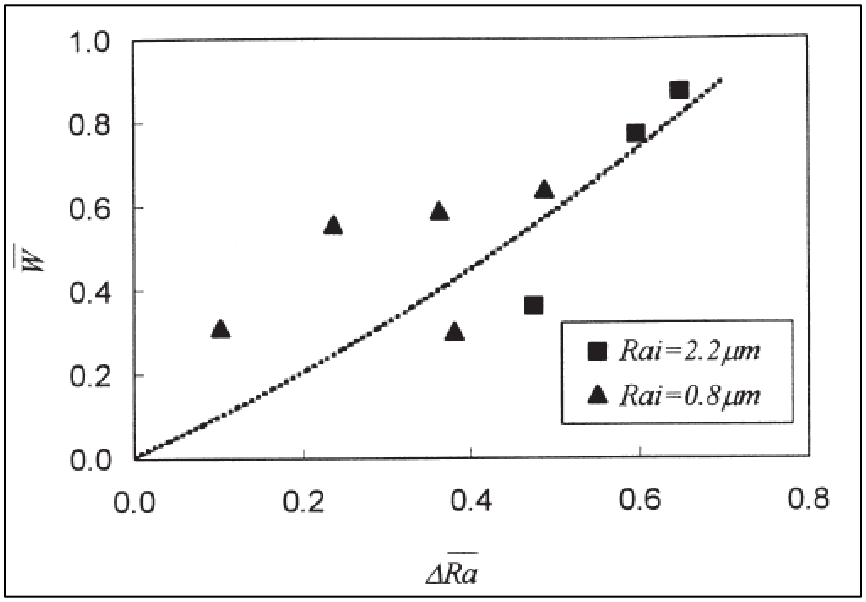


Figure 2.2 Relationship between average roughness and wear volume, two experimental data and simulation in dotted line [32]

The comparison of local surface heights to measure and characterize wear and material transfer at the microgeometry level was also performed by [9]. Changes in rolling surfaces was attributed to plastic deformation and contributed to wear particles forming [16]. The changes in the surface topography can be measured at the asperity level and nano-level [11, 12]. Even the surface is under a heavy loads, the surface still having roughness R_a due to asperity persistence [17, 19].

Each of surface parameter indicates particular property of the surface and surface parameters are different and wide-ranging as it required in different application[23, 24]. The Abbott- Firestone or bearing area ratio curve (BAC) is used to explain the wear of the asperities by monitoring the BAC surface parameters (S_k, S_{pk}, S_{vk}) and amplitude parameter (S_a) is comparable with the BAC parameters which also can be used to explain the wear of the asperities[25]. The values of the areal surface roughness parameter (S_a) can be used to represent surface wear [2]. The surface profile, the density function of surface height, root-mean square, and skewness were measured using a computerized surface measurement system[8].

Jamari [32] presented the wear-time curve which consists of three wear phases: running-in, steady state and finally wear-out as shown in Figure 2.3. Each phase has different wear behaviour. The first phase occur at the early cycle of rolling contact is known as running-in phase. At this phase, the wear rate is decrease and the surface of the material gets adjusted to the contact condition and the operating environment. This is followed by phase two which is steady-state. During this period , the wear rate is almost constant where the components operate in high efficiency. Finally in the wear-out regime, the wear rate increases rapidly because of the surface deformation lead to material loss. There are several factors lead to the wear out such as breakdown of lubrication due to temperature increase, lubricant contaminants or environmental factors.

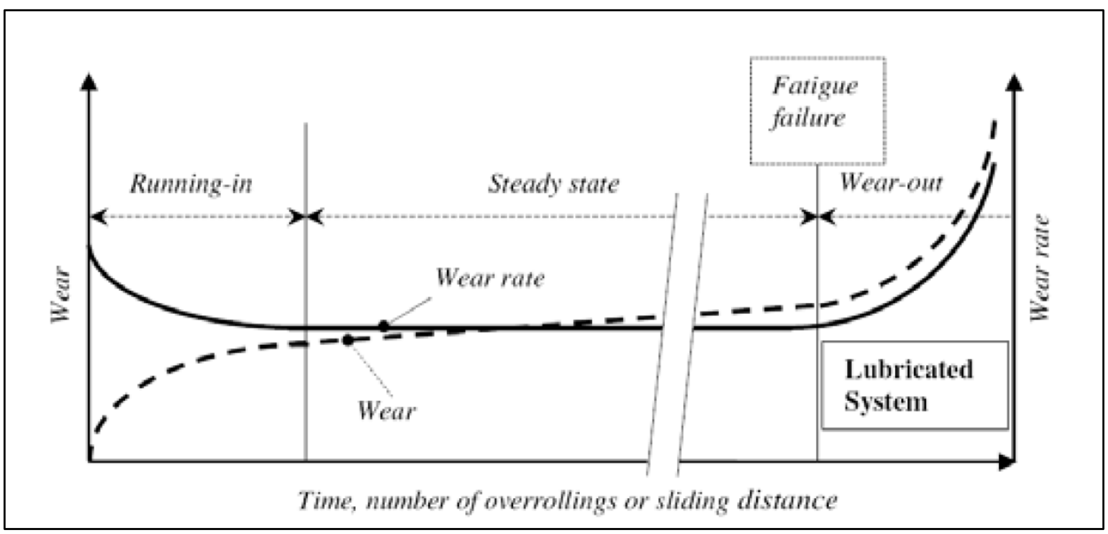


Figure 2.3 Wear curve [20].

Running-in plays an important role in plastic deformation, friction and wear of tribology systems during the steady-state period [20]. The interactions with different wear mechanisms such as adhesive, abrasive, fatigue and corrive and different stress concentration mechanisms such as asperity, dent, debris and etc might accelerate and decelerate the overall wear progress[21, 22]. During running-in, the load carried by the asperity (R_a, R_q, R_{sk}) decrease and the surface topography reaches to a particular surface level, then stay the same[8, 17]. In running-in phase, the continuous rolling contact caused mild plastic deformation resulting in the reduction of the surface roughness is called flattening effect[5, 18]. Large ratio of change in average roughness, R_a and large wear loss during running-in are induced from a high loading and specimen surfaces with different initial roughness will end up with different final roughness after running-in[4, 7, 19].

2.3 EFFECTS OF MATERIAL PROPERTIES ON THE SURFACE DEFORMATION

Fujita and yoshida [27] studied the effect on surface durability of differences in the hardnesses of mating rollers. The tests were performed under rolling-sliding where 0.45% C steel S45C rollers with a surface roughness of about 1 pm were thermally refined, through-hardened and induction hardened to produce different hardness. The results show that the difference in hardnesses between the mating rollers had little effect on the surface durability of the softer roller. Surface durability increased as hardness increased, and the surface durability, expressed as the maximum Hertzian stress, and the surface hardness were related using equation.

Another work state that most of the wear occurs in the softer material than the material which posses higher hardness and soft roller experiences more reduction in surface roughness[5]. It is observed that the increased hardness and roughness affect the shear yield strength which attributed to the strengthening of the material, the rise of stress concentrators and also reduction of material's ability to plastic deformation [3, 26]. Higher hardness also improves the wear resistance of the material if it retains sufficient ductility which can cause fracture and wear rate rising due to the impact of wear particles[28]. When carbon content increases, hardness and strength increases which improves the hardenability [29]. The plasticity index is directly related to the ratio between the modulus of elasticity and the actual material hardness[19].

CHAPTER 3 : METHODOLOGY

3.1 OVERVIEW

This chapter highlights the methods used to conduct this research. It includes the experimental setup, selection of roller material and fabrication and the measurement of surface asperities deformation and wear in rolling contact. Each subsection explains in detail the methods used and illustrates the process taken in order to complete the task.

3.2 EXPERIMENTAL SETUP

In this study, a test rig for measuring rolling contact surface deformation is used as shown in Figure 3.1. The rig is consist of roller specimens, stepper motor, ball bearing, linear guide, a stepper motor and four ball bearings. The test rig is put directly under Alicona Infinite Focus Microscope therefore the surface scanning can be carried out directly.

The experimental rig is small enough that fit into Infinite Focus Microscopy (IFM). The on-line method can be used which measures specimen directly under IFM. This enables precise measurement of the surface deformation. Load is applied to top roller which the load frame is attached at the top with the dead weight mounted on the load holder. During conducting experiment, the IFM table is not moving, while the surface scanning, the microscope lens will move in the z axis to the required surface height. An access hole is made to allow the microscope scan the surface of the specimen as shown is Figure 3.2. The bottom roller is supported by two ball-bearings, while the top roller is free to move in the vertical direction, and the movement in the horizontal direction is limited because of linear guides and the holders. The rolling stepper motor drives the lower roller which subsequently drives the upper roller via the line contact.

The rolling stepper motor is controlled by using Arduino which is Adafruit Motor Shield v2. The programming is written in the Arduino Software as shown in Figure 3.3. The speed for the stepper motor is set at 10 rpm. The delay time after a complete cycle is set at 2 second. The programming is uploaded using Arduino Software.

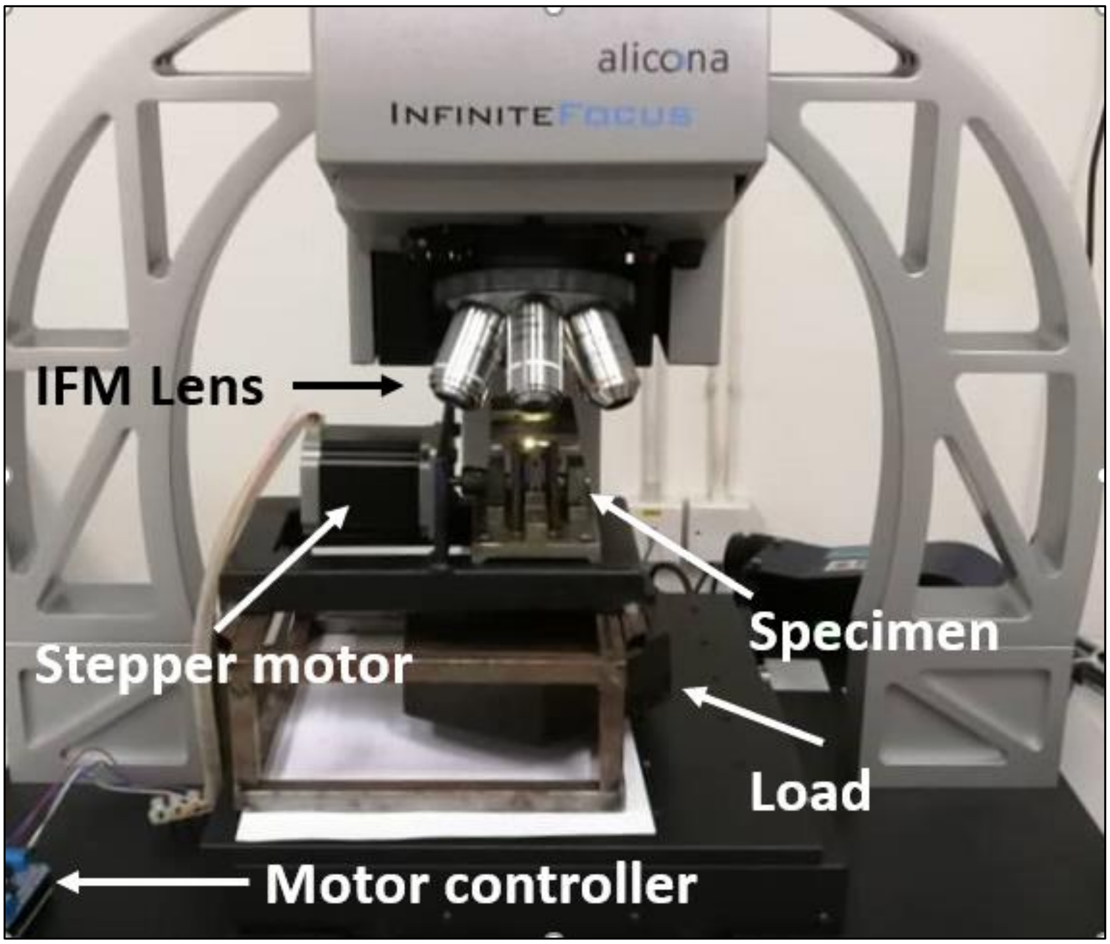


Figure 3.1 Experimental Setup

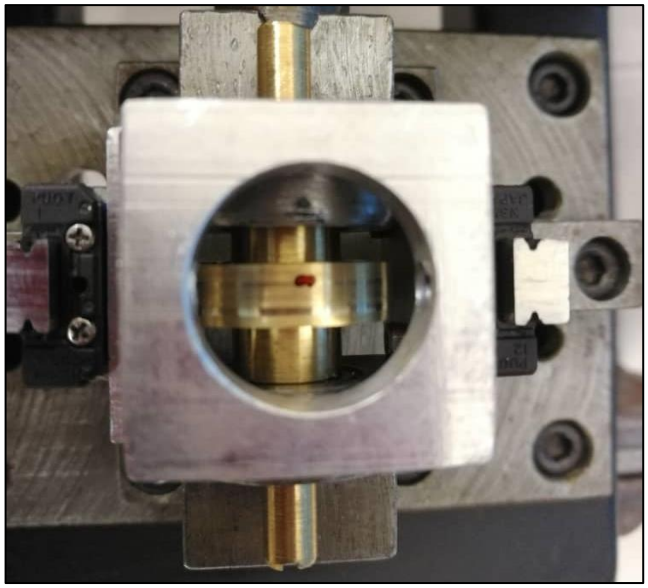


Figure 3.2 Top View


```
// Adafruit Motor shield library
// copyright Adafruit Industries LLC, 2009
// this code is public domain, enjoy!

#include <AFMotor.h>

// Connect a stepper motor with 48 steps per revolution (7.5 degree)
// to motor port #2 (M3 and M4)
AF_Stepper motor(48, 2);

void setup() {
  Serial.begin(9600);           // set up Serial library at 9600 bps
  Serial.println("Stepper test!");

  motor.setSpeed(10);  // 10 rpm
}

void loop() {
  Serial.println("Single coil steps");
  motor.step(200, FORWARD, SINGLE); // 1 cycle
  delay(2000); // 2 sec
  // motor.step(100, BACKWARD, SINGLE);

}
```

Figure 3.3 Programming for Stepper motor

3.3 SPECIFICATION OF ROLLER SPECIMENS

Four types of metal were chosen for this project to study the effect of different material mechanical properties on the deformation rate. Aluminium rod, brass rod, mild steel rod and stainless steel rod were used to fabricate top roller and stainless steel rod were used to fabricate four bottom roller. Stainless steel was selected for bottom roller because it has relatively adequate hardness to ensure no plastic bulk deformation and only asperities level will undergoes plastic deformation during surface contact [1]. The dimensions of the rollers are shown in Appendix C.

The top roller is made from aluminium, brass, mild steel and stainless steel, while the bottom roller are made from stainless steel in all tests. The experiment parameters are listed in Table 3.1. Stainless steel is selected for bottom roller is because of the adequate hardness to ensure that it will give effect to the top roller which has lower hardness.

Table 3.1 Characteristics of roller's material

Parameter	Value
Brinell Hardness Number	Top roller : Aluminium : 15 BHN : Brass : 55 BHN : Mild Steel : 120 BHN : Stainless Steel : 250 BHN Bottom roller : Stainless Steel : 250 BHN
Young's Modulus	Aluminium : 69 GPa Brass : 97 GPa Mild Steel : 200 GPa Stainless Steel : 200 GPa
Poisson's Ratio	Aluminium : 0.334 Brass : 0.331 Mild Steel : 0.303 Stainless Steel : 0.305
Ultimate Tensile Strength	Aluminium : 310 MPa Brass : 345 MPa Mild Steel : 440 MPa Stainless Steel : 505 MPa

The slow speed is necessary in order to avoid slip and dynamic loading. Higher speed will cause higher deformation rate and as most materials are strain rate dependent, this may affect the deformation of the asperities. The high speed and dynamic loading condition may affect the ball bearings. During the experiment, the contact is dry and the nominal contact length is 5 mm. The applied load is 50 N.

3.4 PREPARATION OF SPECIMENS

For the fabrication of specimen, a few steps have to be taken in order to fit the specimens into the experimental rig. The specimen's dimension must be considered to make sure it fit into the experimental rig. After the specimens have been fabricated, the surface finish is produced.

3.4.1 FABRICATION OF SPECIMENS

The top roller and bottom roller has been drawn using SolidWorks 2016 that comprises the dimension of the roller as shown in Appendix C. The specimens are fabricated by using CNC lathe machine (Okuma LB-15C) according to SolidWorks 2016 CAD model.

Before that, the metal rod of aluminium, brass, mild steel and stainless steel were cut into smaller rod using metal cutting hacksaw machine to reduce material waste. The specimen was tightly gripped into a chuck of the CNC lathe machine and the coolant was supply to the tip of the tool to avoid damage to the surface of the specimen and also the tool. Then, the dimension of the specimen need to be set up into the programming of the machine and then the machine was run. The machine door was closed for safety precaution which is avoid the chip from specimen leaps out.

Figure 3.4 CNC lathe machine (Okuma LB-15C)

3.4.2 PREPARATION FOR INITIAL SURFACE ROUGHNESS

After the bottom roller and top roller have been fabricated, the surface finish is produced. The specimen is gripped into a chuch of Conventional Lathe Machine as shown in Figure 3.5. Then, the machine is run at 180 rev/min. The lower speed is selected as higher speed may effect the deformation rate of the asperities. The surface is being polished using 600 grit sand paper. 600 grit sand paper are used for all material rollers to produce the same surface roughness. The specimen is furthered cleaned with acetone solution to remove dirt.

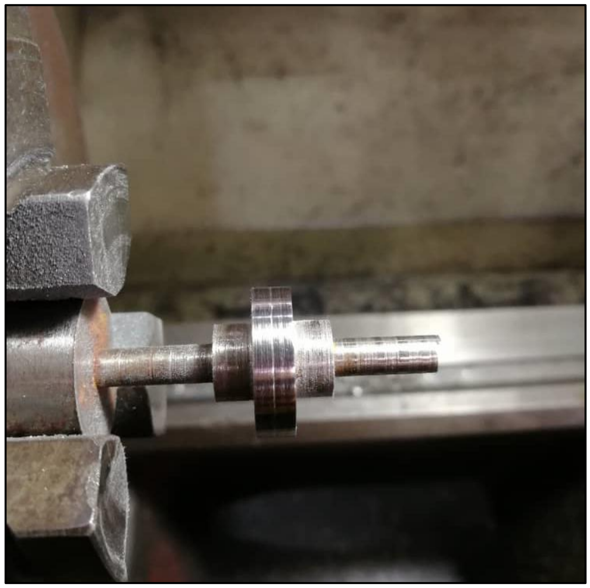


Figure 3.5 The roller is gripped into the chuck of lathe machine

3.5 SURFACE ROUGHNESS AND PROFILE MEASUREMENT

Surface scanning is carried out using Infinite Focus Microscope (IFM) as shown in Figure 3.1. The IFM is able to scan surface topography and to measure surface roughness of the surface. The reference point is the scratch marks made by pen knife at the side of the roller in order to get a fixed datum for each measurement. The specimen is assembled on the test rig and mounted on the IFM table. The reference point is identified from the scanned image to set the start position before rolling stepper motor is switched on. The changes in surface geometry are measured from the datum when the stepper motor is stopped after every complete cycle. The scanning is repeated until the final cycle and the images are saved for further analysis. For the two-dimensional (2D) measurement, a single line of 4.5 mm length is selected as shown in Figure 3.5.

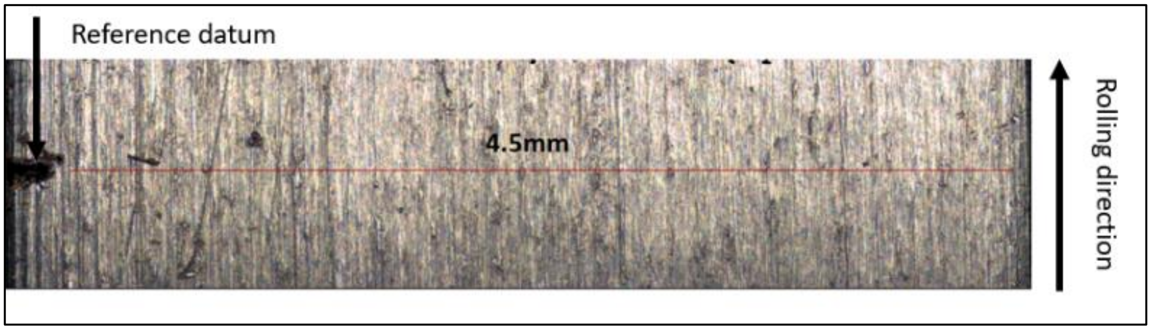


Figure 3.6 Reference datum for line measurement

The roller surface roughness is evaluated using average roughness R_a parameter. It is described as the arithmetic average of the absolute values of the profile height deviations from the mean line, recorded within the evaluation length. Graphically, the average roughness is the area (shown below) between the roughness profile and its center line divided by the evaluation length (normally five sample lengths with each sample length equal to one cut). The average roughness, Ra, is an integral of the absolute value of the roughness profile. It Is the shaded area divided by the evaluation length, L.

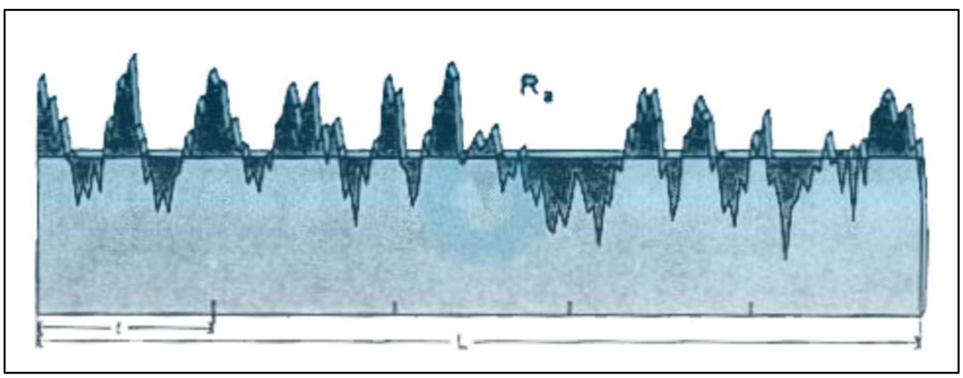


Figure 3.7 Example of surface asperities

The asperities height of the surface roughness profile is evaluated using Bearing Area ratio Curve (BAC) or also known as Abbott-Firestone Curve. The curve is based on a division of the depth scale into three regions (top, or peak region; middle, or core region;

bottom, or valley region). The gradient of BAC curve can be measure to explain the change in the surface asperities profile.

3.6 CONTACT STRESS DETERMINATION

The contact stress that occur during the contact between two rollers made of different material is determined using Hertzian contact pressure equation [30] as shown below:

$$\text{Effective Young's Modulus, } \frac{1}{E^*} = \left(\frac{1-v_1{}^2}{E_1} + \frac{1-v_2{}^2}{E_2}\right) \tag{3.1}$$

$$\text{Effective Radius Of Curvature, } \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \tag{3.2}$$

$$\text{Max Contact Pressure, } P_O = \left(\frac{PE^*}{\pi R}\right)^{0.5} \tag{3.3}$$

$$\text{Shear Stress, } \tau = 0.31\, P_O \tag{3.4}$$

Whole calculation for different material are in Appendix A.

From the equation, it is expressed that the contact pressure is contributed by material properties, there are Young's modulus and Poisson's ratio and also specimen geometry which is the radius of the rolling elements that were in contact. In this work, the roller geometry is similar for all specimens and only different materials were used. Therefore the different contact pressure obtained in all 4 tests are contributed by the material properties.

CHAPTER 4 RESULT AND DISCUSSION

4.1 OVERVIEW

In this chapter, the two dimensional (2D) and three dimensional (3D) images of the tested rollers are presented followed by the resulting contact pressure during the contact. The surface roughness, surface asperities profile and BAC curve of the roller surface are shown.

4.2 SURFACE CHARACTERIZATION

Figure 4.1 show the images of the roller after subjected to rolling contact for 100 cycles. After experiment, roller made from aluminium has most significants scratch lines compared to other materials as seen in Figure 4.1 (a). Brass roller in Figure 4.1 (b) has less significant scratch lines followed by mild steel in Figure 4.1 (c) and stainless steel in Figure 4.1 (d).

The scanned surfaces in two dimensional (2D) and three dimensional (3D) images are shown in Figure 4.2 to 4.5. The images have been captured by using Infinite Focus Miscrospy (IFM) showing the initial condition at 0 cycle and final condition at 100 cycles of the surface texture.

For aluminium roller in Figure 4. 2, it is observed that the original surface texture has been diminished after 100 cycles of rolling contact. The brass roller shows color changes at certain location due to surface polishing during the contact as shown in Figure 4.3. The mild steel and stainless steel did not show much change compared to the new roller where the surface texture pattern seems to be remain the same after 100 cycles.

The surface texture pattern and colour changed after the experiment shows that the peak of the surface asperities were exposed to the contact. This has resulted in surface roughness polishing process and finally reduced the asperities peak height.

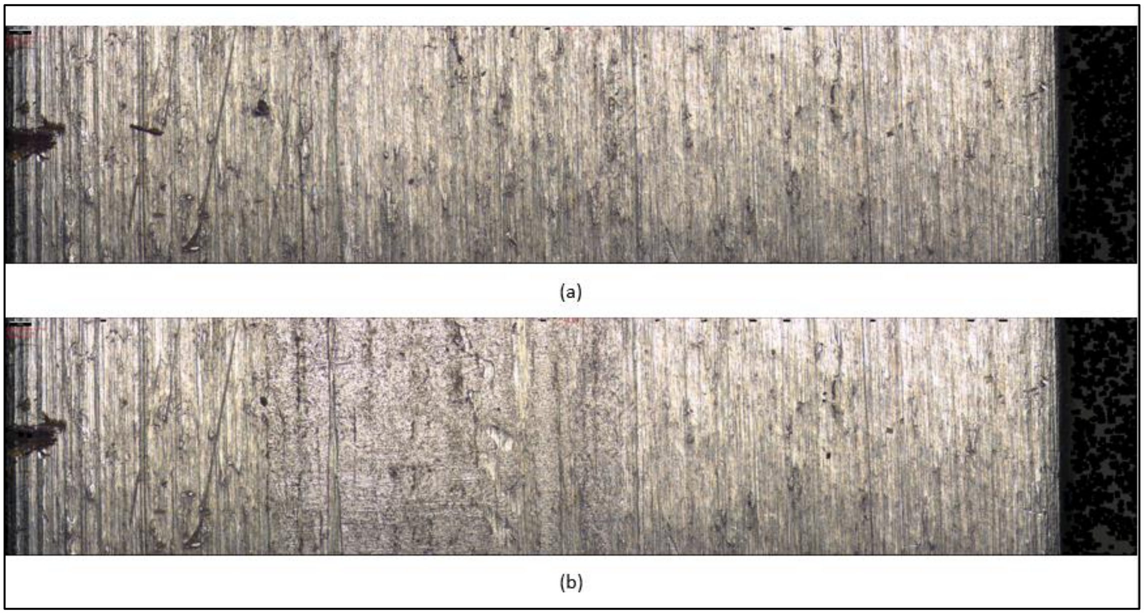
(a)

(b)

(c)

(d)

Figure 4.1 The images of (a) aluminium (b) brass (c) mild steel (d) stainless steel after experiment



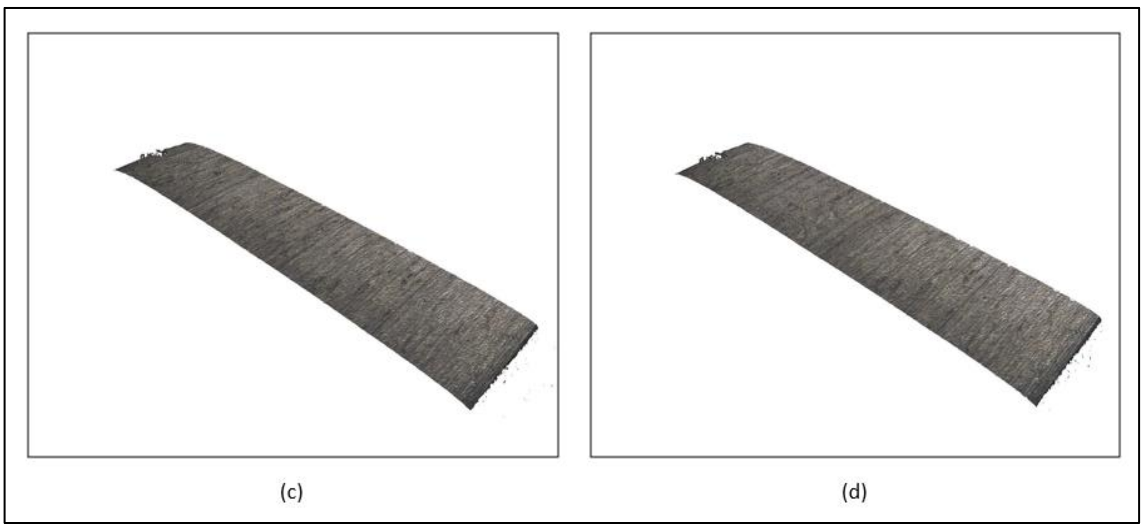


Figure 4.1 2D image of aluminium at (a) initial condition (0 cycle) (b) final condition (100 cycle)and 3D image of aluminium roller at (c) initial condition (d) final condition

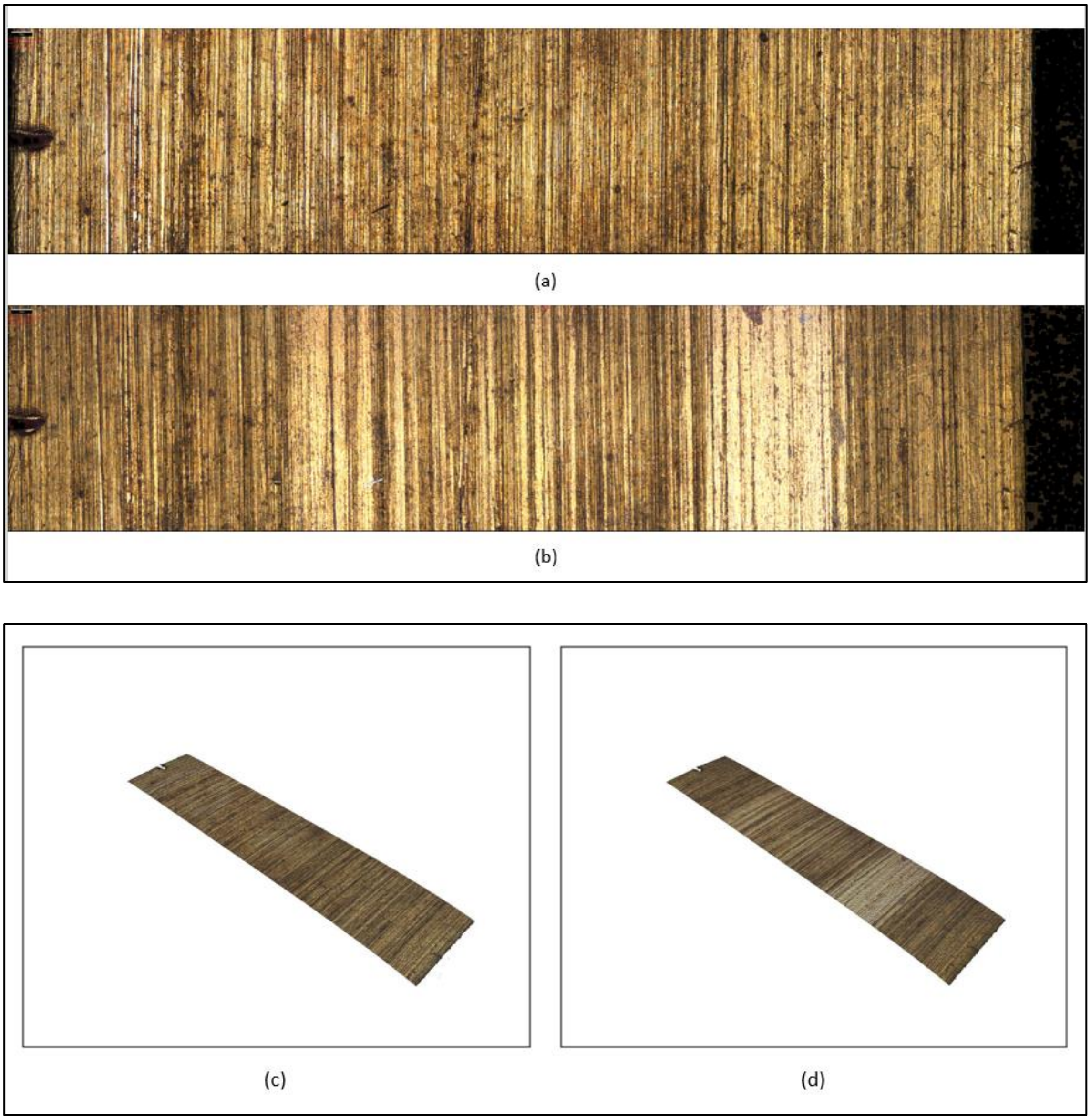
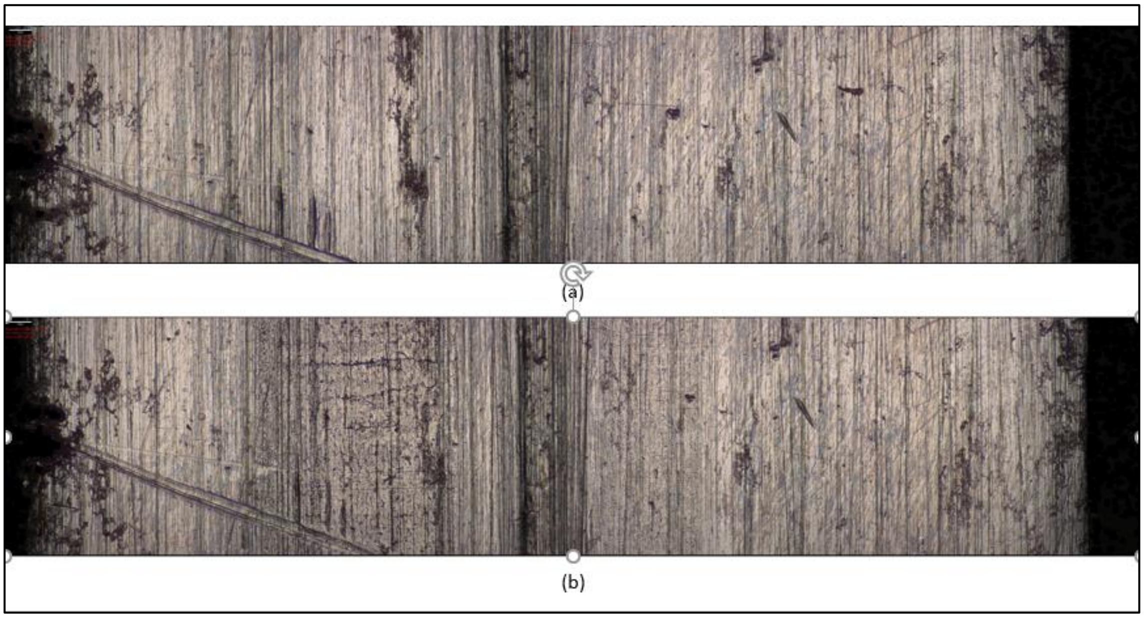


Figure 4.3 2D image of brass at (a) initial condition (0 cycle) (b) final condition (100 cycle) and 3D image of brass roller at (c) initial condition (d) final condition



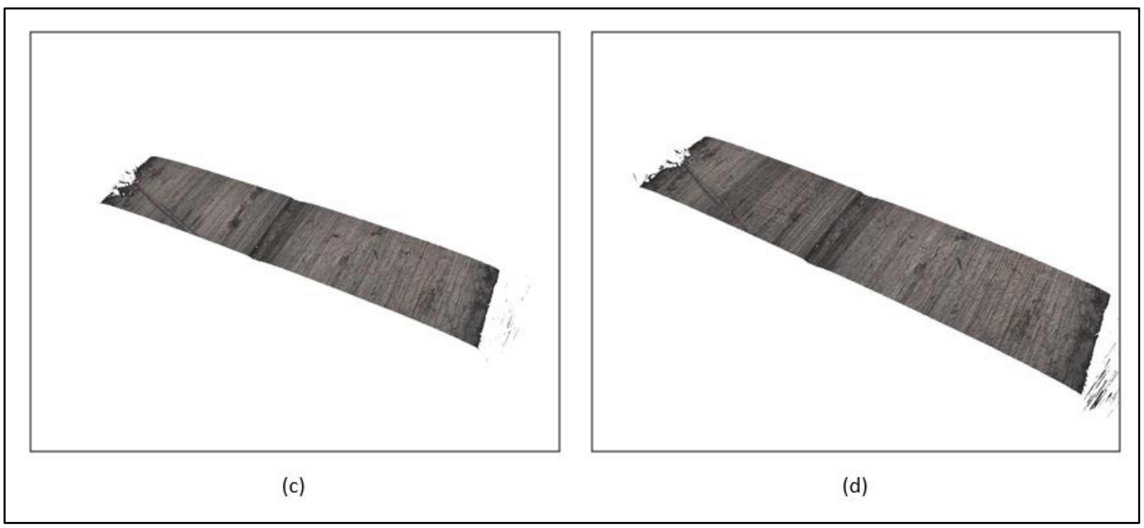


Figure 4.4 2D image of mild steel at (a) initial condition (0 cycle) (b) final condition (100 cycle) and 3D image of mild steel roller at (a) initial condition (b) final condition

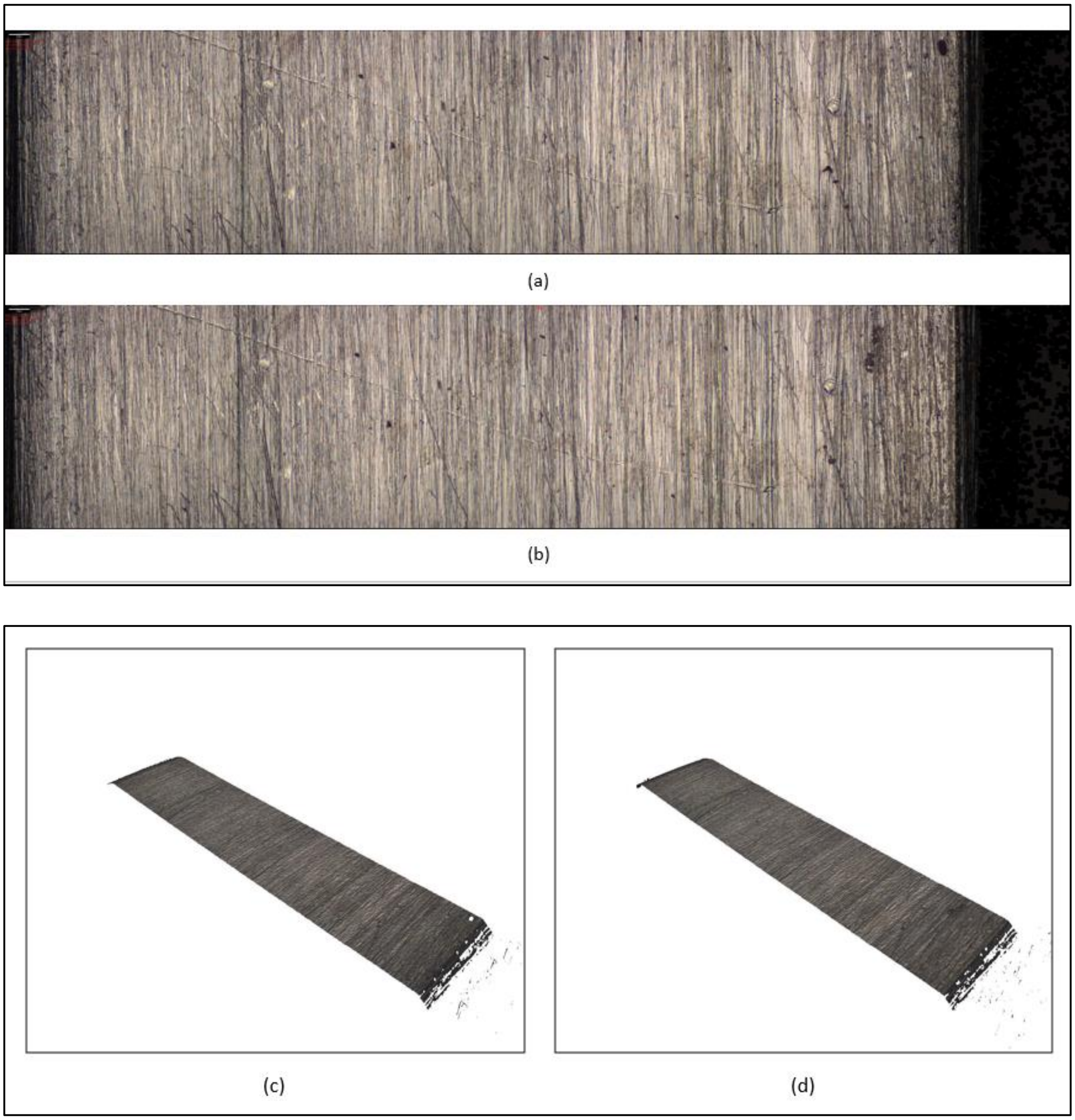


Figure 4.5 2D image of stainless steel at (a) initial condition (0 cycle) (b) final condition (100 cycle) and 3D image of stainless steel roller at (a) initial condition (b) final condition