DRY FRICTIONAL CHARACTERISTIC OF SURFACE TEXTURED ACRYLIC USING PIN-ON-DISC

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Project report submitted in fulfilment of the requirement for the Bachelor of Mechanical Engineering

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DECLARATION

I hereby declare that the effort put into this thesis entitled “Dry frictional characteristic of surface textured acrylic using pin-on-disc” is the result of my own research except for references which have been cited.

Signature : ....

Name : ....

Date : ....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality as a partial fulfillment of Bachelor of Mechanical Engineering.

Signature : ....

Supervisor's Name : ....

Date : ....

DEDICATION

To my beloved mother and father, family members and friends who been with me throughout the journey of this 24 years of amazing life.

ABSTRACT

This project focus on study the different in surface texturing pattern towards tribological performance. Tribological performance means friction, wear and lubrication. The dry frictional characteristic of a surface textured acrylic disc is investigated. By using laser engraving method, several types of texture pattern are produced on testing specimen. These textured specimens are then run on Pin-on-disc machine to find out its friction and wear performance. Only textured pattern is concern in this project, type of material is not in the scope. Calculations of friction coefficient and wear rate is determined through certain formulas. 3D non-contact profilometer is used to obtain the magnified image of wear track and debris entrapment inside the dimple for further analysis. Coefficient of friction and wear rate is the data that is going to be used to compare tribological performance of different surface texturing.

ABSTRAK

Projek ini bertujuan untuk mengetahui prestasi tribologi untuk permukaan yang ditekstur. Prestasi tribologi termasuklah geseran, kadar kehausan, dan pelinciran. Acrylic akan digunnakan sebagai bahan kajian dan menggunakan laser untuk menghasilkan bentuk tekstur yang berlainan. Bahan kajian akan diuji pada keadaan yang tidak dilincirkan. Mesin Pin-on-disc akan digunakan untuk mengaji geseran and kadar kehausan. Pengiraan untuk pekali geseran dan kadar kehausan adalah menggunakan rumus. Mesin 3D non-contact profilometer digunakan untuk mengambil gambar diperbesar untuk analisa yang lebih teliti. Pekali geseran dan kadar kehausan adalah data yang akan digunapakai untuk membandingkan prestasi tribologi untuk setiap spesimen.

ACKNOWLEDGEMENTS

First, I would like to take this opportunity to express my gratitude to my supervisor, Mr Mohd Rody bin Mohamad Zin from Faculty of Mechanical Engineering Universiti Teknikal Malaysia Melaka (UTeM) for his patience supervision, advice and support towards the completion of this thesis.

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Thanks also to Faculty of Mechanical Engineering of Universiti Teknikal Malaysia Melaka in funding me the cost for this project. Specials thanks to all the laboratory staff and technician who help me during my effort in completing this experiment.

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LIST OF ABBREVATIONS AND SYMBOLS

N	-	Newton
g	-	Gramm
m	-	meter
µm	-	Micro meter
R_a	-	Roughness average
RPM	-	Revolution per minute
m/s	-	Meter per second
L	-	distance travelled
R	-	wear track radius
t	-	time
k	-	specific wear rate
V_L	-	volume loss
F	-	load
F_L	-	applied load
F_f	-	friction force
COF	-	Coefficient of friction
LST	-	Laser surface texturing
PKAC-E	-	Palm kernel activated carbon-epoxy
Fs	-	Femtosecond

ns	-	Nanosecond
SEM	-	Scanning electron microscope
SIMPS	-	Snake inspired microstructured surface
UHMWPE	-	Ultra-high-molecular-weight polyethylene
PMM	-	Poly(methyl methacrylate)

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CHAPTER 1

INTRODUCTION

1.1 Background

Tribology is defined as the study of friction, wear and lubrication of two interaction surface that is undergoing relative motion. Whenever two surfaces are sliding against each other, there will be some forces that resist the motion. That force is known is friction force. Coefficient of friction is the parameter that used to measure the degree of friction. Nearly every applications, motion, or movement happens in our daily life deals with friction. For example, we can hold onto something using our hand is because of the textured palm surface. The texture on our hand creates an interlocking phenomenon between our palm and the object. This will prevent the object from slipping away from our hand. If we are born with smooth palm, we will unable to hold any object using our hand. Some of application requires even greater friction such as racing cars. The racing cars tires requires a lot of traction to allow sufficient power transmission to move the car on road. So, the design of tires must have high friction with the road but not too high that it will negatively affect the car performance on road. However, there are also some cases where low friction is desired. In car engine, piston moves reciprocatively. The high moving speed of piston requires low friction contact with the cylinder wall for highest possible efficiency.

There are few ways to reduce friction effect, lubrication, using low shear material or smoothen the contact surface. Each of this method has its own pros and cons. Lubrication is very effective in reducing friction however the lube might trap dirty particle and thus reducing its effectiveness. Lube might also need to often be replaced, the cost and sustainability is also a concern. Material choice mainly depends on the molecular structure and operating condition required. There are some previous research which validate the effect of surface texture on reducing friction effect (Mat Tahir, Abdollah, Hasan, & Amiruddin, 2016; Navale, Aher, Nagare, Bajaj, & Wakchaure, 2016; Wos, Koszela, & Pawlus, 2017).

1.2 Problem Statement

Various studies had been done regarding the effect of surface texture on friction effect. Study by (Mishra & Polycarpou, 2011) shown that surface textured improves tribology effect. Since the dimples on contacting surface act as a lubrication reservoir and the texture reduce the total contacting surface. However not every dimple size or texture pattern is ideal for reducing friction. Besides, the theory of surface texture act as lubricant reservoir and debris entrapment is validated. What if lubrication is not available in surface textured condition. Thus, testing must be performed to identify how different surface texture will affect the friction and wear rate. Application of textured surface to reduce friction can be widely used if the operating condition and working rate is identified.

1.3 Objectives

The objectives of the project are as follows:

i. To study the effect of surface textures on dry friction and wear of acrylic disc

ii. To propose the optimum characteristic of acrylic disc surface textured for dry friction and wear condition

1.4 Scope of project

The scopes of the project are:

i. The project only focusses on the effect of surface texture towards testing performance

ii. Testing will only seek for two results, coefficient of friction and wear rate

iii. No lubrication will be used to achieve dry frictional condition

1.5 General Methodology

i. Literature review

Journals and articles or any suitable material that are related will be reviewed. This is for finding the gaps between previous researches. Based on the gaps, the objectives of this study are identified.

ii. Sample preparation

In this study, the sample is prepared by using laser engraving machine. The sample is acrylic disc which is engraved according to proposed design.

iii. Testing and analysis

The testing is performed by using Pin-on-disc machine. The results will be coefficient of friction and wear rate of the disc. To investigate the characteristic of friction and wear of the disc, the optical images of wear track will be analyzed. The images are obtained by using 3D non-contact profilometer.

iv. Report writing

Testing results will be written into a complete report.

The methodology of this study is summarized in the flow chart as shown in below.

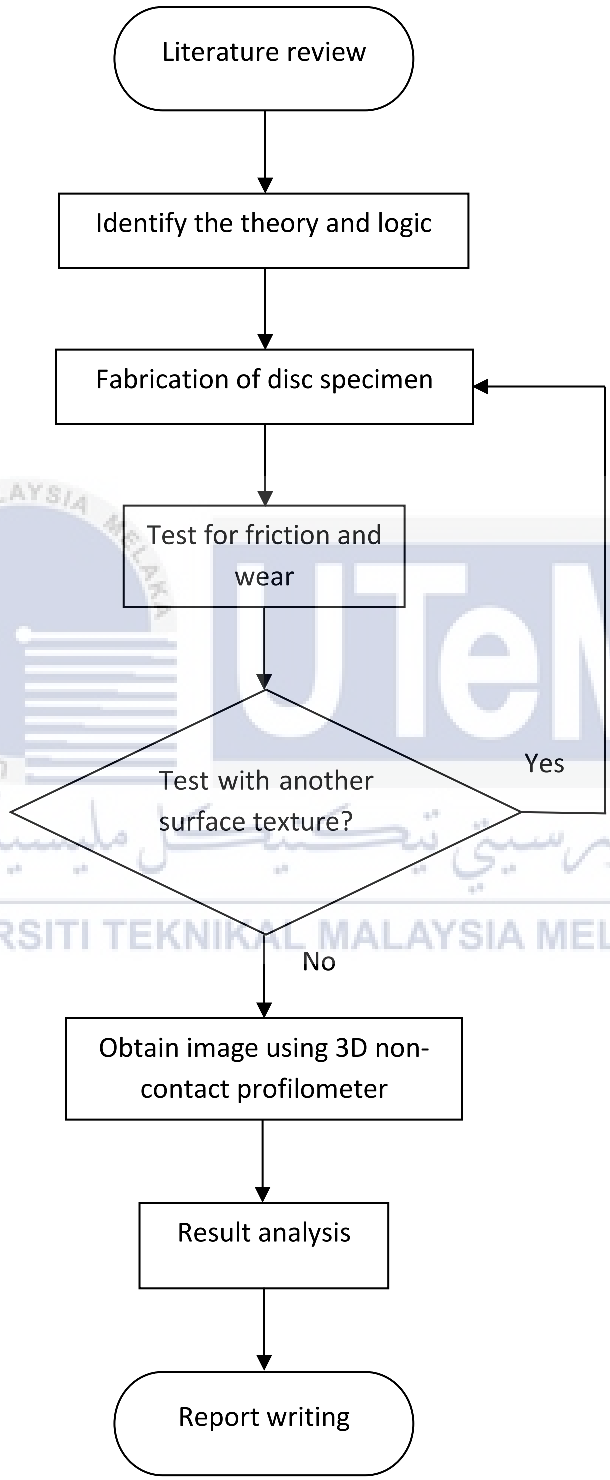


Figure 1.1: Flow chart of the methodology

Chapter 2

Literature Review

2.1 Tribology

The term tribology refers to the study of friction, wear and lubrication of two contacting surface that are moving relative to each other. The main parameters in tribology study is coefficient of friction COF, wear rate and lubrication (boundary lubrication, mixed lubrication and full film lubrication). According to (Gachot, Rosenkranz, Hsu, & Costa, 2017) during the Tong Dynasty in China, the people carve patterns on their shoe to allow them walking on slippery surface. As human technology evolves, vehicles wheels are also textured for better traction performance on road. Both of this cases are related to tribological properties of contacting surface. (Hirano, 1995) said that the stimulus to research in tribology started from the needs to reduce material and saving of energy. A lot of machines or mechanism requires low friction to operate ideally such as engine piston and gear mechanism. High friction and high wear rate will not only reduce the efficiency but also reduce lifespan of the parts. Author also mentioned that tribological studies is now a main consideration and aspect in engineering design. Most often the effect of tribology defect is shown after the design process is completed. Only if we acquire sufficient knowledge about tribology studies then we can implement the design before product completion. It means that when we design a certain product we take consideration of the tribological properties into it during the design process.

2.2 Surface texturing

Surface texturing is a way to change the topography of a surface. It can be used to create pattern or microstructure on a surface. There are a lot of method to perform surface texturing. Commonly known methods include laser surface texturing LST, maskless electrochemical texturing, abrasive jet machining and reactive ion-etching. Each of the method have its own pros and cons, it comes to the user to decide which type of texturing method they want to use. Surface texturing also can be categorize into few types, material adding, material removal, material moving, self forming(Costa & Hutchings, 2015). The technology for surface texturing improves rapidly. People are looking at how to increase the texturing speed, the accuracy, the feature size, operating cost. The demand for good quality, low cost and rapid surface texturing technology lead to the fast development in equipment today.

Currently surface texturing is one of the option to improve tribology properties. This includes wear resistance, loading capacity, friction coefficient and lubrication. The basic concept of texturing to improve tribology properties is by creating micro structure on a certain surface. This micro structure will act as entrapment for debris, reservoir for lubricant and reducing the total contact surface.

According to (Costa & Hutchings, 2015), maskless electrochemical texturing is the cheapest but the minimum feature size is very large. It can only used on material with good electrical conductivity. In contrast, ink jet printing followed by etching is better in producing smaller features with good resolution. The setback is the lengthy processing time. Laser texturing is considered to best available method currently. This method is capable of handling wide range of material and feature size is a lot encouraging compared to others. Notable issue with laser texturing is the rims produce around the pockets. The rims can be removed with certain method, either is by manual polishing, chemical polishing or laser polishing depends on requirement.

2.3 Surface texture and tribology

As today, numerous studies about how surface texture can improve tribological properties is performed such as to reduce coefficient of friction and wear rate. Research from (Mishra & Polycarpou, 2011) indicates that the surface texture on two contacting surface greatly improves the wear and friction. The objective of their study is to figure out tribological performance of surface textured pattern under operating condition imitating the actual condition of air conditioning and refrigerator compressor. The disc and pin is made from gray cast iron. Each of the pin is surface textured with laser. It is then tested using pin-on-disk tribometer. They are using a custom designed tribometer with a pressurized chamber to simulate the working condition of a compressor. A load of 178N is used since the actual working condition of a compressor is under extreme and aggressive motion. A drop of lubricant (22mg of Polyalkylene Glycol) is used on every specimen testing. Lubricant was added to create the operating condition of starved lubrication.

Below is the specification of each specimen. Pattern A1 and A2 having the same diameter and depth, the only different is the area density. Subsequent patterns for B1 and B2, C1 and C2 follow the same trend.

Table 2.1: Specification of each texture patterns

Pattern designation	Diameter d (µm)	Depth h (µm)	Diameter to depth ratio (d/h)	Area density (%)	Bulge height h_o (µm)	Ratio of bulge height (h_o) over roughness (R_a)
A1	40	10	4	5	9	32.1
B1	60	7.5	8	5	6	21.4
C1	60	4	15	5	4	14.3
A2	40	10	4	20	9	32.1
B2	60	7.5	8	20	6	21.4
C2	60	4	15	20	4	14.3

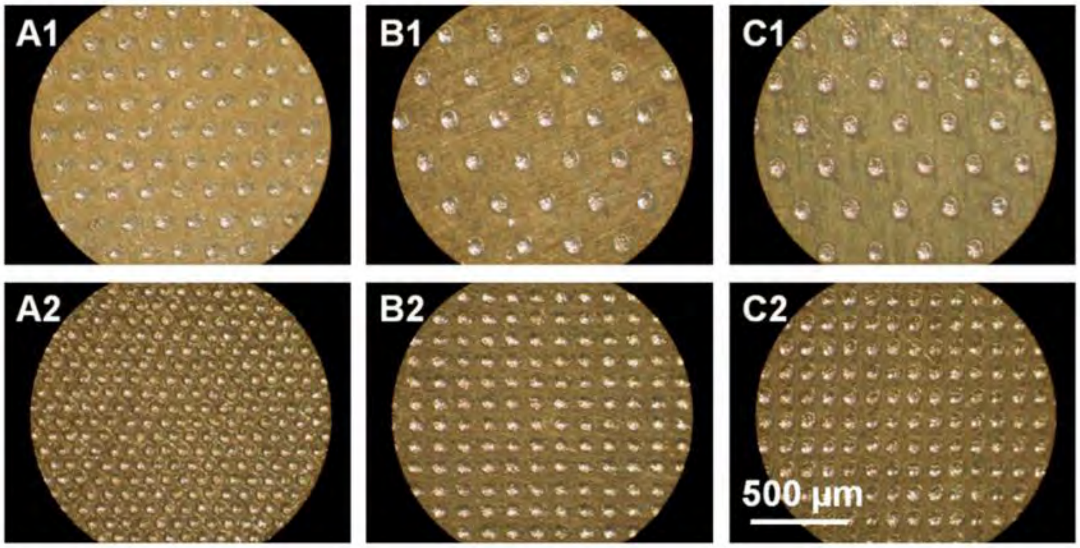


Figure 2.1: Optical images of the unpolished surface texture patterns

From the optical image above, we can notice the different of each specimen. The main variation that we can identify is the dimple diameter and the area density.

There are two testing condition set up for the experiment. The first one is wear test and the second is durability test. Different between two experiments is the duration of testing. Wear experiment (Set I) only run for 1 hour for each specimen. While durability test (Set II) is run for 3 hours. The author first tested all the specimen under condition of Set 1. The graph below illustrates the result of the testing. The result is the average COF value obtained over the final 20 minutes of the testing. Note that the testing is one hour long for each specimen.

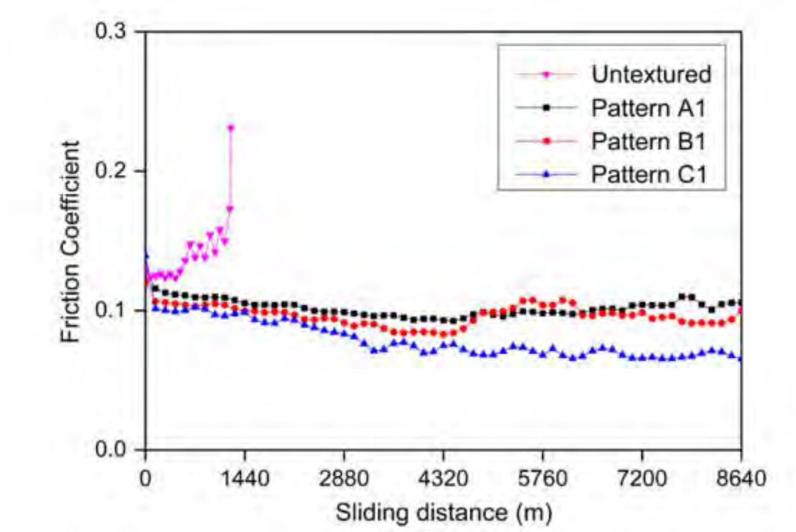


Figure 2.2: Friction coefficient of untextured pattern A1, B1 and C1 under wear test

Above graph shows the variation of friction coefficient of untextured, A1, B1 and C1 under wear test. We can observe that the friction coefficient of untextured pattern raises abruptly when it reaches 1400m of sliding distance. Pattern A1 and B1 friction coefficient is quite same at the end of the testing. Pattern C1 is the best among the 4 patterns where it reaches a lowest friction coefficient value. Similar testing condition is also used on another set of specimens. Below is the result of all the specimen tested under wear experiment.

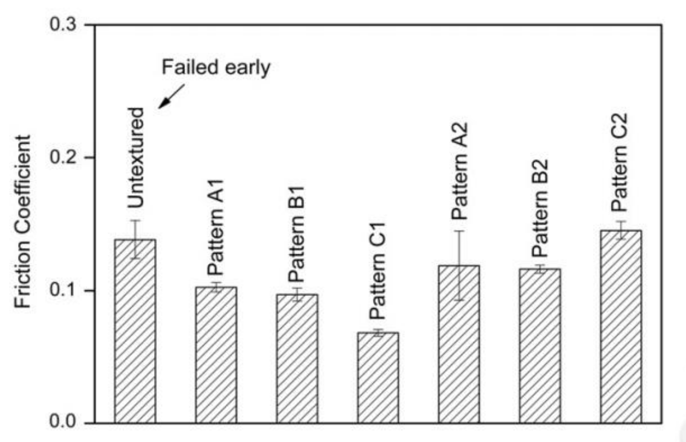


Figure 2.3: Comparison of friction coefficient for all specimen tested under condition Set 1

Their results show that area density of 5% is the best for reducing the friction coefficient. The lowest friction coefficient obtained is pattern C1 where the specification of the specimen is dimple diameter 60μm, depth 4μm, area density 5%. Pattern A2, B2 and C2 have higher friction coefficient compared to Set 1. Author explains that this is due to the higher area density of dimple. Meaning that there are more dimples per area for Set 2. As result there will be more debris produced when sliding. The debris will act as third-party abrasives which increase the friction.

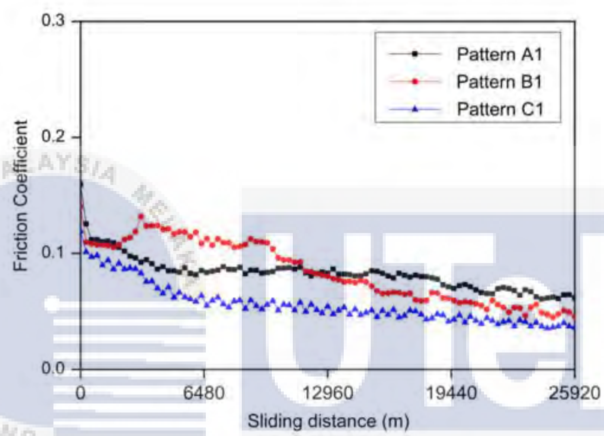


Figure 2.4: Friction coefficient of texture pattern A1, B1 and C1 under durability test

The graph above illustrates the result of durability test. From observation we can notice that the final friction coefficient is lower compare to the result in wear experiment. Researcher conclude that this phenomenon is because stable sliding interface is established after 60min. Note that durability experiment is conducted for 3 hours. It can be concluded that the surface texture is effective is reducing friction. The best result is obtained when suitable dimple size is used on the area density is within optimal range. In this experiment, the best texture pattern is C1.

A relatively similar but less complicated research from (Mat Tahir et al., 2016) shows that surface finishing with suitable dimple size can reduce the wear and COF of interacting surface.

The aim of their study is to investigate how dimple size will affect tribological properties of laser surface textured palm kernel-activated carbon-epoxy (PKAC-E) composite.

By using laser surface texturing method, a few samples of specimen are textured with various dimple sizes. A total of 5 disc were textured with different dimple sizes. A non-textured disc, 500µm, 800µm, 1000µm and 1200µm. All these sample having the same area density depth and contact ratio which is 19%, 1000µm and 0.21. These specimens are then tested using ball on disc tribometer.

Compared to the previous study where the load is 178N, this experiment only uses a load of 20N. The testing speed is set at 20RPM. Coefficient of friction and wear rate is obtained through the experiment. The result of their study shows that dimple diameter of 800µm to 1000µm will significantly reduce the coefficient of friction and wear rate under boundary lubricated condition. Below is the table which shows the result of their findings.

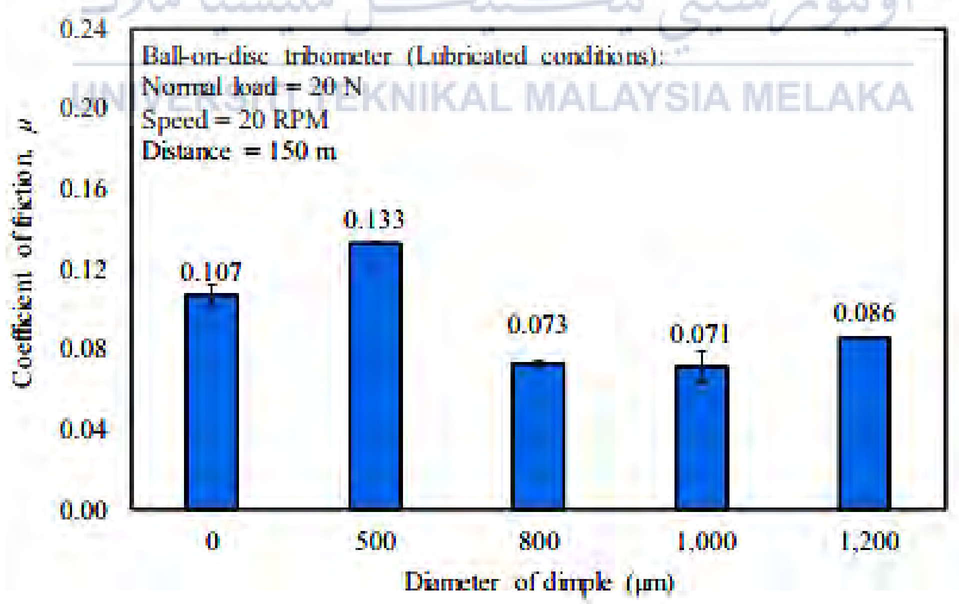


Figure 2.5: Coefficient of friction for different dimple sizes

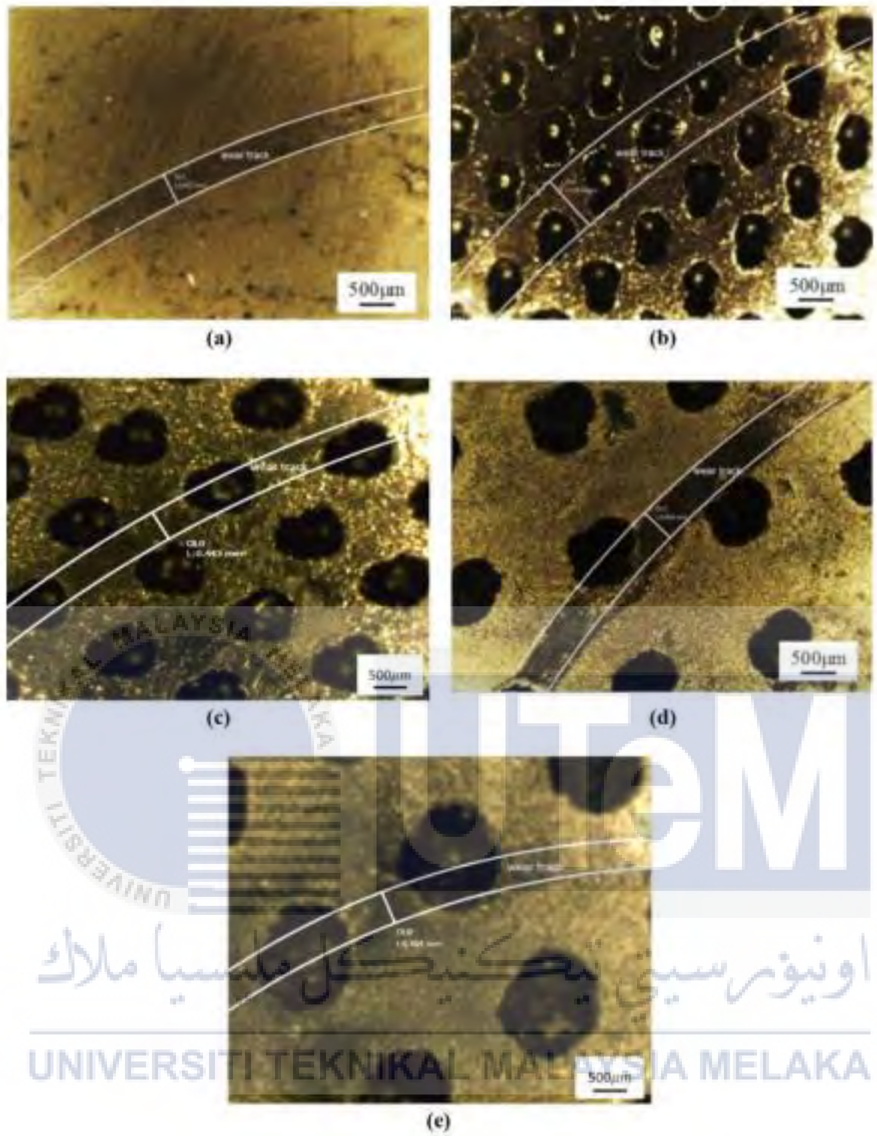


Figure 2.6: Magnified images of the wear track

Researcher evaluate the wear performance of each specimen by measuring the wear track. As show in figure above. The measurement result indicates each of the wear track for every disc.

Table 2.2: wear track size of every dimple size

Dimple size, µm	Wear track, µm
Non-textured	467
500	800
800	443
1000	434
1200	464

The result of friction and wear are comparable. As we can see the dimple size of 800 to 1000µm exhibited the best experimental result. The author suggested that overlarge dimple sizes will increase the surface roughness of the disc and thus increasing the coefficient of friction. However, if the dimple size is within optimal range, it will greatly reduce the friction and improve wear performance. Their experiment proved that the dimple can act as lubricant storage which is good in reducing friction. (Mohmad, Abdollah, Tamaldin, Amiruddin, & Jaharah, 2016) research also support the findings of optimal dimple size to reduce wear and friction coefficient with a quite similar experiment.

Another experiment by (Wos, Koszela, & Pawlus, 2015). Using 42CrMo4 as specimen material, surface texturing is done by abrasive jet machining method. 3 specimens are prepared for testing. Using load of 20N and one drop of L-AN 46 for lubrication. Note that no further lubrication is added during the testing.

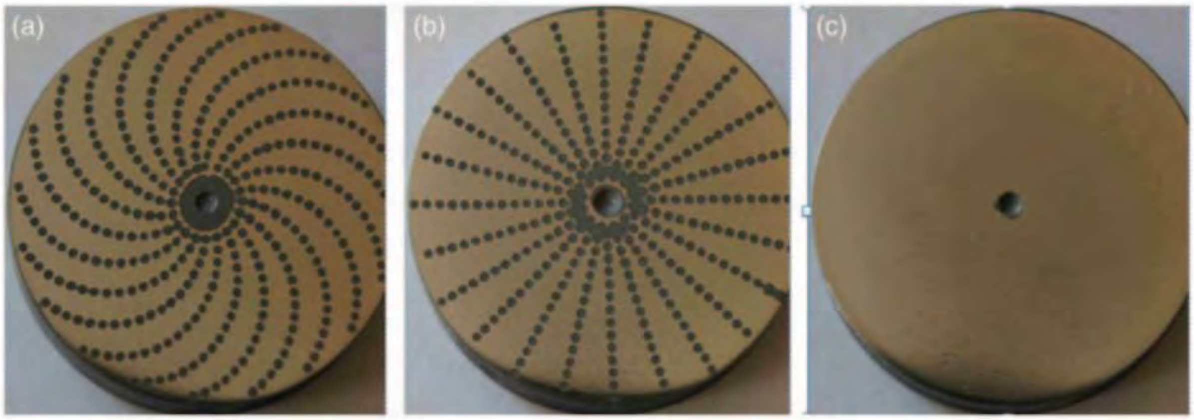


Figure 2.7: Photo of texture disc a) type 1, b) type 2, c) untextured

For type 1 the dimple is in spiral form. There are total of 20 dimples around the disc circumference. Each of them is equally space and the angle between each row is 18°. For type 2 the radial row is 15° between each other. Both type of texture is having the same dimple diameter of 0.5mm and depth of 10µm. The depth over diameter ratio is 0.02. Unlike the previous studies, this author tested their specimen under different sliding speed. The rotational speed ranged from 100 to 1000 rpm or 0.1 to 1.04 m/s. The increase of speed in a stepwise manner where every 60 seconds the speed is increase by 100 rpm.

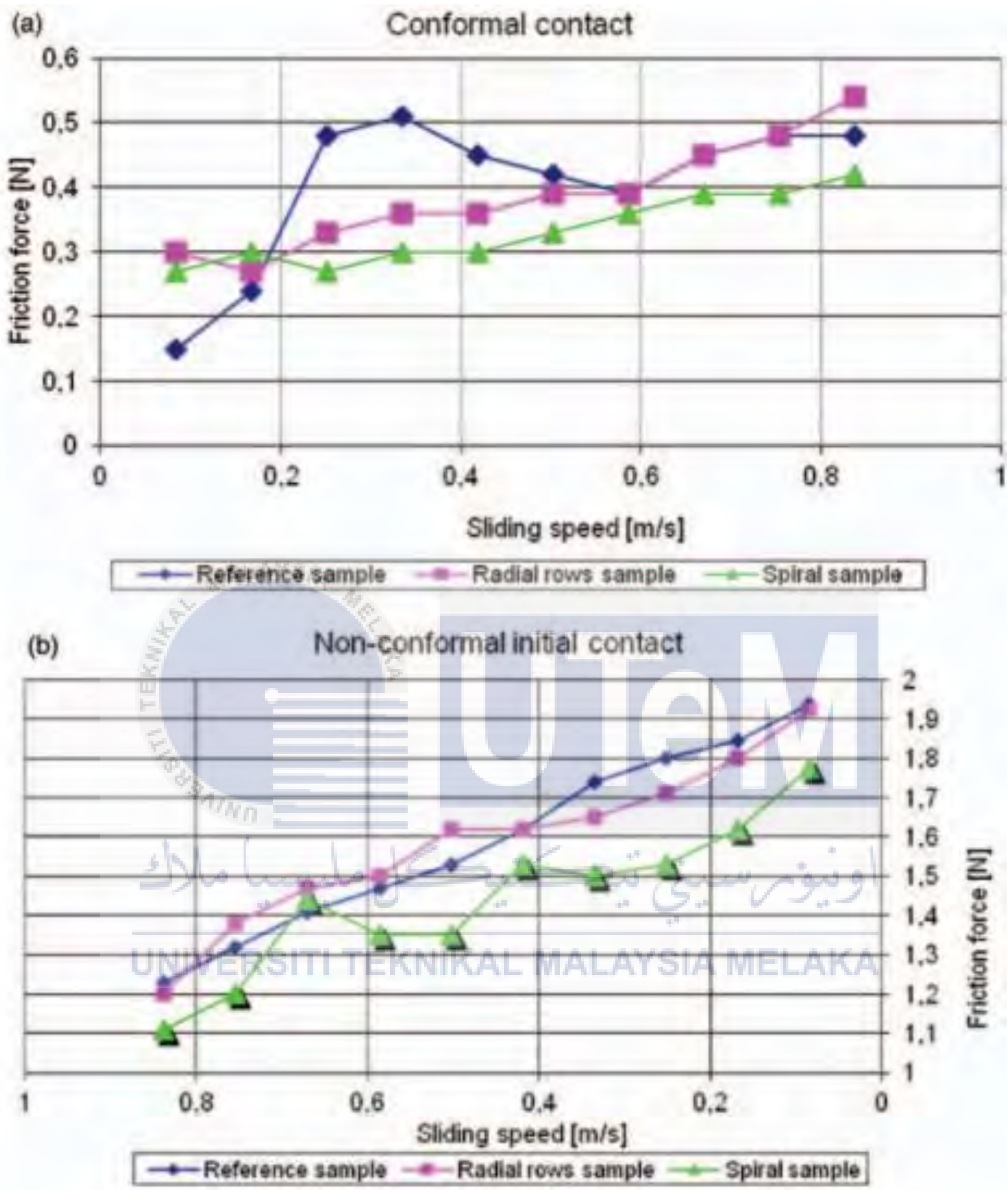


Figure 2.8: Variation of friction force with sliding for 3 surface types

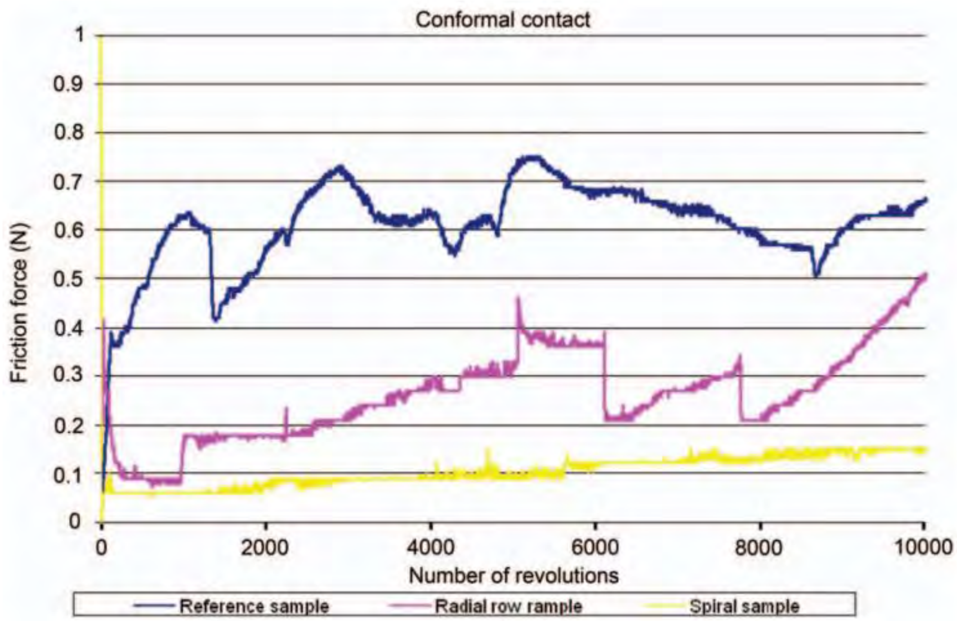


Figure 2.9: Friction force variation with number of revolution under sliding speed of 0.4 m/s

The graph above can validate the effect of surface texturing in reducing friction force. The reference sample (untextured) is having much higher friction force throughout the experiment. While both sample with surface textured have lower friction force. From the result obtained, it can be concluded that texture with spiral shape have the lowest friction force when tested. Later that (Wos, Koszela, & Pawlus, 2016) found that high dimple density will results in lower friction coefficient, lesser demand for lubrication and tiny fluctuation of force. For sample with lower dimple density the overall performance is better than untextured surface. Author also mentioned that spiral dimple is better than radial dimple.

In another study, the researchers (Bhaduri et al., 2017) found out that micropores on surface can act as entrapment for debris. In their experiment, dimple of diameter 40 μm and depth of 15 μm is laser textured on specimen. Two types of pattern are used, dimples and grooves. Pattern a) is dimple produce by ns laser and c) is dimple produced by fs laser. Meanwhile groove b) is ns laser groove and d) is fs laser groove.

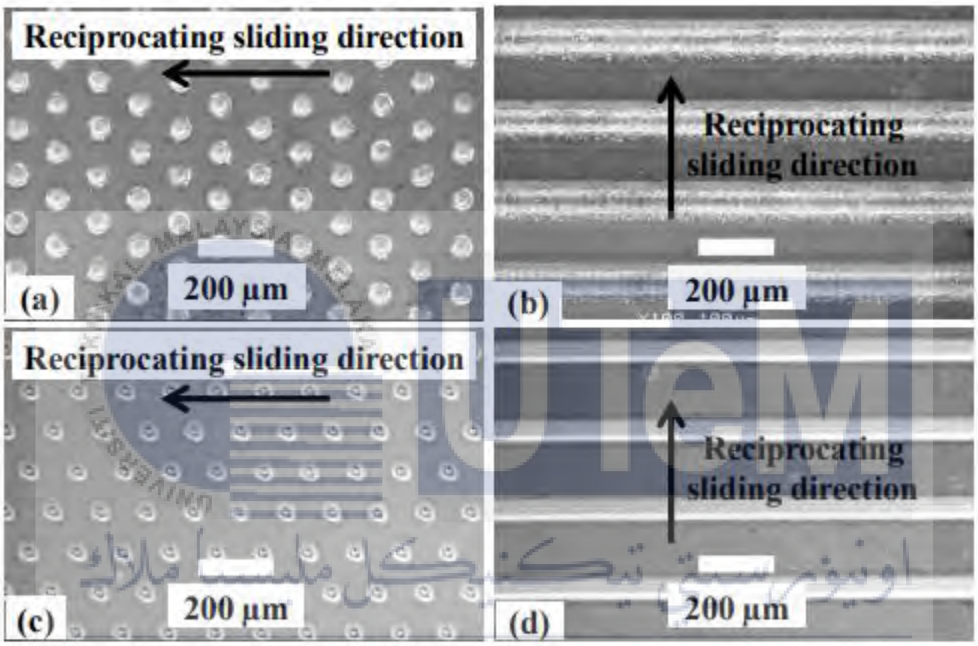


Figure 2.10: Different pattern of texturing and the sliding direction

By using ball on disc tester with load of 20N, speed of 10 mm/s and run for 1000 cycles. The testing is done under dry friction condition where no lubrication is added at all. The variation of friction and wear is recorded throughout the experiment.

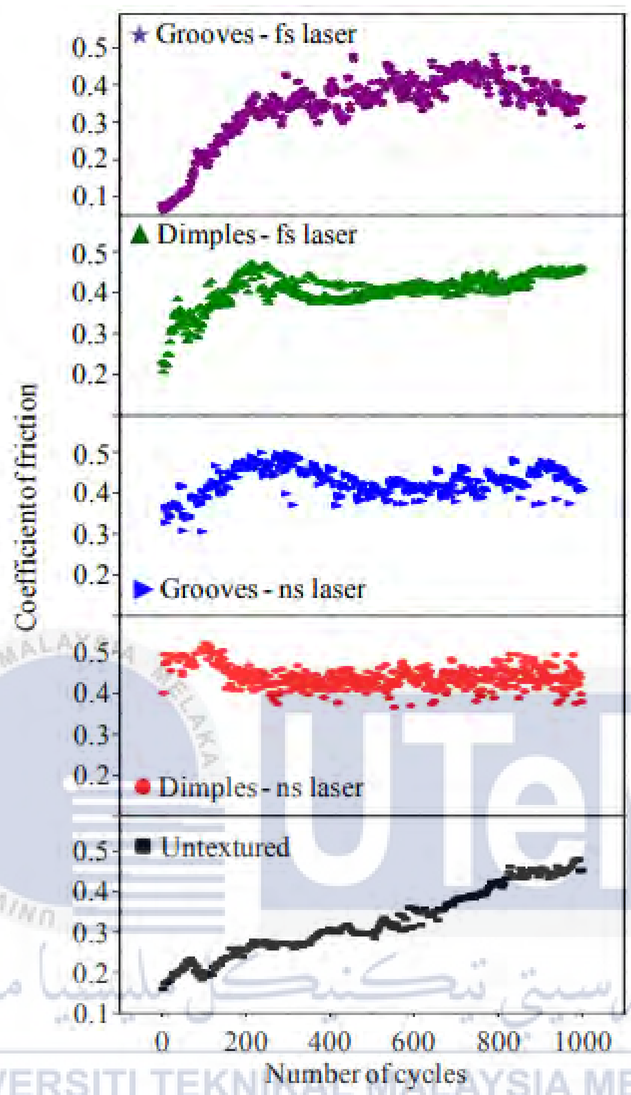


Figure 2.11: Coefficient of friction vs number of cycles for all texture pattern

From the graphs we can notice that untextured pattern exhibit low fiction coefficient when test started, as the testing progress the coefficient of friction increases until it reaches the value of 0.5. Compared to untextured surface, those with laser textured reaches a steady value after 200 cycles. From the result obtained, the average value of friction coefficient range between 0.35 to 0.45.

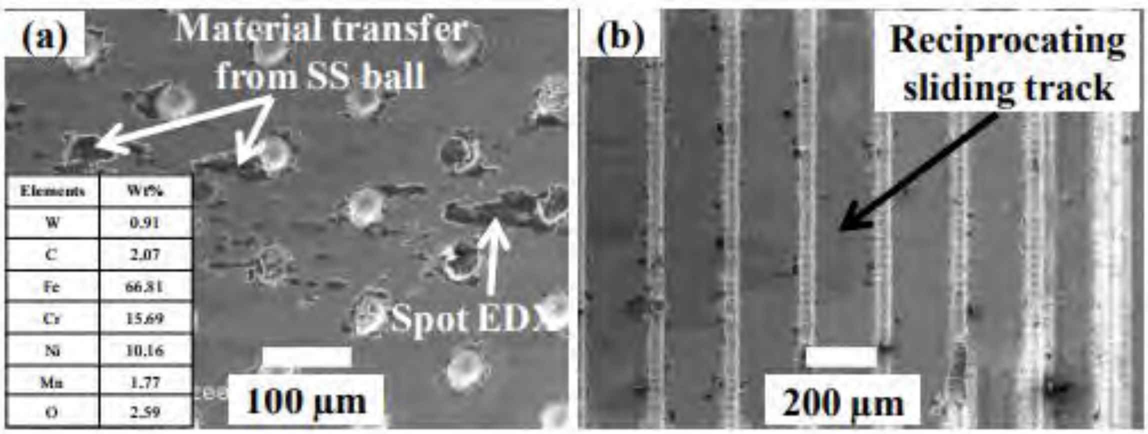


Figure 2.12: SEM images of a) dimples b) grooves

From magnified images obtained from SEM, author validate that surface texture provides storage for wear debris. In image a) material from counter surface localized into the dimples. Author also mention that from observing the SEM images, the grooves also partially filled with steel.

Meanwhile in the research published by (Jones & Schmid, 2016). The author suggest that laser texturing is a recommended method to reduce friction in lubricated area particularly in boundary and mixed lubrication regime. In their experiment, the dimples size used is 80-100 µm and 6-10 µm deep. The objective of their study focuses on performance of rim free surface. Therefore, all the specimens are polished to remove the rims.

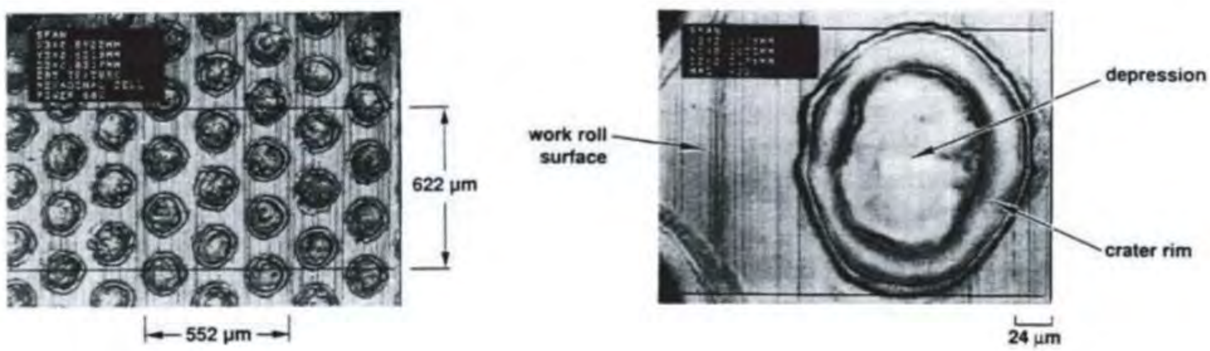


Figure 2.13: Laser texture pattern

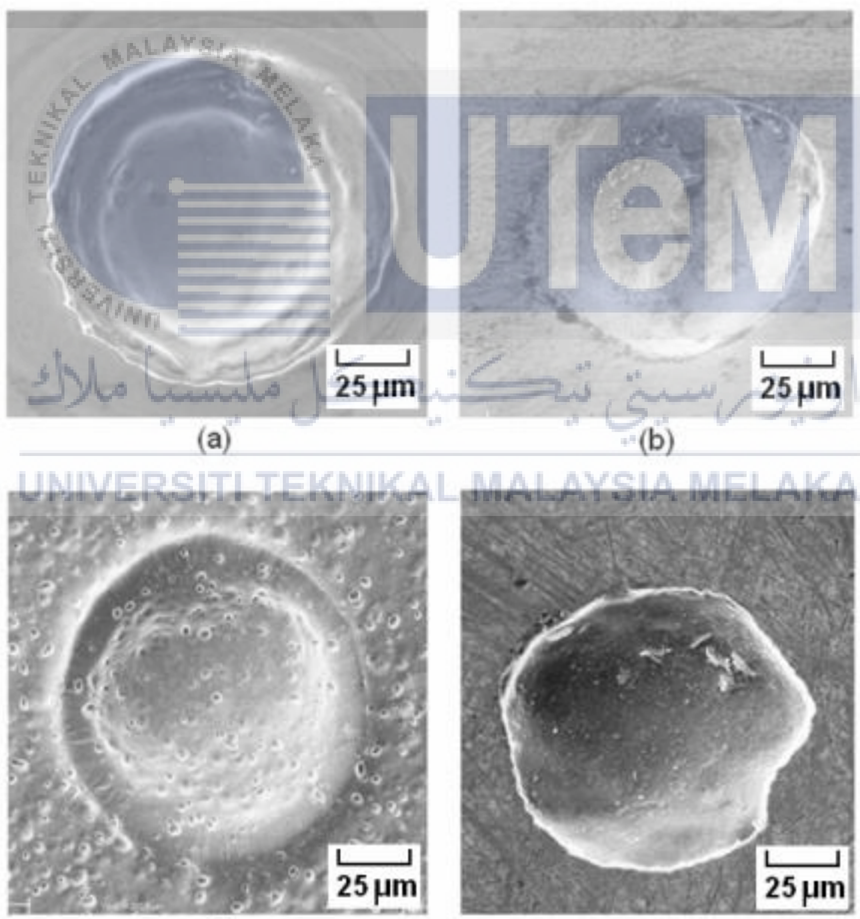


Figure 2.14: Rim removal. a) Dimple before rim removal; b) rim removal via polishing; c) rim removal via chemical etching/ultrasonic cleaning; d) rim removal via isotropic super finishing

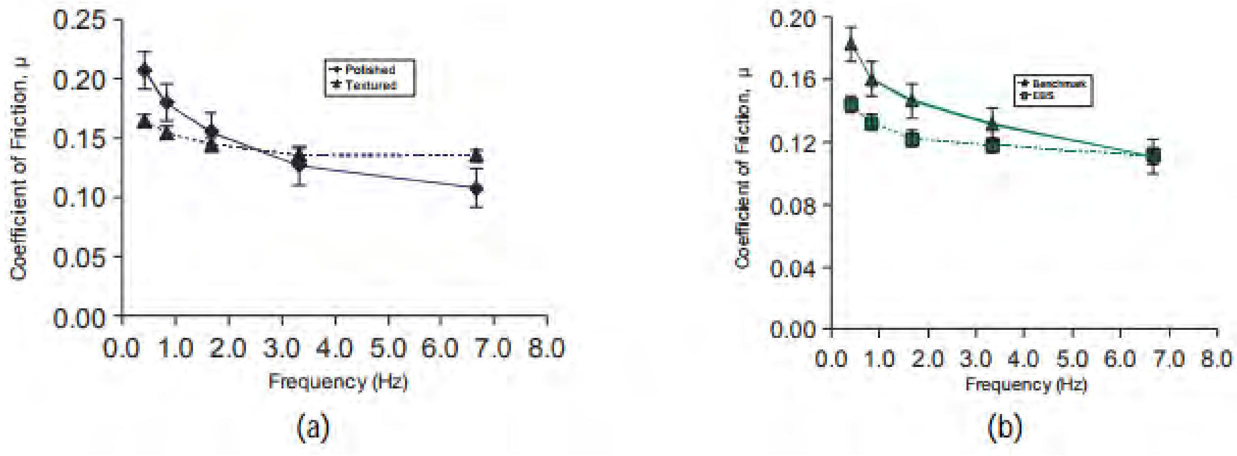


Figure 2.15: Coefficient of friction as a function of reciprocating frequency using low viscosity lubricant (Norpar-18). a) Normal load of 90 N; b) normal load of 130 N

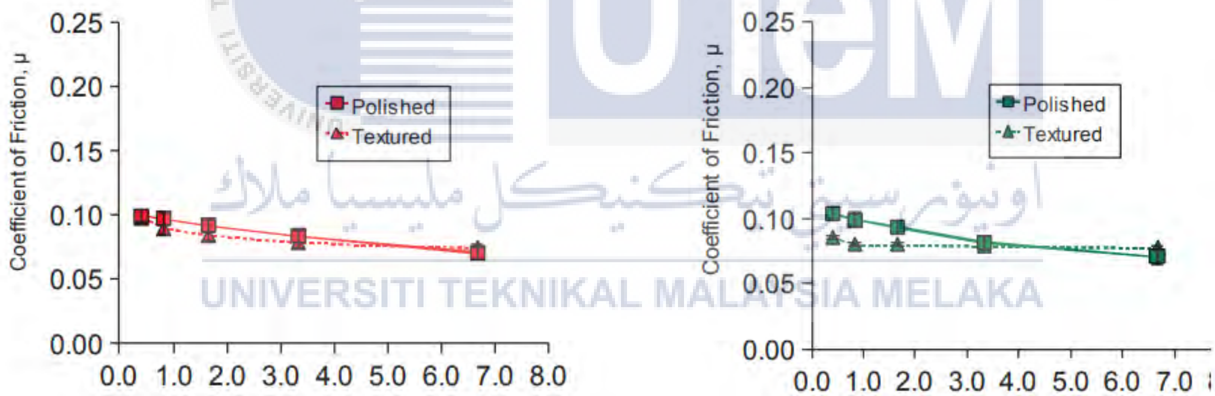


Figure 2.16: Coefficient of friction as a function of reciprocating frequency using high viscosity lubricant (Krytox). a) Normal load of 90 N; b) normal load of 130 N

Another group of researcher (Xing, Deng, Wu, & Wu, 2017) studied the friction and wear properties of laser textured ceramic under dry friction. However, their results showed that laser surface texturing will increase the friction force and wear resistance. The reason given is that surface texturing will increase the surface roughness, reduce the real contact area and introducing micro cutting effect by the texture edges. The main different with other experiment is that the texture pattern used in this study is grooves, not dimples.

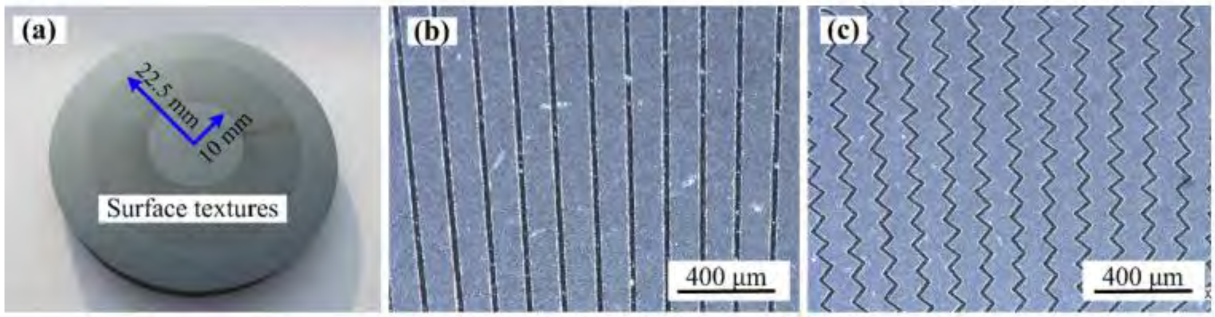


Figure 2.17: Photo of sample and texture pattern a) textured ceramic disc, b) linear grooves, c) wavy grooves

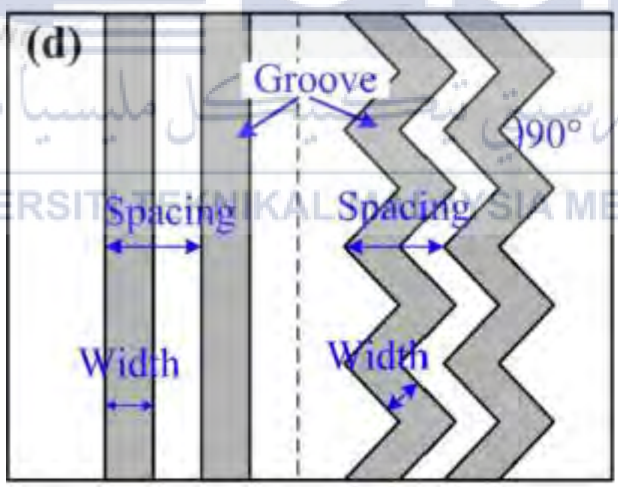


Figure 2.18: Schematic diagram of the texture

The depth and width of the grooves is about 40-50 µm. The authors conduct the experiment to identify the friction force under different texture pattern and spacing. The load applied is constant 15N and sliding speed of 1.33 m/s.

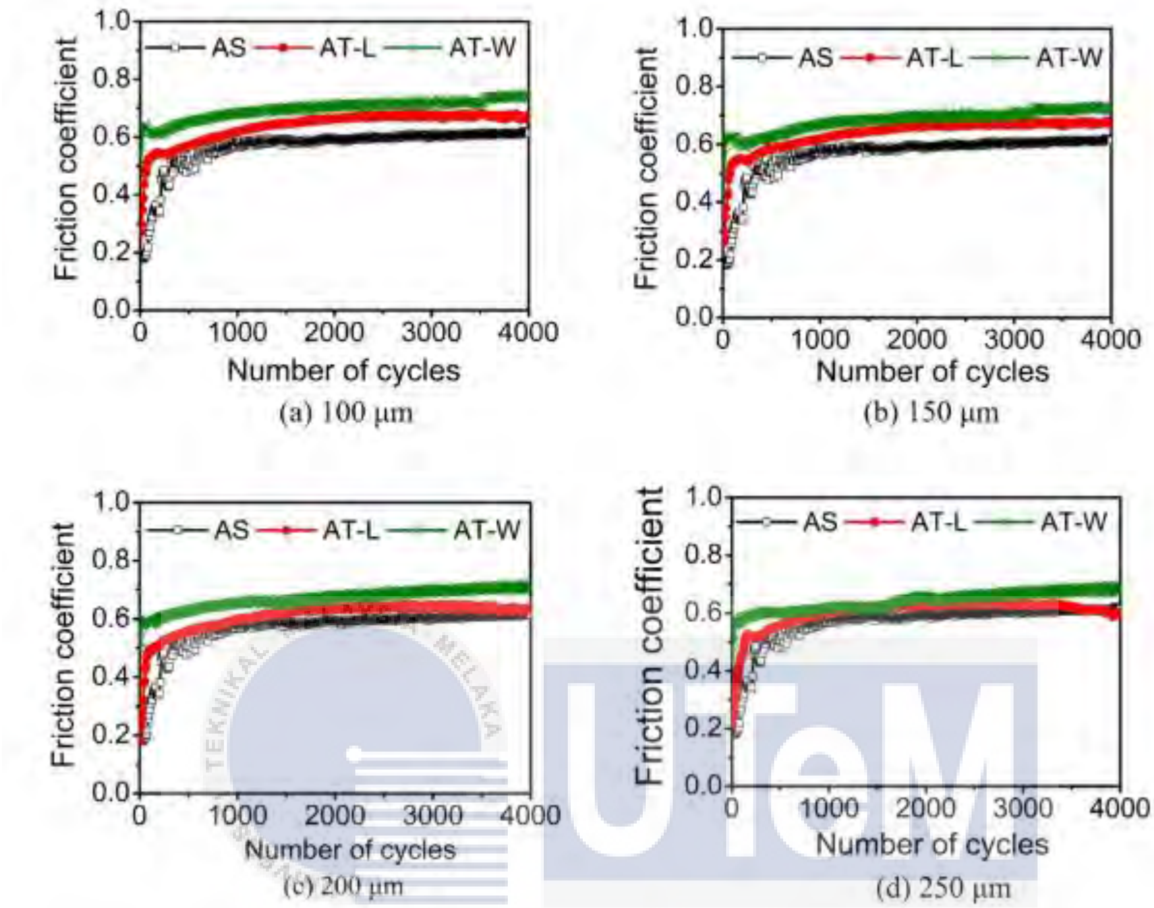


Figure 2.19: Variation of friction coefficient of smooth and textured sample with number of cycles for different spacing

Note that AS= Area smooth, AT-L= Area Textured-Linear, AT-W= Area Textured-Wavy.

From the result we can notice that wavy grooves exhibited highest friction coefficient, next is the linear pattern. Smooth surface has the lowest friction coefficient. Below is the average friction coefficient for 3 samples with different spacing.

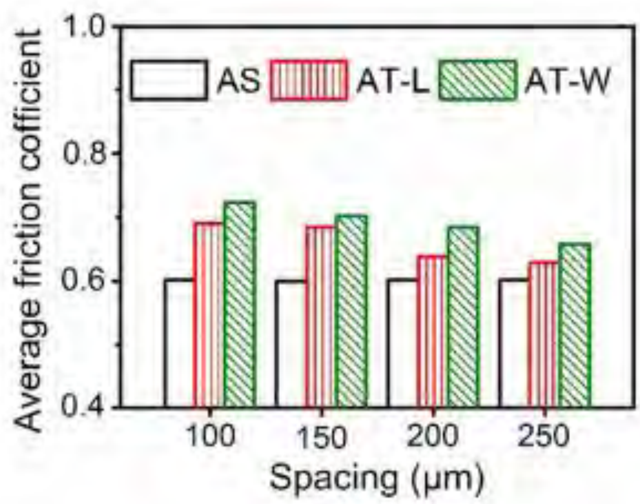


Figure 2.20: Average friction of different texture surface

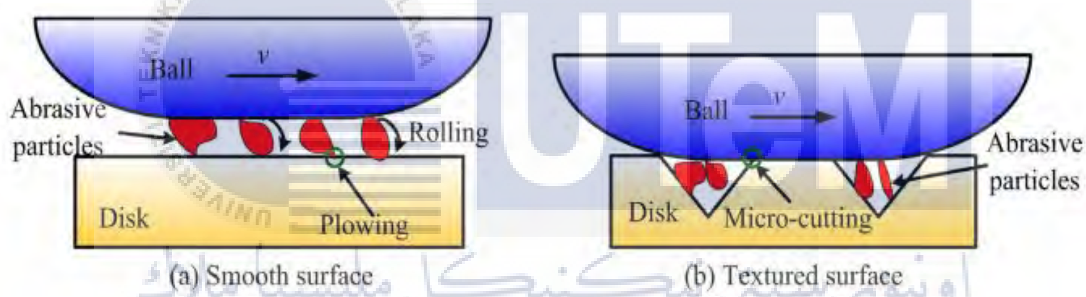


Figure 2.21: Friction and wear mechanism of the smooth and textured surface

The figure above illustrate how surface texture can improve tribological properties. The author mentioned that the groove will act as entrapment for the abrasive particles. Leaving the contact surface free from any wear debris. Without these debris interfering the sliding of both surface, wear performance will be increase. However, for surface textured samples, there is increasing of friction coefficient. According to author, abrasive particles changes to friction regime of both contacting surface from sliding friction to rolling friction. This transition will promote improvement in friction coefficient. When surface texture is available, the abrasive particle will store inside the groove, there is no particles that allow rolling resistance and thus increasing friction coefficient. From the graphs of variation of friction with different spacing, we can notice that the friction increases as the spacing reduced. This is due to the reducing spacing will increase the surface roughness.

Worth to mention, a very unique experiment by (Baum, Heepe, Fadeeva, & Gorb, 2014) studied about snake inspired polymer surface. Due to the ability of snake to move their body by generating friction force through their skin structure but at the same time reducing the friction force to prevent excessive skin abrasion. In the experiment, the subject of study is California King Snake (Lampropeltis getula californiae). The reason to choose this particular snake is because this snake live in area with various kind a surface. The unique skin structure is key reason that allow the snake to survive in the environment. Samples for SIMPS (surface inspired microstructured surface) were made from epoxy resin, imitating the surface pattern of the snake skin. Testing were done by sliding the surface with smooth glass ball under different directions. The performance of SIMPS is compared to variety of surface type.

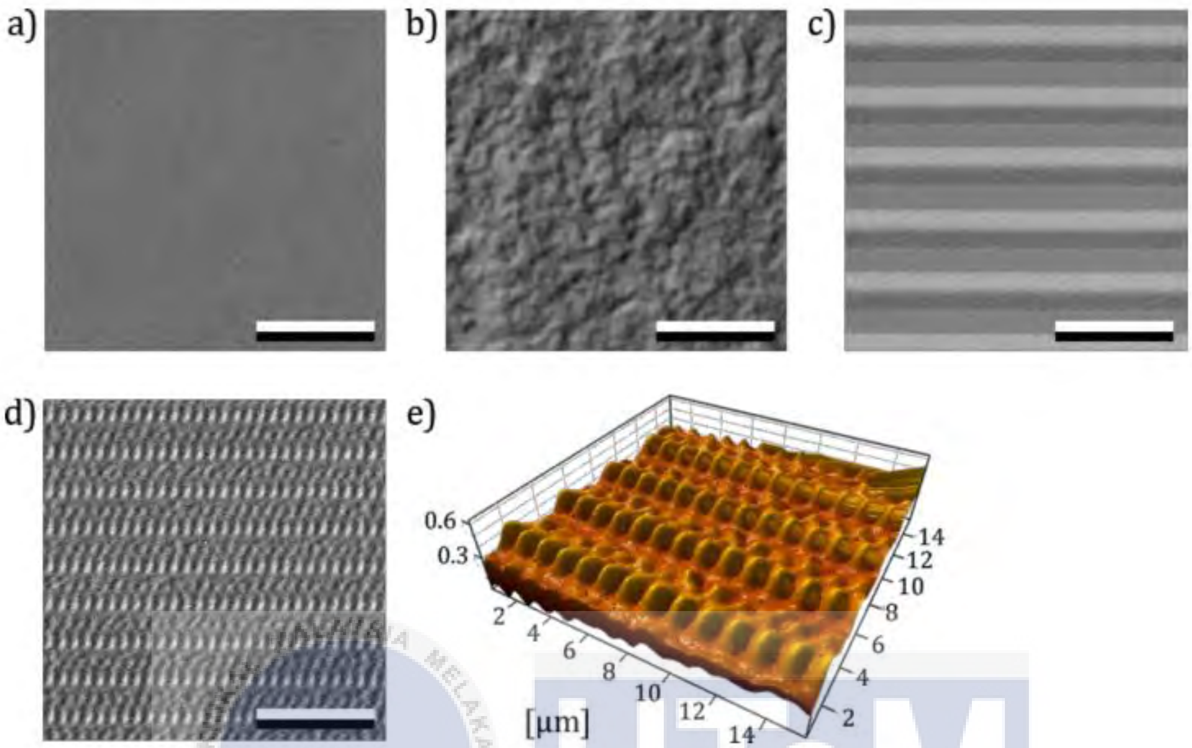
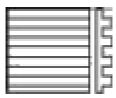
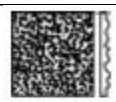
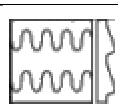
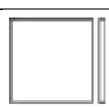


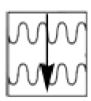
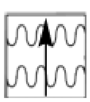
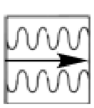
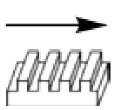
Figure 2.22: a) Smooth surface. b) Random rough surface. c) Periodic groove with 5μm wavelength. d) SIMPS. e) 3D surface profile of SIMPS

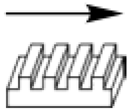
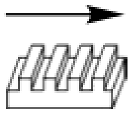
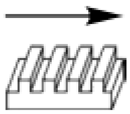
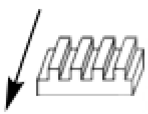
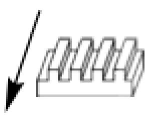
Table 2.3: Surface roughness of all sample surface

Sample			Ra ± SD [µm]
	periodic groove-like microstructure	PGMS - λ = 5 µm	0.18 ± 0.022
		PGMS - λ = 25 µm	4.95 ± 0.369
		PGMS - λ = 50 µm	21.75 ± 0.262
		PGMS - λ = 100 µm	42.50 ± 1.465
		PGMS – on line	0.03 ± 0.005
	randomly rough surface	RRS - 0.3 µm	0.23 ± 0.004
		RRS - 1 µm	0.41 ± 0.013
		RRS - 3 µm	1.11 ± 0.106
		RRS - 9 µm	2.39 ± 0.072
		RRS - 12 µm	7.64 ± 0.127
	snake-inspired microstructured surface	SIMPS	0.10 ± 0.130
	smooth surface	smooth surface	0.02 ± 0.007

From table above the snake-inspired microstructured surface have a very low surface roughness. It is almost equivalent to a smooth surface. The result for SIMPS and direction of sliding is along the microstructure exhibits the best friction coefficient.

Table 2.4: Frictional coefficient of different surface type

Surface type	Frictional coefficient
Smooth surface	0.318 ± 0.024
Randomly rough surface - 0.3 µm	0.284 ± 0.027
Randomly rough surface - 1 µm	0.264 ± 0.008
Randomly rough surface - 3 µm	0.214 ± 0.011
Randomly rough surface - 9 µm	0.192 ± 0.007
Randomly rough surface - 12 µm	0.250 ± 0.013
 SIMPS - along the microstructure	0.165 ± 0.010 0.245
 SIMPS - against the microstructure	0.245 ± 0.019
 SIMPS - lateral to the microstructure	0.250 ± 0.018
 λ = 5 µm	0.290 ± 0.006

 $\lambda = 25\ \mu m$	0.167 ± 0.008
 $\lambda = 50\ \mu m$	0.181 ± 0.006
 $\lambda = 100\ \mu m$	0.232 ± 0.006
 $\lambda = 5\ \mu m$	0.228 ± 0.016
 $\lambda = 25\ \mu m$	0.196 ± 0.011
 $\lambda = 50\ \mu m$	0.198 ± 0.022
 $\lambda = 100\ \mu m$	0.172 ± 0.024

2.4 Acrylic/Poly(methyl methacrylate)

Acrylic or Poly(methyl methacrylate) is a very common material in modern industry. The benefit of Poly(methyl methacrylate) includes strength, clarity, chemical resistance, electric resistivity and easy to fabricated. Mostly used in manufacturing industry especially signboard. Due to its ease to fabricate and lightweight, acrylic is favor by a lot of people in designing sign boards or lightning equipments. Moreover, the material itself is invulnerable against weather. Meaning that signboard made from acrylic even is installed outdoor will still retain it shapes and color for a very long period. Good resistance towards chemical make it a very ideal material to make replacement parts for human part for example bone or joint. Acrylic is so good that even high performance machine or mechanism uses it. For example, acrylic is used to make aircraft canopy. The material itself is so strong and lightweight which become a priority for the design. Other usage of acrylic are such as helmet visor, transparent wall for aquarium etc. Several experiment were done to increase the strength and scratch resistance of poly(methyl methacrylate). (An, Kang, Choi, & Kim, 2014) experiment on adding acrylic rubber into poly(methyl methacrylate) and then tested it with static and progressive scratch test.

Joint in human body is moving parts which connect two or more bones together. The usage of Poly(methyl methacrylate) in human part replacement such as joint. Tribological phenomenon happens in human body all the time. It is important for deep studies into mechanism of tribology in human body. The advantage and disadvantage of each material and geometry, surface design need to be explored so that the design of artificial replacement part can cope with high workload and durability(E, Shi, Guo, & Liu, 2015).

(Morales-Nieto et al., 2013) experimented on Poly(methyl methacrylate) as coating on UHMWPE to study the tribological performance different when coating is applied. They found that mixture of poly(methyl methacrylate)/carbonated hydroxyapatite have better adhesion on the UHMWPE compared to pure PMM coating. The result shows that the application of this coating improved the tribological performance compared to other surface treatment method.

In the journal published by (Suñer, Bladen, Gowland, Tipper, & Emami, 2014), UHMWPE has been extensively used in artificial human part. However. the wear produce from this material constantly occur which end up lose in the contact between counter-reacting surface. As this problem arise there is a need to frequently replace the parts. Such issue is very inconvenient for patient and medical staff. Initiative was taken to figure out solution such as coating, filling or alternative material.

(Jin, Zheng, Li, & Zhou, 2016) say that artificial joint is one of the most important medical achievement. There more at least 300 joints in a human body. Among them, shoulder, knee, hip provide large movement for a person. With these joints, human can perform rather complex motion. However, some people suffer from problems relating to artificial joints. Acrylic is a very good example of alternative material to use in any scenario which requires high strength, good resistivity towards chemical and ease to manufacture. However, if we are going to apply such material is mechanism which involve contacting surface and relative motion, the tribological properties of the material need to be identify. One of the way is to apply surface texturing on the surface.

2.5 Summary

From the article and journals reviewed, it can be concluded that surface texturing is beneficial on improving tribological properties of contacting surface. However, most of the texture pattern are dimples and groove. Dimples are proved to having greater benefit on improving tribological properties. Groove are less efficient and probably will increase the friction and wear. The direction of sliding is also important, sliding direction along the texture pattern is better compared to sliding perpendicularly against it. Small dimple density provides better overall performance. If the dimple density is too large, surface roughness will increase and the friction and wear. Surface texturing to improve tribological properties is mainly due to the ability of the increase ability to store lubricant and debris. During contact motion, large amount of lubricant will remain on the surface. If there are no texturing, the lube will loss very fast and lead to high friction condition. Wear debris is also well solved using texturing. Debris that are formed during sliding will trapped inside the textured surface, leaving the contact surface free from any abrasive particles.

Acrylic or poly(methyl methacrylate) is a great material that are easy to get and fabricated, most of the tribology experiment mentioned above uses composite material and steel. Since acrylic itself is a type of material which can be surface textured, it is possible to implement the technology to find out the tribological performance when surface textured. Previous studies mostly focus on how well the dimples and engraving will improve the sliding and wear performance under lubricated condition. But how well the texturing will work under dry condition is yet to be discovered especially using acrylic as sample material.

Chapter 3

Methodology

3.1 Introduction

This chapter describes the method and equipment used to perform surface texture on specimen and how to study its tribological properties. The project is started by reviewing all the suitable journals and article that are related to this topic. After gathering enough information and understanding, by using the knowledge learnt and use it on this project. Numbers of journal or article related to surface texturing and tribological performance is studied. Based on the previous research done by each author, identify the method they used to conduct their experiment. Since there are many ways to analyze tribological performance of a surface textured specimen. We can study what are the material they used, how to surface texture the specimen, number of specimen, testing condition, lubrication regimes used etc. From the previous studies, we can decide on which method of testing that have not been done before. By focus on that ways or method, we can prepare the suitable apparatus, equipment and preparation to conduct the experiment.

There are three machines used in this experiment. The first is laser engraving machine, to create texture on the disc specimen. Secondly is the Pin-on-disc tester, a machine used to analyze the tribological performance of specimen. The third machine will be a 3D non-contact profilometer to get a magnified image of the specimen after experiment. Below is the workflow for this experiment.

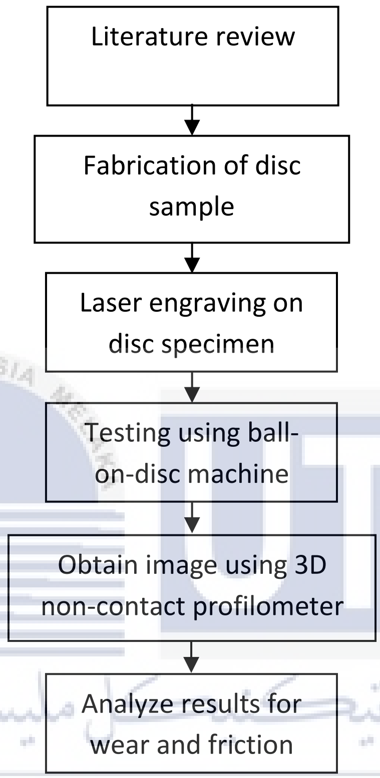


Figure 3.1: Work flow of experiment

3.2 Sample preparation

Testing sample for this experiment is a laser surface textured disc specimen. The disc is made from acrylic or its scientific name is Poly(methyl methacrylate). The acrylic is fabricated into the shape and dimension as below. The holes on the disc is to allow screw to the sitting place. Acrylic is chosen as specimen material because the aim of this study is only to identify how different dimples patterns will affect the tribological properties. Acrylic is cheap and easy to get. Most important it can be laser textured. In this experiment the acrylic disc is specially ordered from third party manufacturer. Each of them is 4 mm thick and made from clear acrylic material.

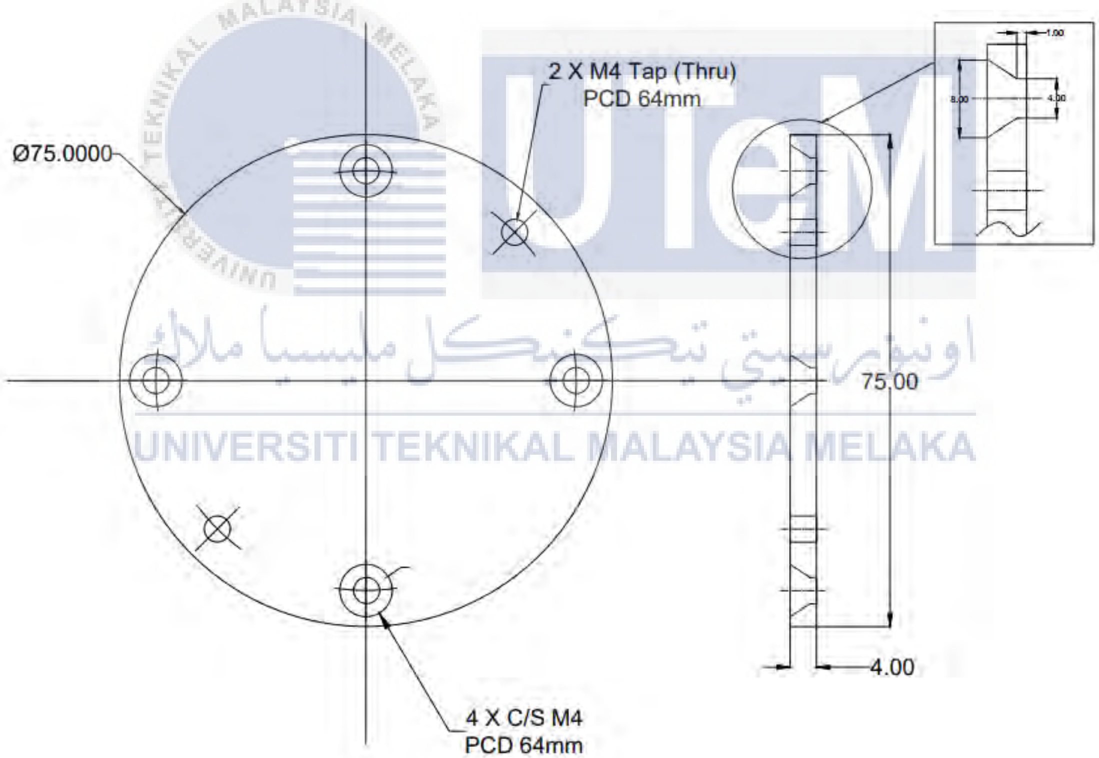


Figure 3.2: Dimension of acrylic disc specimen

3.3 Laser surface texturing

The texturing machine used is Trotec Speedy 300 laser engraving machine. Design of texture pattern is using software CorelDraw12. Texture pattern is drawn into the software. After drawing is complete, place the specimen into the engraving machine, load the texture pattern and start the texturing process. Safety precaution must be taken when using the laser engraving machine. Air must be well ventilated, compressor must be turn on to optimize air flow when engraving process is ongoing. Failure to allow optimal air flow might cause the specimen to burn when engraving.

Figure 3.3: Trotec Speedy300™ flexx laser engraving machine

3.4 Pin-on-disc

Pin-on-disc is a machine used to study the tribological performance of a specimen under pure sliding motion. There is a stationary pin or ball clamped and located on top of the rotating disc. A load will be applied on the specimen. Either a pin or disc can be used as specimen, then the other will act as counterpart. Sometimes ball is used instead of a pin, so the name ball-on-disc also applicable. In this experiment stainless steel ball is used instead of pin.

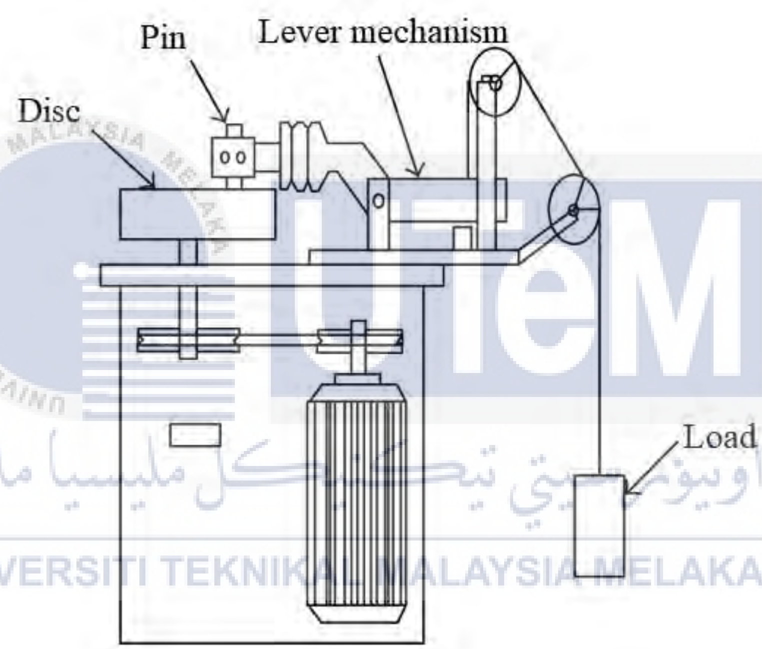


Figure 3.4: Schematic diagram of a pin-on-disc tester

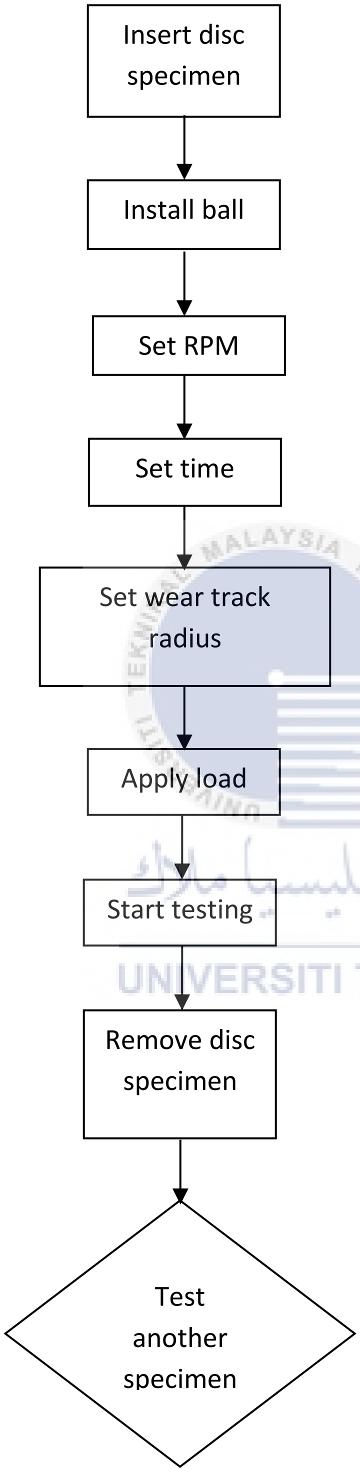
Figure above shows the schematic of a pin-on-disc tribometer. When the machine is turn on, the disc will rotate by motor. The ball is lowered down to touch the upper disc surface. The amount of weight applied will cause different loading of ball. If higher load is used, then the ball will apply a greater force on the disc surface. Friction is produced when the sliding disc is touching the ball. The machine will read the friction value between the ball and disc specimen. Data obtained will then transferred to computer. There are few parameters that are involved in tribometer which is speed(RPM), time(second/minute), wear track radius(mm) and friction force(N).

3.5 3D non-contact profilometer.

3D non-contact profilometer is used to obtain the magnified image of specimen after experiment is done. The machine can focus on the wear track and dimple and capture the image. The machine also capable of produce a 3D profile of magnified image. There are few things that can be analyze from the 3D profile which is dimple depth and amount of wear debris inside the wear track.

Figure 3.5: 3D non-contact profilometer

3.6 Work flow of testing.



1. Insert the disc specimen into sitting area and fix it with screw.

2. Install the ball.

3. Set the desired RPM.

4. Set the testing time.

5. Set the wear track radius.

6. Apply desired load.

7. Press the Start button to initiate testing.

8. After the test is complete, remove the disc specimen.

9. Place a new specimen to run a new test. Or else switch of the machine

Figure 3.6: Work flow of testing

3.7 Determination of testing time

The equation below is used to decide the time for testing. The time value is then insert into the tester. Where *L* is the total travel distance in meter, *r* is the radius of wear track in meter, *N* is speed(RPM) and *t* is time in minutes.

$$L = 2\pi rNt$$

3.8 Determination of wear rate.

Wear measurement is to determine the amount of material that is loss or worn out during experiment. Before and after the test all the disc are measured their weight and put into the formula below to calculate the wear rate for each specimen.

$$k = \frac{V_L}{FL}$$

Where k is specific wear rate, V_L is volume loss, F is the applied load in Newton and L is the distance travelled in meter. Volume loss is the total volume different of specimen before and after the testing. The volume loss can be calculated with the density value of specimen material and mass loss.

$$\text{Volume loss, } V_L = \frac{mass_{initial} - mass_{final}}{density}$$

3.9 Determination of friction coefficient

The machine can only detect friction force. To find out the friction coefficient, equation below is needed. F_L is the applied load, F_f is the friction force. The data obtained from testing which is the friction force is divide with the applied load to get coefficient of friction.

$$COF = \frac{F_f}{F_L}$$

CHAPTER 4

RESULT AND ANALYSIS

4.1 Results

4.1.1 Testing parameter

Table 4.1: Testing parameter for each specimen

<table>
<tr><th>Specimen</th><th>Dimple (diameter/gap)</th><th>Ratio of diameter/gap</th><th>Load</th><th>Speed</th><th>Wear track diameter</th><th>Testing distance</th></tr>
<tr><td>A</td><td>1mm/2mm</td><td>0.50</td><td rowspan="3">1kg</td><td rowspan="3">300RPM</td><td rowspan="3">30mm</td><td rowspan="3">1000m</td></tr>
<tr><td>B</td><td>1mm/3mm</td><td>0.33</td></tr>
<tr><td>C</td><td>2mm/5mm</td><td>0.4</td></tr>
</table>

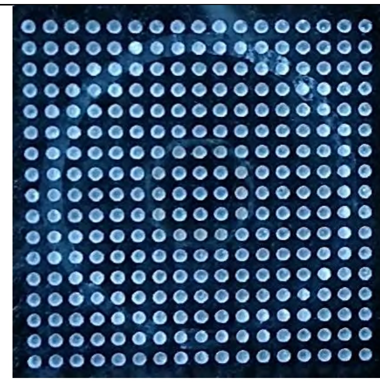
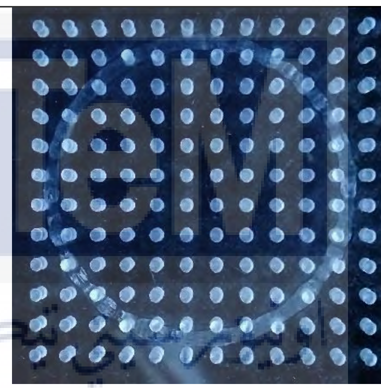
Table 4.2: Specific gravity of acrylic specimen

Specific gravity			Average
1.174	1.182	1.161	1.172

Specific gravity of acrylic measured using electronic densimeter. Conversion to density will get the average of $1.172 g/cm^3$.

4.1.2 Wear track

Table 4.3: Wear track for each specimen

Specimen	Image
A(2mm)	
B(3mm)	
C(5mm)	

4.1.3 Weight of specimen

Table 4.4: Weight different for each specimen

Specimen	Weight (grams)		
	Before	After	Different
A	17.9536	17.9508	0.0028
B	17.4445	17.4410	0.0035
C	17.8921	17.8842	0.0079

4.1.4 COF variation of each specimen

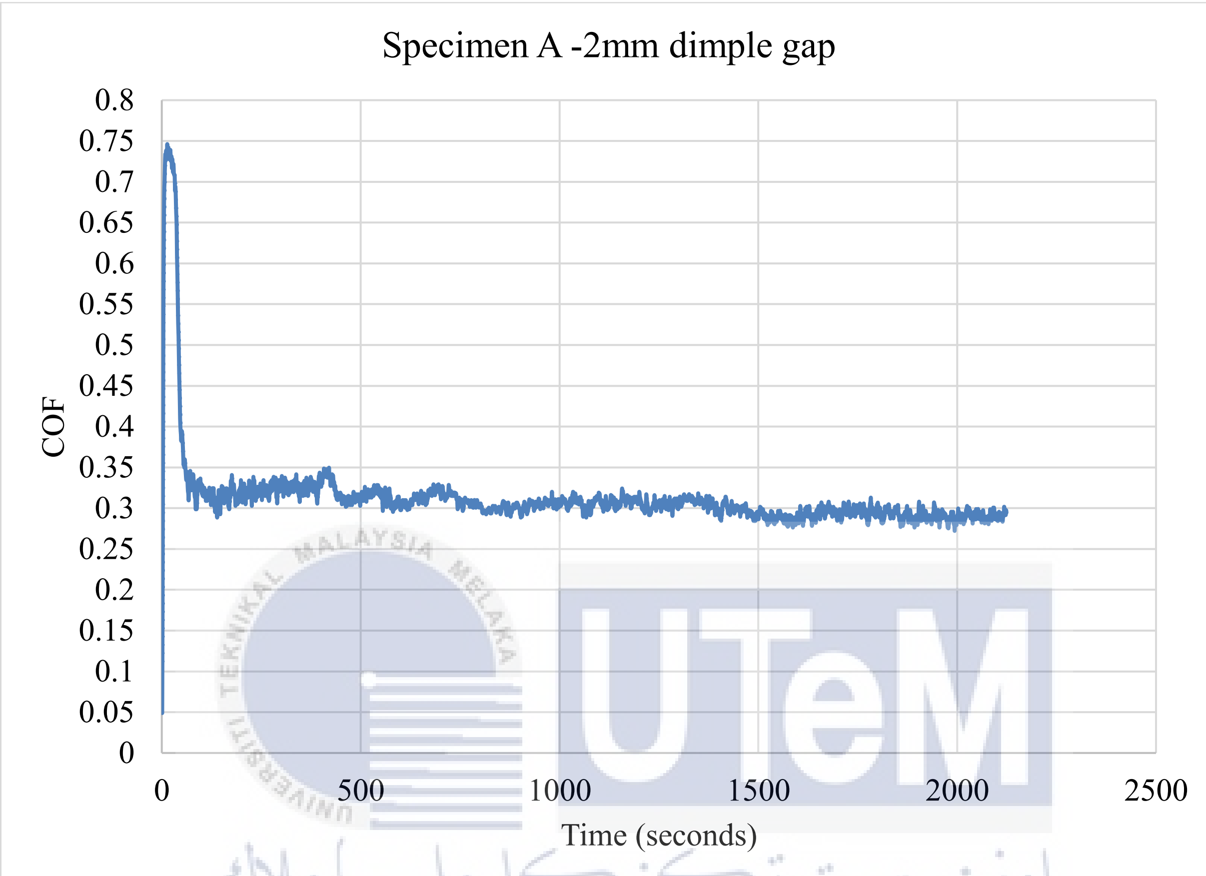


Figure 4.1: The effect of 2mm dimple gap on COF of acrylic disc against stainless steel ball at room temperature

Average COF upon reaching steady state (1500 seconds) = 0.291947

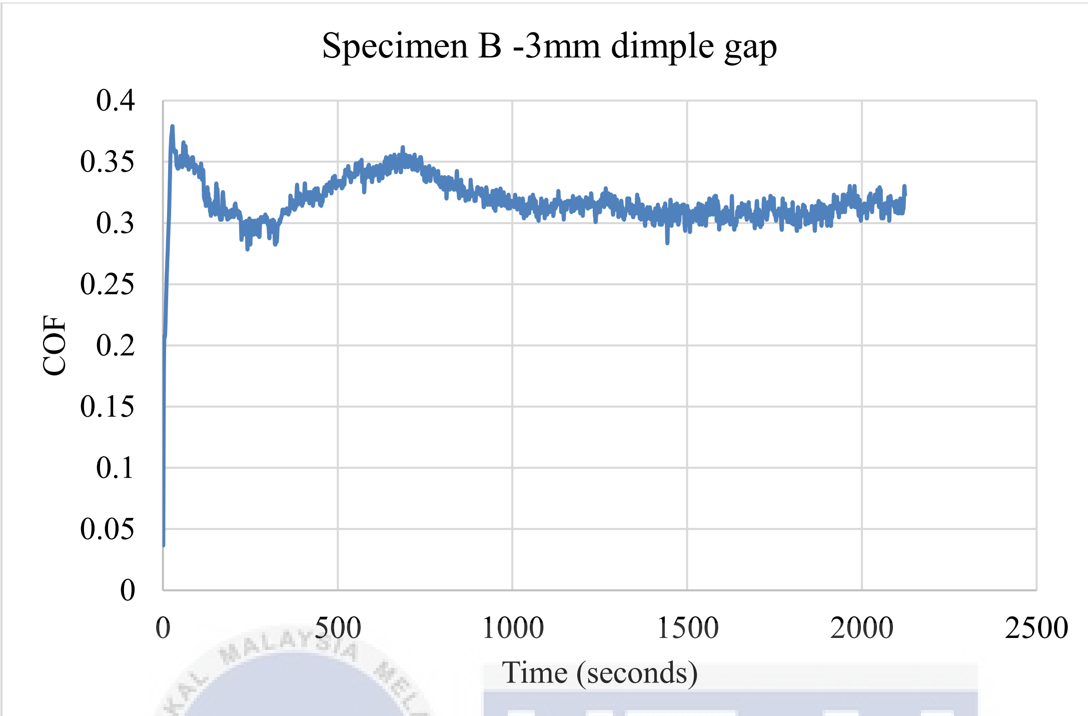


Figure 4.2: The effect of 3mm dimple gap on COF of acrylic disc against stainless steel ball at room temperature

Average COF upon reaching steady state (time 1400 seconds) = 0.309492

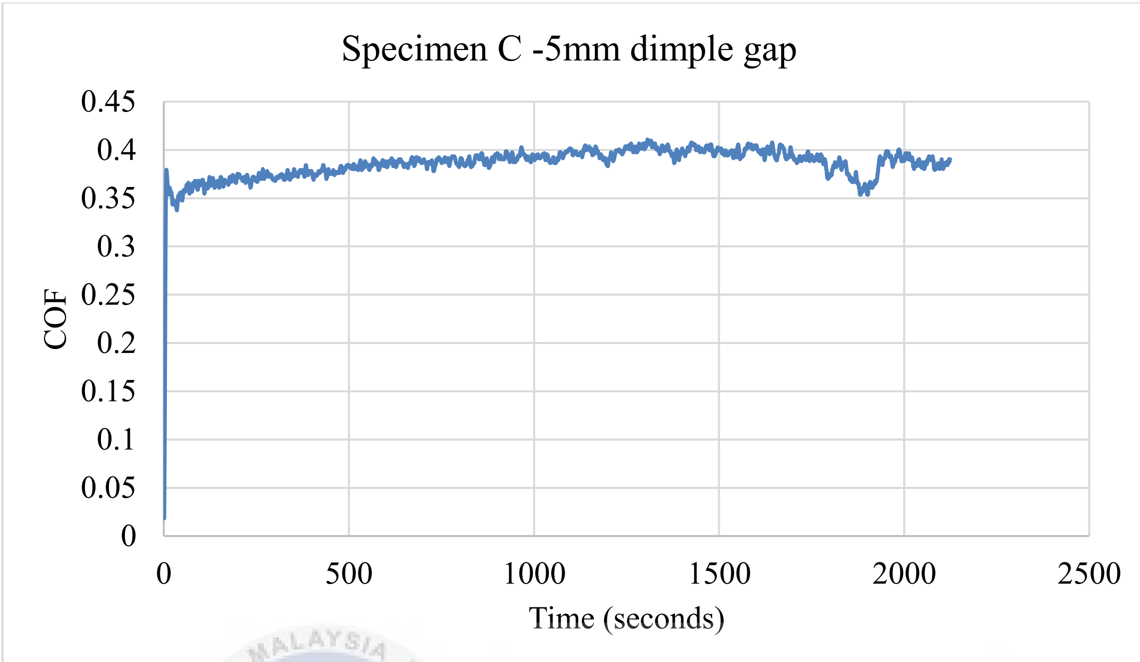


Figure 4.3: The effect of 5mm dimple gap on COF of acrylic disc against stainless steel ball at room temperature

Average COF upon reaching steady state (time 1000 seconds) = 0.392684

4.1.5 Calculation of wear rate

Specimen A - 2mm dimple gap

$$Volume\ loss = \frac{17.9536 - 17.9508}{1.172}$$

$$= 0.002389 cm^3$$

$$Wear\ rate = \frac{0.0002389}{9.81 \times 1000}$$

$$= 2.435 \times 10^{-7} cm^3/Nm$$

Specimen B - 3mm dimple gap

$$Volume\ loss = \frac{17.4445 - 17.4410}{1.172}$$

$$= 0.002986 cm^3$$

$$Wear\ rate = \frac{0.002986}{9.81 \times 1000}$$

$$= 3.044 \times 10^{-7} cm^3/Nm$$

Specimen C - 5mm dimple gap

$$Volume\ loss = \frac{17.8921 - 17.8842}{1.172}$$

$$= 0.0067406cm^3$$

$$Wear\ rate = \frac{0.0067406}{9.81 \times 1000}$$

$$= 6.871 \times 10^{-7} cm^3/Nm$$

4.1.6 Comparison between specimens

Table 4.5: Dimple depth, wear rate and COF of each specimen

Specimen	Average depth (μm)	Wear rate (cm^3/Nm)	Average COF
A (2mm gap)	470	2.435×10^{-7}	0.291947
B (3mm gap)	550	3.044×10^{-7}	0.309492
C (5mm gap)	350	6.871×10^{-7}	0.392684

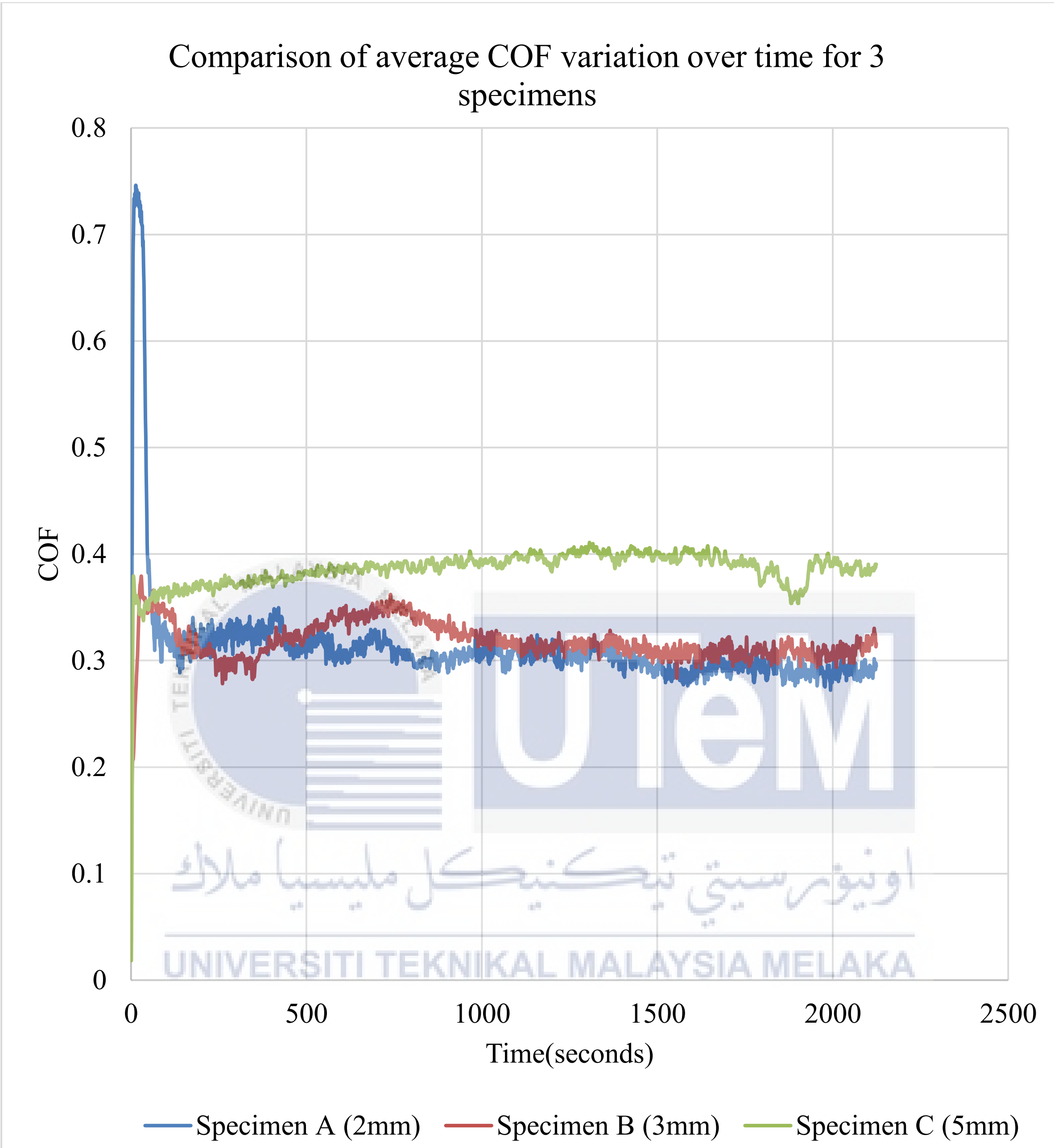


Figure 4.4: Variation of COF between each specimen over time

Figure 4.5: Comparison of average COF between each specimen

Average COF of specimen A is 0.291947, specimen B increase by 6% which is 0.309492 and specimen C increase by 34% to 0.392684.

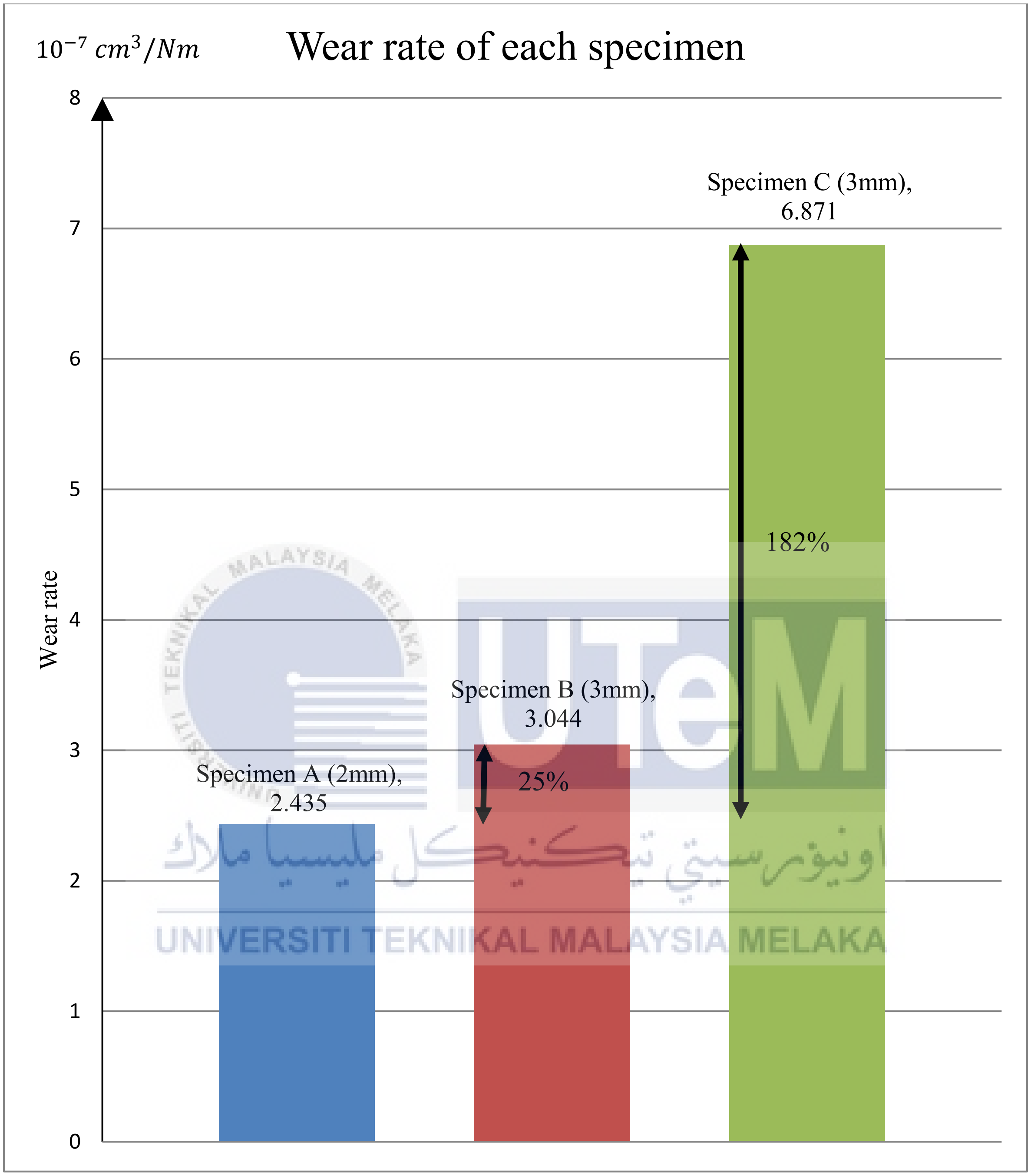
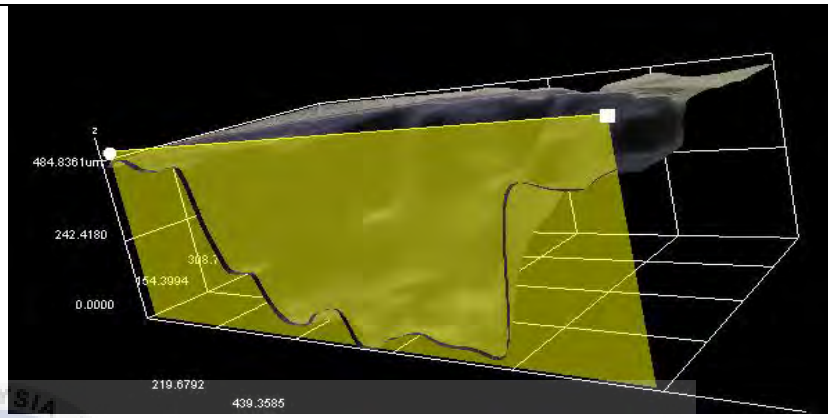
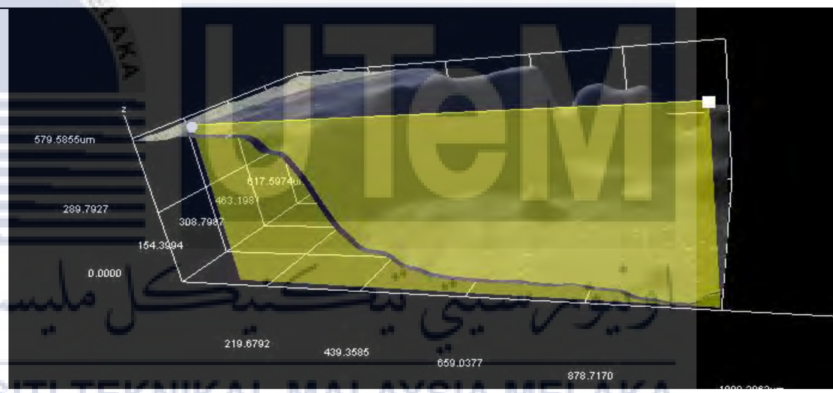
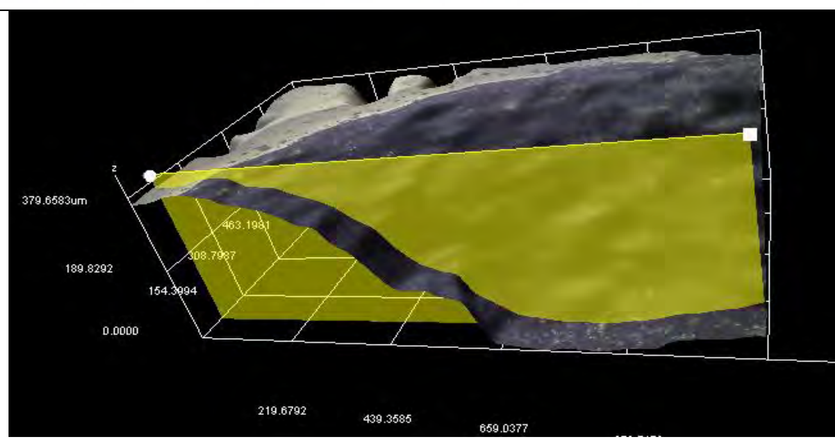


Figure 4.6: Comparison of wear rate between each specimen

Wear rate of specimen A is 2.435 cm^3/Nm, wear rate of specimen B increase by 25%, 3.044 cm^3/Nm while wear rate of specimen C increase by 182%, 6.871 cm^3/Nm.

4.1.7 3D profile of dimple

Table 4.6: Wear track for each specimen

Specimen	3D image
A	
B	
C	

4.1.8 2D profile of dimple

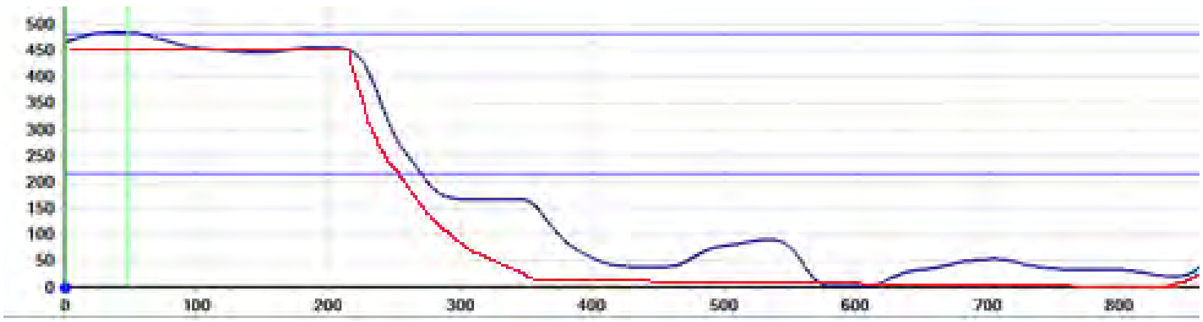


Figure 4.7: Depth of dimple for specimen A

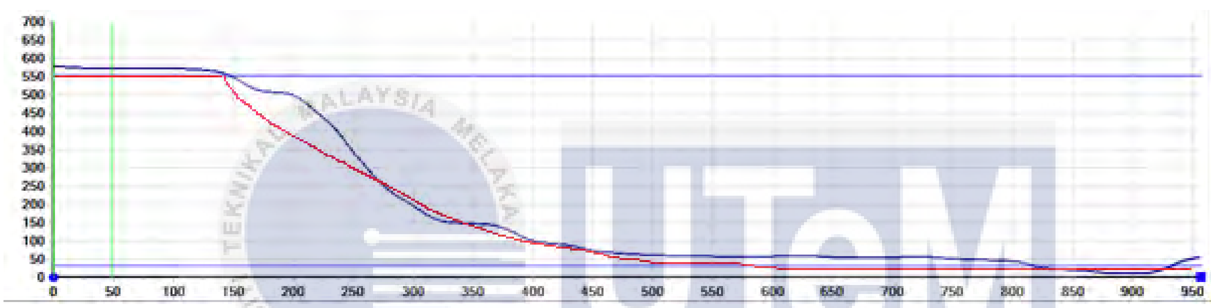


Figure 4.8: Depth of dimple for specimen B

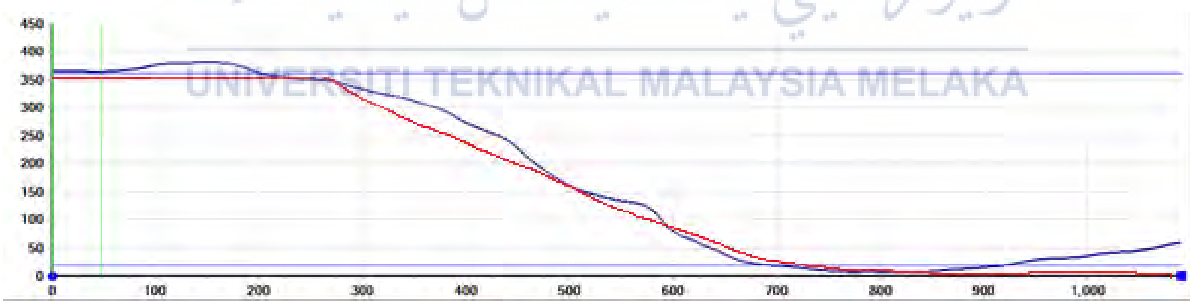


Figure 4.9: Depth of dimple for specimen C

Figures above are the 2D images of the dimple side view. On the Y-axis is the depth of the dimple. Average depth of specimen A 470μm, specimen B 550μm and specimen C 350μm. Three of the specimen have different depth because it is very hard to control the depth when laser engraving.

Note that red line is the surface boundary of specimen, blue uneven line is the wear debris stored inside the dimple. We can notice that specimen A have relatively uneven surface inside the dimple. This is due to the wear debris that accumulated inside the dimple after testing. Compare to specimen A, specimen B and C have smoother lines. This indicate that the dimples are less filled with wear debris. When more debris are filled inside the dimple, indicating that the surface texturing method did achieve its purpose to store wear debris.

4.2 Discussion

From the results obtained, initially the COF is higher especially at the start of testing. After some time, the COF will start to reduce and approaching stable state. Average value of COF is obtained from the time where steady state is reached which is when the graph become stable. According to the result, specimen A (2mm dimple gap) have the best COF, the second is specimen B (3mm dimple gap). Specimen C (5mm dimple gap) have the highest COF. Comparing the wear rate result, we can also obtain the same trend. Highest wear rate is specimen C followed by specimen B and the last is specimen A. The reason for this trend is because the distance of dimple gap. As the dimple gap is increased, the amount of dimple available to trap wear debris decreases. When the distance between dimples are large, there are fewer dimples to act as storage for wear debris. To get a better visual about how the dimples able to store wear debris, microscopic images are taken using 3D non-contact profilometer. Below are some images obtained to look at the debris inside dimples.

Figure 4.10: Debris trapped inside dimple for specimen A

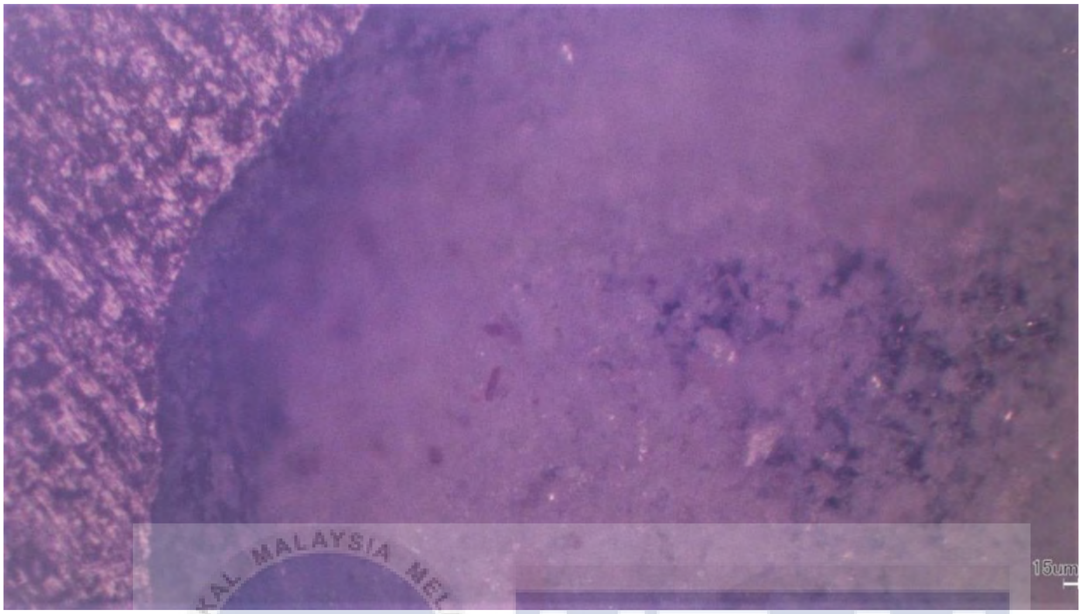


Figure 4.11: Debris trapped inside dimple for specimen B

Figure 4.12: Debris trapped inside dimple for specimen C

From the images, wear debris (white particles) did trap inside the dimples for every specimens. Mostly dimples that are near to wear track will have wear debris trapped inside. Comparing three of the images, specimen A have the most trapped wear debris inside the dimple, specimen B have fewer and specimen C have the least amount of wear debris inside the dimple. If most of the wear debris end up trapped inside the dimples, the will be less debris particle remains on the disc specimen surface. For the case where few debris fell into the dimples, they remain on the specimen surface, these wear debris will act as third party abrasives which increase the friction and wear rate.

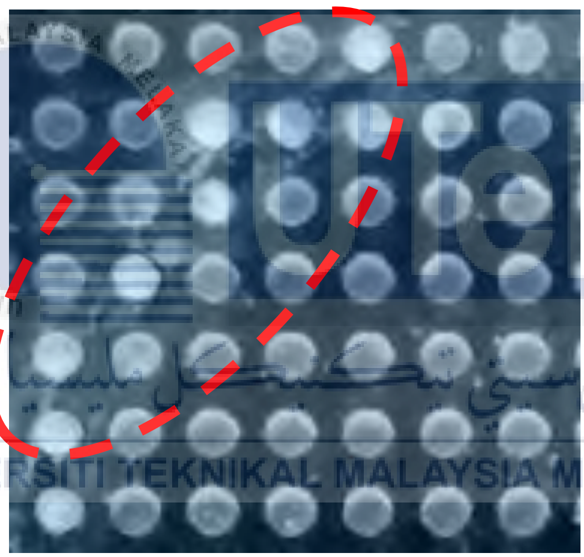


Figure 4.13: Debris along wear track for specimen A

The image above is from specimen A. We can clearly see that there are few white spots within the red dotted area, which are dimples that trapped with wear debris. Implying that the effect of wear debris trapping effect is better with higher numbers of dimples along the wear track.

Figure 4.14: Debris along wear track for specimen B

For specimen B as shown above, notice that there are dimples along wear track that are filled with wear debris. But at the same time there are also wear debris scattered around the wear track. These wear debris that stay on the specimen surface is the reason for higher COF result compared to specimen A. When these particle remains on the surface, it will contribute to higher friction during sliding of ball and specimen.

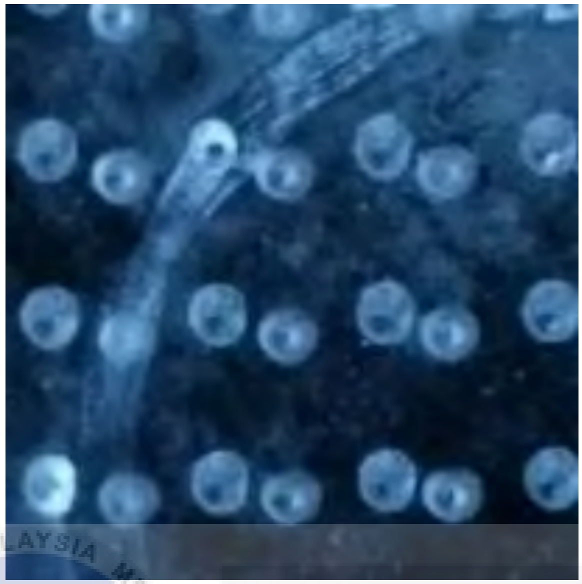


Figure 4.15: Debris along wear track for specimen C

From the image above for specimen C, we can notice that less number of dimple are filled with wear debris. Since the dimple gap for specimen C is the largest between the three specimens. This result suggests that larger dimple gap resulting in fewer amount of dimple along the wear track. In the end, the storage for wear debris which is the dimple is significantly insufficient. Such phenomenon will cause the wear debris remain on the specimen surface and increase the friction.

Comparing three specimen, the amount of dimple available along the wear track have significant variation. Specimen A, B and C have the number of dimples along wear track respectively 52, 22 and 14. From here, the reason tribological performance of each specimen follows a certain trend can be explained. When the dimple gap in closer, there will be more dimples along the wear track thus increasing the wear debris storage ability of surface texturing.

The type of contact also affects the wear debris entrapment. Below is one of the contact type where the ball is moving on the side of the dimple. The ball did not completely go over the dimple when it slide across the specimen. The ball either move at the edge of the dimple or didn't touch the dimple at all. In this type of contact the wear debris will drop into the dimple given it have a lot of space to go through.

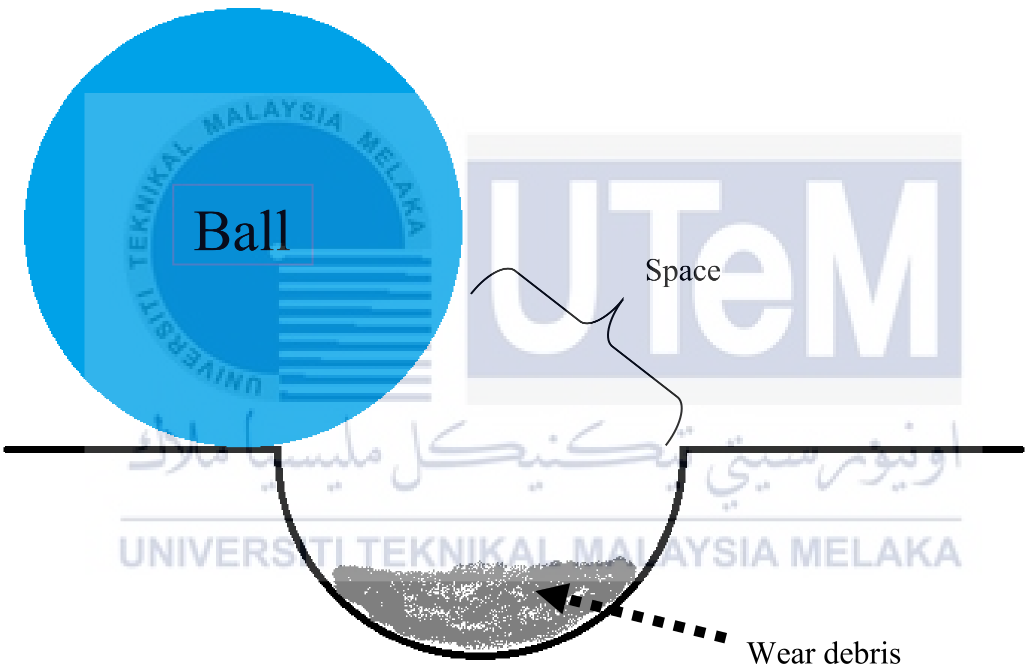


Figure 4.16: Schematic of ball and dimple partial contact

Another type of ball and dimple contact, the ball is entirely covering the dimple when it slides over the specimen. This will result in the debris unable to drop into the dimple because the path to drop into the dimple is blocked (red arrow). Most wear debris remain on specimen surface, only few amount of wear debris will fell into the dimple. The consequence is these debris remains on the specimen surface will become abrasive particles.

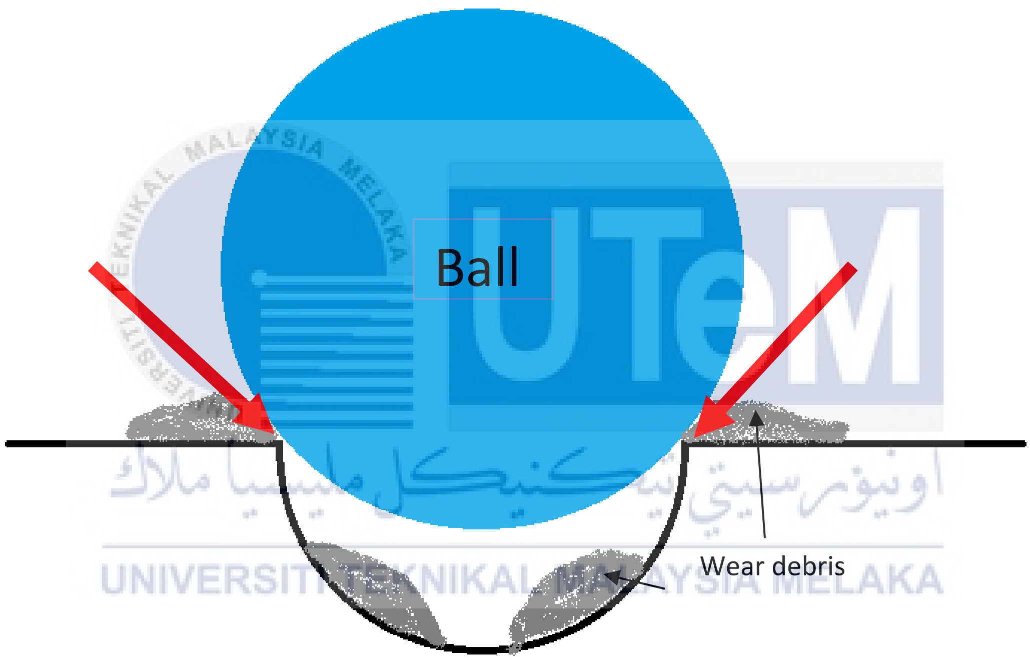


Figure 4.17: Schematic of ball and dimple full contact

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

Based on the result, we can validate that surface texturing did helps to reduce the friction on the specimen. Between 3 specimens that are used, specimen A with 2mm dimple gap have the least COF, specimen B with 3mm dimple gap come second and specimen C with 5 mm dimple gap have the highest COF. Comparing wear rate, it follows the same trend. Specimen A is the lowest, second is specimen B and highest is specimen C.

By observing the image taken using 3D non-contact profilometer, the wear debris did trap inside the dimple thus lowering the friction and wear rate. When wear debris trap inside dimple meaning that fewer debris will remain on specimen surface.

It can be concluded that among 3 specimens with different surface texturing, dimple with 2mm gap have the lowest COF and wear rate. Under dry friction condition the surface texturing of specimen A is the best in term of its tribological performance.

5.2 Recommendation for future studies

Although the variation of COF and wear rate did shows variation between specimens, the whole experiment is only focus on certain testing parameter and material choices. Acrylic is the only material used, most probably different material will behave differently. Besides, the surface texturing only focusses on dimple. There are many possible texture patterns that can be tested depends on requirements. Even the applied load, testing distance and lubrication regime are manipulatable variation to obtain different result.

To have a better understanding of how surface texturing will affect tribological performance, certain things can be focus on for future study. First is the lubrication, since in this experiment there are no usage of any lubrication. The shape and dimension of surface texturing can be manipulated. Besides, depth of surface texturing is also a factor to be considered. Detail study requires a lot of time however the outcomes will be beneficial to many field and industry.

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APPENDICES

Appendix A1: Project Gantt chart for PSM1

No	Topic	Weeks													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Working time for PSM 1														
2	Topic Selection														
3	Topic Confirmation														
4	Literature Review of Tribology														
5	Literature Review of Surface Texturing														
6	Material choosing														
7	Cutting of material														
8	Methodology														

Appendix A2: Project Gantt chart for PSM 2

No	Topic	Weeks												
		1	2	3	4	5	6	7	8	9	11	12	13	14
1	Working time for PSM 2	■	■	■	■	■	■	■	■	■	■	■	■	■
2	Surface texturing	■	■	■	■									
3	Wear and friction test					■	■	■						
4	Data analyze								■	■				
5	Report writting									■	■	■	■	
6	Submission of report												■	■

Appendix B1: Pin, ball and holder

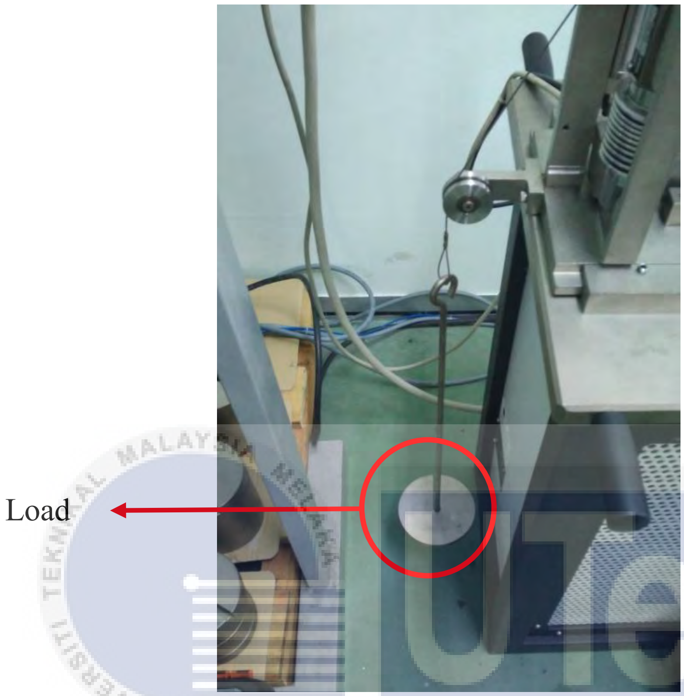
Appendix B2: Wear track adjustment

Appendix B3: Pin holder and disc sitting area

Pin holder

Disc sitting area

Appendix B4: Load



Appendix B5: DUCOM Pin-on-disc tester