WEAR BEHAVIOUR OF 3D PRINTED PART OF CARBON FIBRE REINFORCED ABS COMPOSITE

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Report

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MAY 2017

DECLARATION

I declare that this project report entitled “Wear Behavior of FDM Printed Part of Carbon Fibre Reinforced ABS Composite” is the result of my own work except as cited in the references

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Name	:	MOHAMAD SAFEI BIN SANI
Date	:	....

SUPERVISOR'S DECLARATION

I have checked this report and the report can now be submitted to JK-PSM to be delivered back to supervisor and to the second examiner.

Signature: ………………………………………………

Name of supervisor: DR. MOHD NIZAM BIN SUDIN

Date: ………………………………………………………

ABSTRACT

The main idea of this study is to investigate the wear behavior of 3D printed part of carbon fibre reinforced ABS (acrylonitrile butadiene styrene) and compare the result with the pure ABS that will be printed the same way. The 3D printer used was a FDM (fused deposition modeling) type. The tests were performed on a pin on disk machine according to ASTM G 99 standard under dry sliding condition. The parameters used were 5,10,15,20 and 25 N of applied load and 0.6 m/s or 286 RPM sliding speed for the duration of 3 minutes and 5 minutes. The results of the tests showed that there are two main wear mechanisms that influenced the results of the tests which are abrasive and adhesive. The results also shown that the varied parameters chosen which are applied load and run time duration could affect the wear rate, rate of volume loss, friction force and friction coefficient of the test samples. Carbon fibre reinforced ABS specimens showed a better wear resistance and durability properties than ABS specimens when operating with high load and long time duration. This research could be useful to the wear resistant industries in the future as it could develop a better wear resistance component for various field of applications.

ACKNOWLEDGEMENT

I would like to express my deepest appreciation to my supervisor Dr. Mohd Nizam bin Sudin for giving me this opportunity to do final year project with him. He never hesitated to give me advices and guidances whenever the problems come. I am grateful for his patience and advice while leading me in this project.

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LIST OF ABBREVIATIONS

FDM	-	Fused deposition modelling
ABS	-	Acrylonitrile butadiene styrene
3D	-	Three dimensional
FFF	-	Fused filament fabrication
RP	-	Rapid prototyping
CAD	-	Computer aided design
AM	-	Additive manufacturing
STL	-	Stereolithoghraphy
LOM	-	Laminated object manufacturing
SLS	-	Selective laser sintering
LENS	-	Laminated engineering net shaping
EBM	-	Electron beam melting
CAE	-	Computer aided engineering
CAM	-	Computer aided manufacturing
CATIA	-	Computer aided three dimensional interactive application

CHAPTER 1

INTRODUCTION

1.1 Background of study

The purpose of this study will focus on the wear behaviour of fused deposition modelling (FDM) printed parts of carbon fibre reinforced acrylonitrile butadiene styrene (ABS) composite. FDM is one of the techniques used for 3D printing. FDM also included in additive manufacturing technology commonly used for modelling, prototyping, and production application. FDM produces parts of complex geometry by layering the extruded materials, such as acrylonitrile butadiene styrene (ABS) plastic. The ABS material is initially in the raw form of a flexible filament which is then moderately melted and extruded through a heated nozzle in a specified parallel road pattern onto a platform layer by layer at room temperature. In the late 1980s, S. Scott Crump developed the FDM technology which is later commercialized by Stratasys in 1990. FDM also known as fused filament fabrication (FFF).

In this study, ABS and carbon particles will be combined to produce a composite material. Only 15% of carbon fibre with 250 micron particle size will be extruded along the ABS particles with the same size to produce filament. Acrylonitrile butadiene styrene (ABS) is one of a common thermoplastic polymer. The glass transition temperature of ABS is approximately 105 °C. ABS is useful in manufacturing products such as musical instruments, automotive trim components, automotive bumper bars, and toys because of its light weight and ability to be extruded.

In 1493, Da Vinci identified the laws of friction in a notebook. He stated that the frictional resistance was the same for two different objects of the same weight but making contacts over different widths and lengths. He also found that the force needed to overcome friction doubles when the weight doubles. Charles Hatchet carried out the first reliable test on frictional wear using a simple reciprocating machine to evaluate wear on gold coins in which he discovered that mated coins with grits between them wore at a faster rate than the self-mated coins. The wear test of this study will be performed as recommended by ASTM G 99 standard at room temperature under dry sliding conditions. ASTM international and respective subcommittees such as Committee G-2 define the standard result review for wear tests, should be expressed as loss of material during wear in terms of volume.

In this present research, the purpose is to investigate the effect of dry sliding wear characteristic of FDM printed parts of carbon fibre reinforced ABS composite. In addition, the discussion of numerous wear mechanisms will be made.

1.2 Problem Statement

Wear is erosion or sideways displacement of material from its original position on a solid surface performed by the action of another solid surface. Wear could cause many unexpected things such as slip while walking and road accidents. In other to overcome those problems, the evolution of superior wear resistance components for various field applications should be executed. The potential of this study is to produce FDM parts by using carbon fibre reinforced acrylonitrile butadiene styrene (ABS) composite to meet the needs of wear resistant industrial components.

1.3 Objectives

The objectives of this project are:

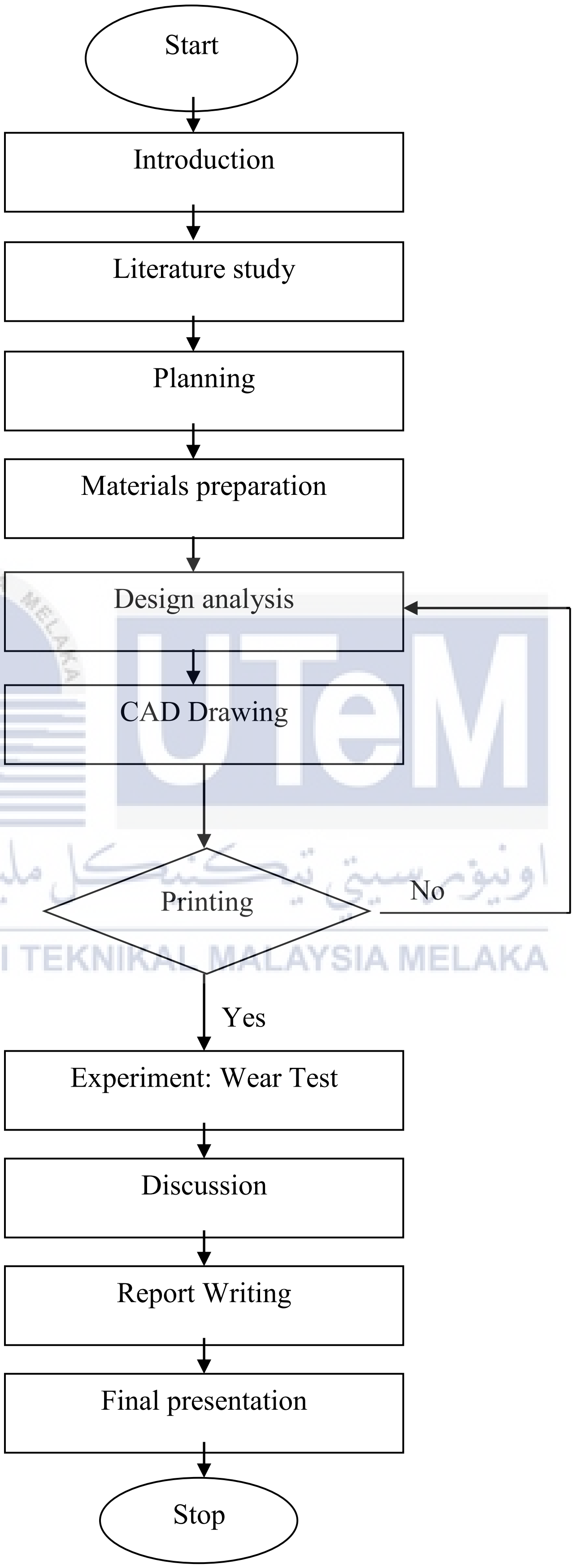
1. To fabricate carbon fibre reinforced ABS printed part by using FDM machine.
2. To study the wear behaviour of the 3D printed part of carbon fibre reinforced ABS composite.

1.4 Scope

The scopes of this study are:

1. Wear behaviour of carbon fibre reinforced ABS printed specimen will be compared with pure ABS printed specimen.
2. Default FDM parameter will be used for the specimens.
3. Based on previous research by Rupinder et al. (2016), The test will be conducted by applying load of 5, 10, 15, 20 and 25 N with sliding velocity of 0.6 m/s for the duration of 3 and 5 minutes at room temperature.
4. The results may be different in practical applications due to different operating conditions.

1.5 General Methodology



CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to collect all related information from journals, internet articles and previous research notes regarding this study. New technologies for part fabrication were introduced due to increased competitiveness and fast changing customer demand in marketplace. One of the technologies is rapid prototyping (RP) technologies (Bernarand, A. 2002). Fused deposition modelling (FDM) is deemed as best process for RP because it is easy to operate, less expensive and produces durable built parts (Levy et al. 2003). Currently, industrial application of FDM process biggest issue is the quality of parts produced by the process. Hence, it is important to understand the performance of FDM built parts. Previous studies mainly focus on characterization of mechanical strength, improvement of surface roughness and dimensional accuracy of the processed part. Wear is one of the essential features for the durability of part but the research done to study the wear behaviour of RP built part is very little. Thus, the current study is subjected to comparative analysis of wear characteristic between FDM parts fabricated by ABS (acrylonitrile butadiene styrene) pure material and carbon fibre reinforced ABS composite material.

2.2 Rapid Prototyping

Rapid prototyping (RP) is defined as a group of techniques used to quickly create a scale model of a part or assembly using three dimensional computer aided design (CAD) data. RP was developed in the 1980's for fabricating models and prototype parts. RP also one of the first additive manufacturing (AM) processes. There are many crucial benefits that this process delivered to product development such as the time and cost reduction and the possibility to fabricate complex shape design that could be very demanding to machine (Ashley, S. 1991). Figure 2.1 shows all the steps involved in product development using rapid prototyping. RP decreases development time by allowing corrections to a product to be made early in the process.

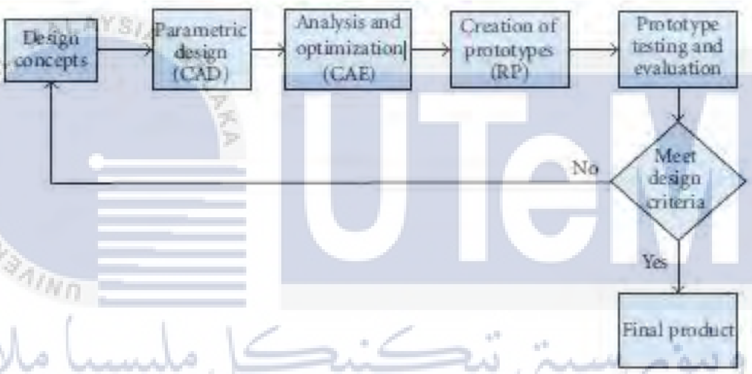


Figure 2.1: The steps involved in product development using rapid tooling (Hernandez et al. (2012))

In Figure 2.3, there is an analysis of the different additive manufacturing processes that are going to be further considered. Here in this figure adapted from Kruth (1991), the processes are classified into liquid base, solid based, and powder based. The processes included in this review are considered the most applicable in the past, and promising for the future of the industry. The processes considered are stereolithography (SL), Polyjet, fused deposition modelling (FDM), laminated object manufacturing (LOM), Prometal, selective laser sintering (SLS), laminated engineered net shaping (LENS), and electron beam melting (EBM). The liquid-and powder-based processes seem more promising than solid-based processes of which LOM is the predominant one today.

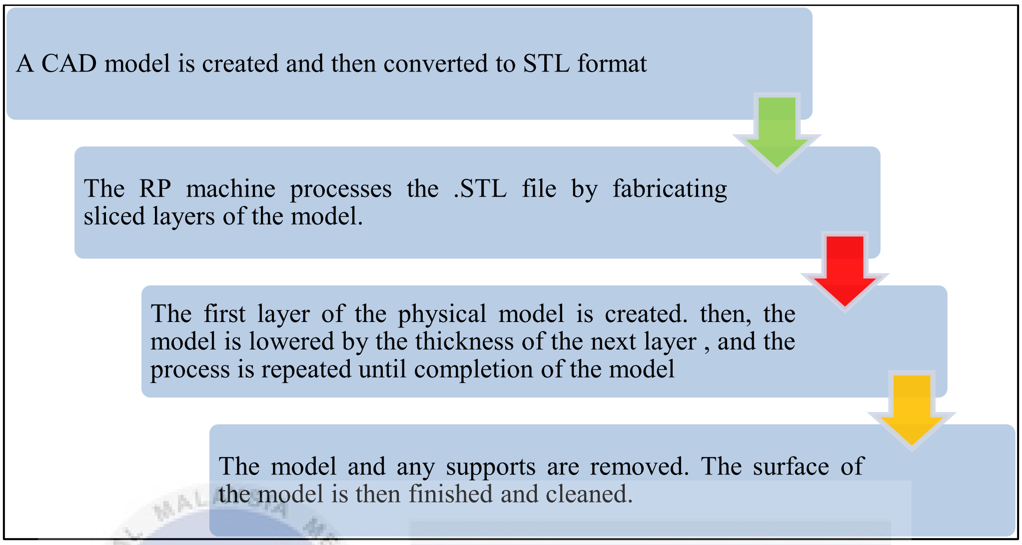


Figure 2.2: Basic methodology for rapid protyping

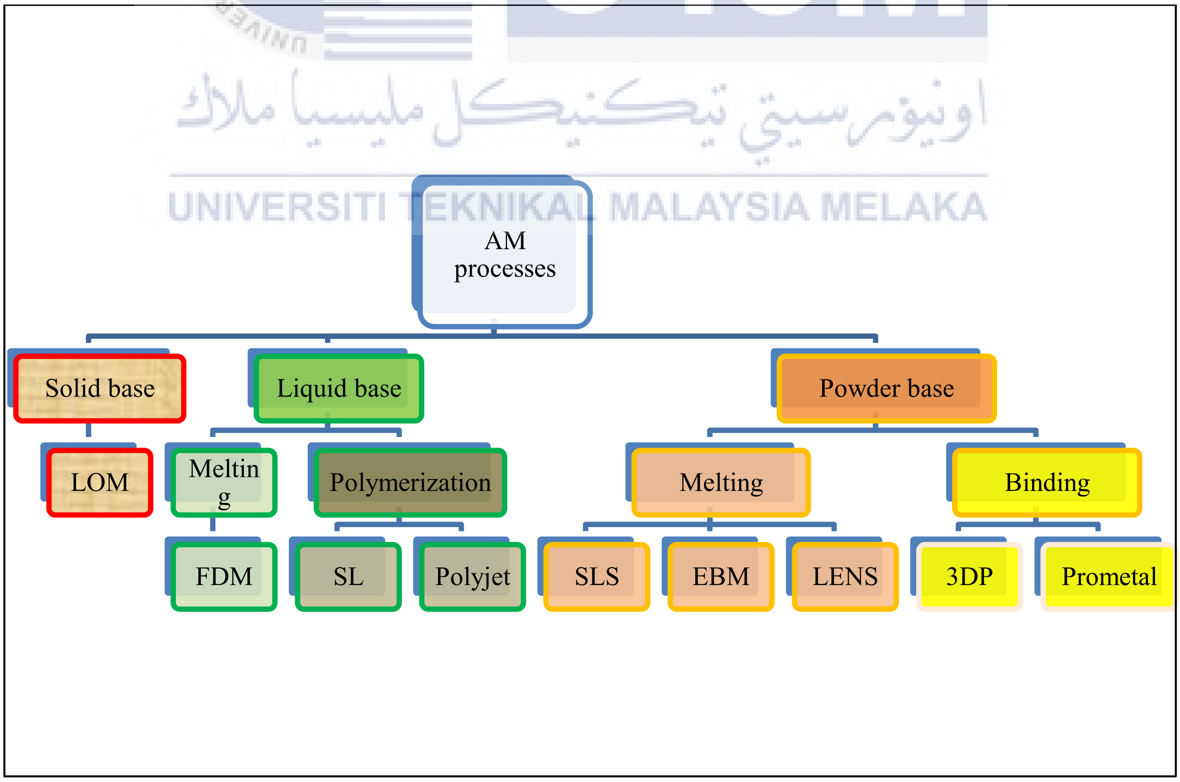


Figure 2.3: Different additive manufacturing processes (Hernandez et al. (2012))

2.2.1 Fused Deposition Modelling (FDM)

Lee et al. (2005) stated that fused deposition modelling (FDM) is one of the RP systems that created prototype from plastic materials by lying tracks of semi molten plastic filament on to a platform in a layer wise manner from bottom to top. The first step in producing an FDM part is to create a three dimensional solid model by using commonly available CAD softwares such as CATIA V5R20. Next, the 3D solid model will be converted to stereolithography (STL) format and exported to the FDM slicer software. Most CAD systems are compatible to STL format. Once the STL file has been transferred to slicer software, STL file is horizontally divided into many thin sections after it has been transferred to slicer software. FDM process will generate the two-dimensional contours that these sections represent. The two dimensional contours will closely resemble the original three dimensional part when they are stacked upon one another. Basically, all present RP processes are familiar with the sectioning approach. Clearly, the part will be more accurate when the sections are thinner. Next, the FDM machine's hardware is controlled by the process scheme that had been created by the software.

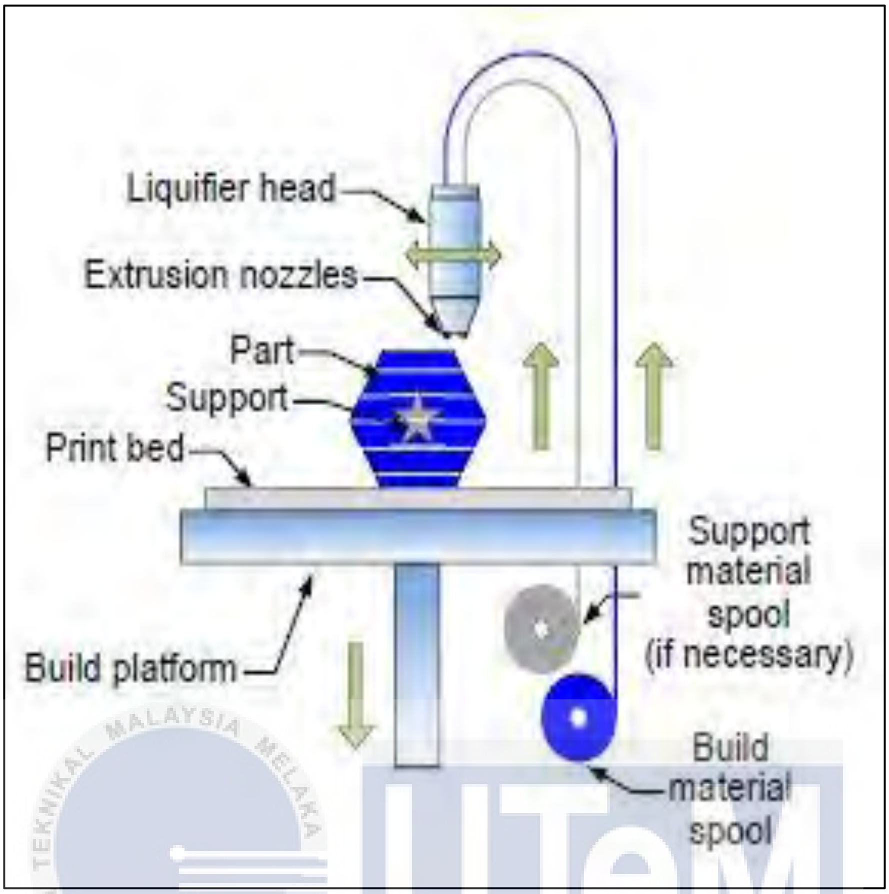


Figure 2.4: FDM apparatus set up

(Fahraz et al. (2014))

The concept of FDM is that its filament is fed through a heating element or liquefier head, which heats it to a semi-molten state. After that, the filament is fed through an extrusion nozzle and deposited onto the partially constructed part. Since the material is extruded in a semi-molten state, it merges with the material around it that has already been deposited. Then the head is moved around the X-Y plane and deposits material as specified to the part requirements from the STL file. After the previous layer is completed, the head is then moved vertically in the Z plane to begin depositing a new layer. After a period of time, normally several hours, the head will finish the deposition of a full physical representation of the original CAD file. This procedure may require a support structure to be created below the sections. The FDM machine has a second nozzle that extrudes support material. The support material is identical to the model material, but it is more brittle so that it can be easily extracted after the model is finished. Generally, the FDM machine fabricates support for any structure that has an overhang angle of less than 45° from horizontal as the default. As an example, if the angle is less than 45°, more than one half of one bead is overhanging the contour below it, and therefore is likely to fall (Montero, M. 2001).

2.2.2 Laminated Object Manufacturing (LOM)

Figure 2.4 demonstrates a common type of the laminated object manufacturing (LOM) process. As in other additive manufacturing, LOM process is conducted by layered manufacturing. Three main components of the LOM machine are a feed mechanism, a heated roller and a cutting tool. Chua et al. (2010) stated that stacking, bonding and cutting layers of adhesive-coated sheet material on top of the previous one are the processes involved in LOM part production. A cutting tool cuts the outline of the part into each layer according to prepared CAD data. After each cut is completed and another sheet is loaded on top of the earlier accumulated layers, the platform is lowered by a depth equal to the sheet thickness. After that, the platform is rises slightly, and the heated roller applies pressure to bond the new layer. The cutting tool cuts the outline, and the process is repeated until the last layer.

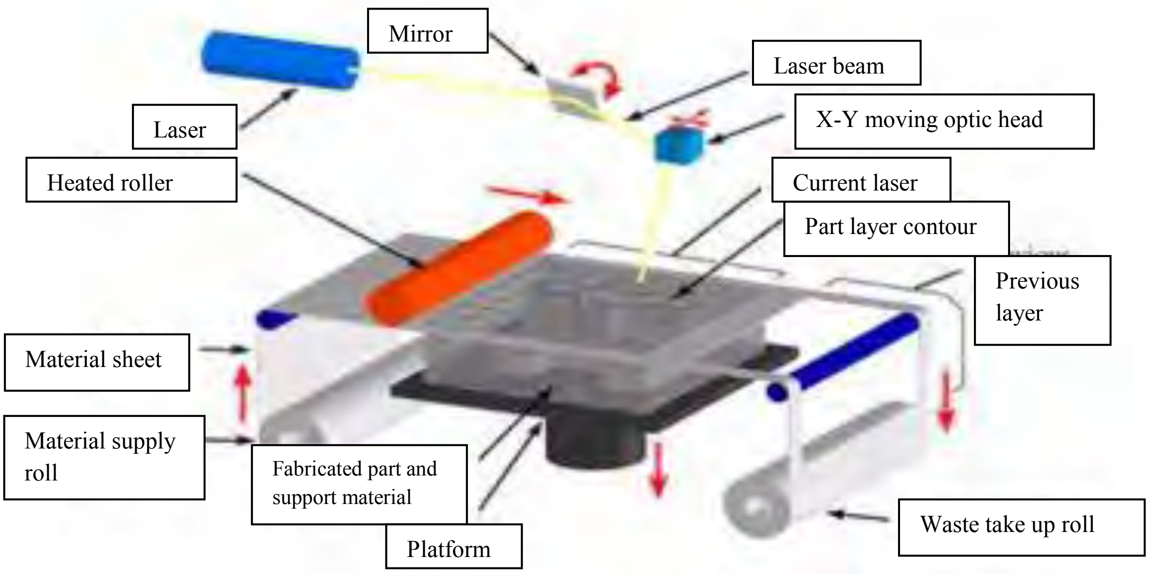


Figure 2.5: Example of LOM mechanism
(Chua et al. (2014))

2.2.3 Selective Laser Sintering (SLS)

Selective laser sintering (SLS) is one of the most common additive manufacturing processes that emerged in the last decades (Levy et al., 2003 and Kruth, J. 1991). SLS enables the fabrication of three dimensional polymer components with complicated shapes according to CAD data instantly out of powdery material without the need of tooling and setup. Hence parts are built layer by layer. Hopkinson et al. (2005) stated that three steps are repeated for each layer:

1. Firstly, the platform is lowered by the thickness of one layer.
2. Next, powder is deposited on the building platform using a moving roller or blade device and preheated to a temperature close to the material melting point.
3. After that, laser beam scans the powder layer with arbitrary trajectories in order to melt specific powder layer areas.

These steps are applied from time to time until the part is finished. Before the parts can be removed from the machine, consistent cooling has to occur while the viscose melted polymer crystallizes with minimal distortions.

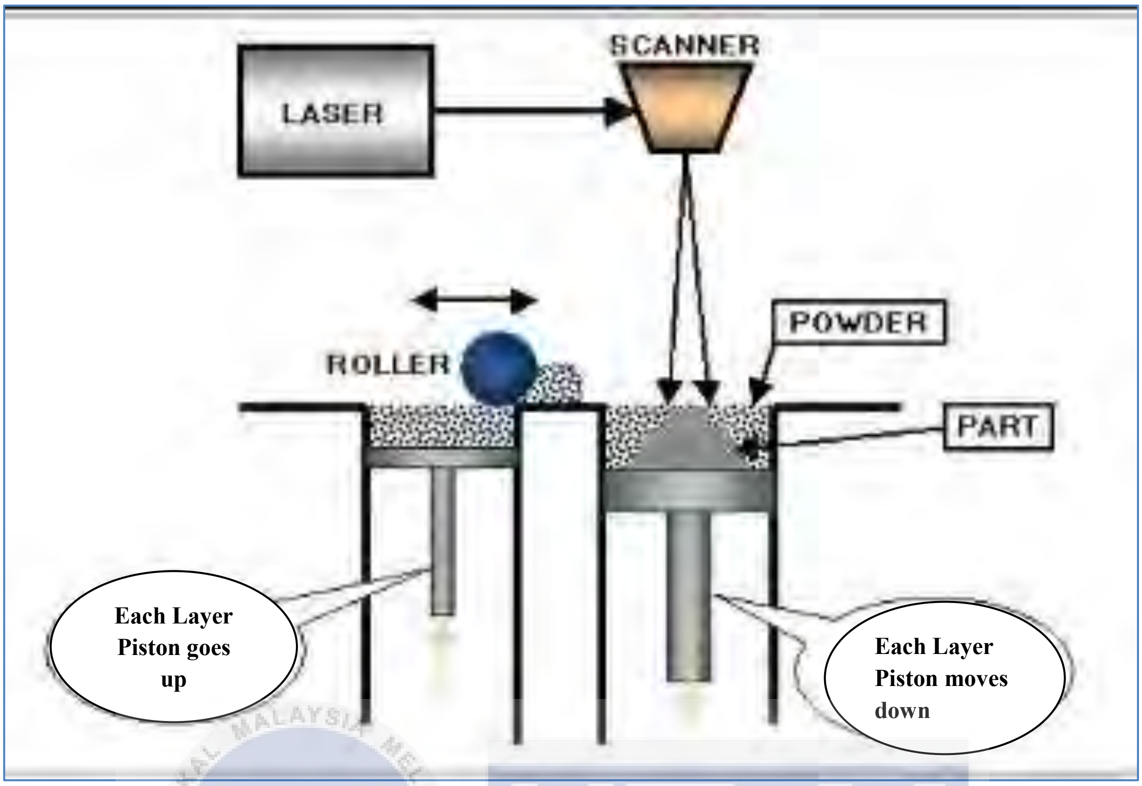


Figure 2.6: Example of SLS mechanism

(Pham et al. (2000))

2.3 FDM Parameters

Fused deposition modelling (FDM) is the RP technology that fabricates three dimensional objects from CAD file. A challenging research issue in RP is how to shorten the build time, improve the mechanical properties and surface accuracy, especially where numerous interactive process parameters are present. Distribution of influential parameters in the fabrication of FDM parts is shown in Figure 2.7 while the distribution of critical performance measures for FDM process is shown in Figure 2.8.

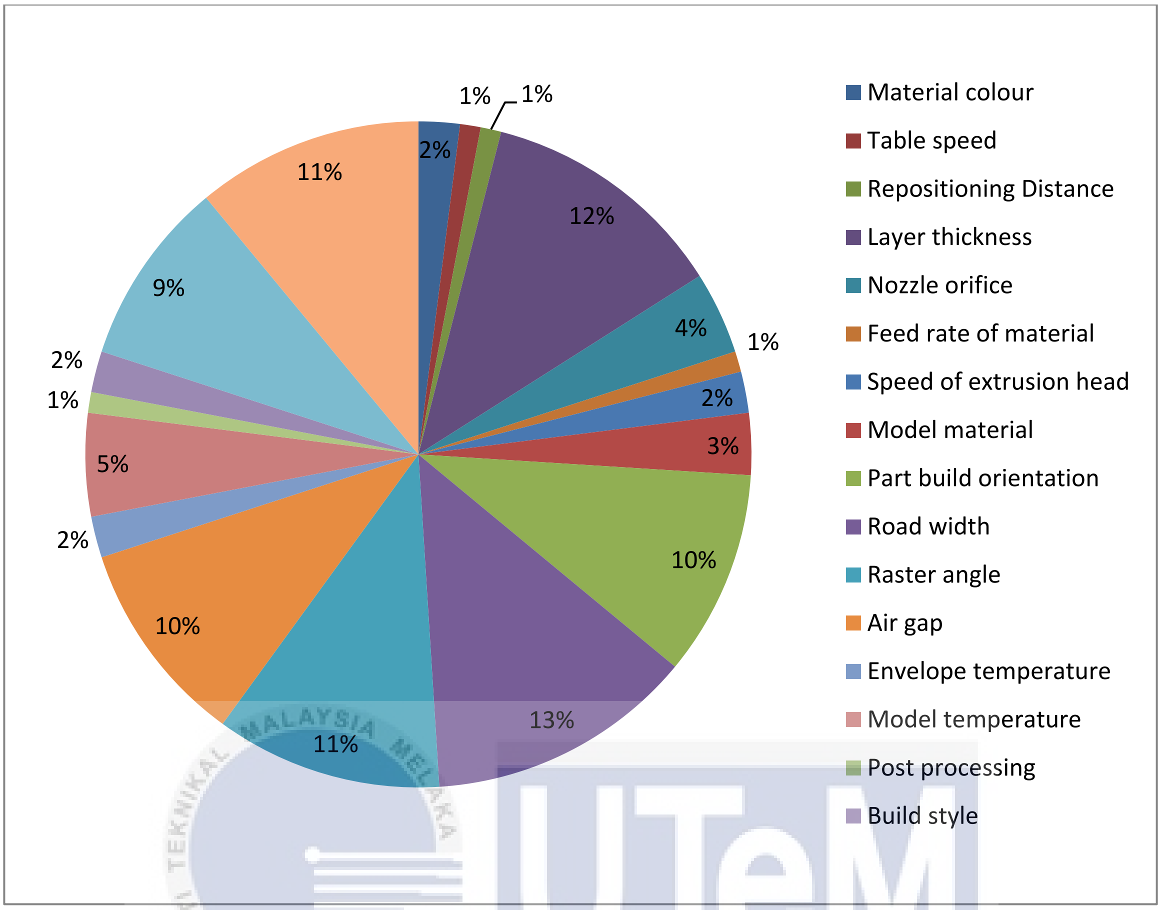


Figure 2.7: Distribution of influential parameters in the fabrication of FDM parts

(Fahraz et al. (2014))

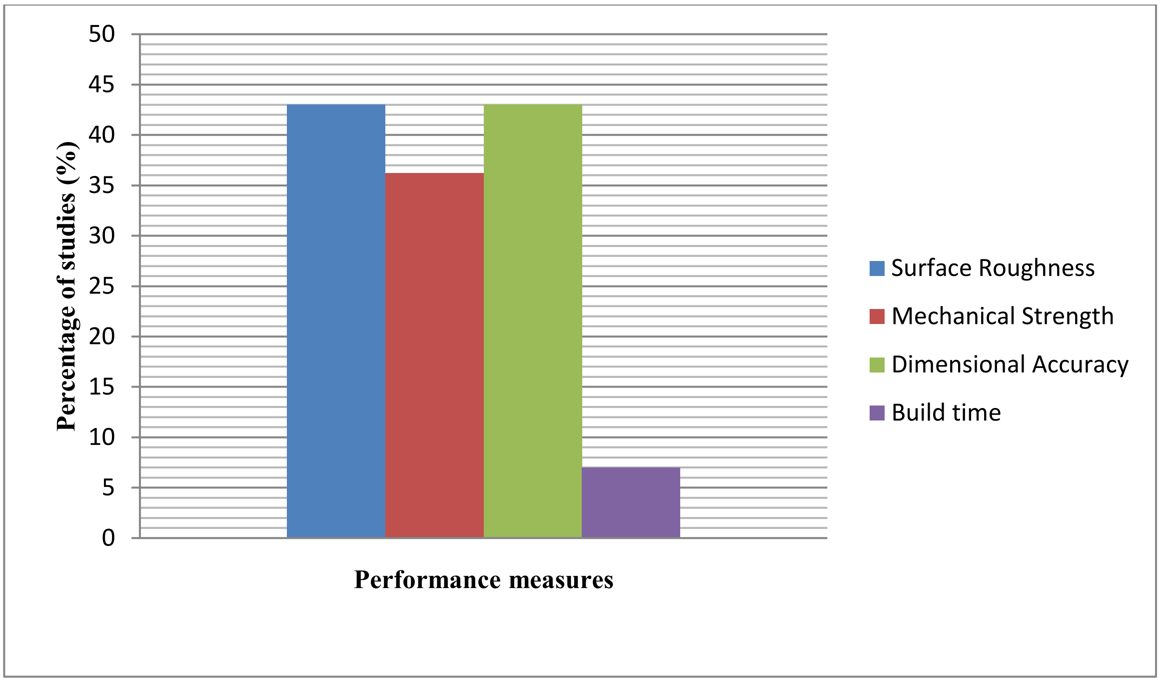
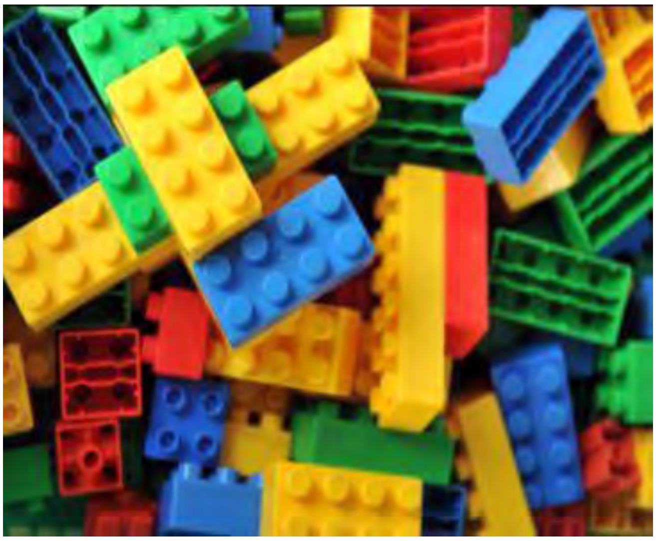


Figure 2.8: Distribution of critical performance measures for FDM process (Fahraz et al. (2014))

2.4 Acrylonitrile Butadiene Styrene (ABS)

In this review, the wear behaviour of FDM built parts printed with acrylonitrile butadiene styrene (ABS) pure material and carbon fibre reinforced ABS composite will be compared under dry sliding condition. Polymers are widely used in various engineering application such as sliding bearing, shaft seals, bushes and gears (Bijwe and Nidhi, 2007; Nagaraju et al., 2011; Aigbodion et al., 2012). ABS is one of the most common thermoplastic polymer. The glass transition of polymer is approximately 105 ˚C. One of the most important properties of ABS is impact resistance. The impact resistance can be improved by adding the proportions of polybutadiene in relation to styrene and also acrylonitrile, but may causes changes in other properties. While ABS plastics are generally used for mechanical and engineering purposes, they also have electrical properties that are fairly constant over a wide range of frequencies (Sa'ude, N. 2013). Light weight aspect of ABS and its ability to be extruded makes it beneficial in manufacturing products such as musical instruments and toys. Household and consumer goods are the major application of ABS (Kutsch, O. 2016).



a) Lego bricks made of ABS

(Kutsch, (2016))

b) Pipes made of ABS

(Kutsch, (2016))

c) Toys made of ABS
(Montero et al. (2002))

Figure 2.9 (a),(b) and (c): Daily applications of ABS

2.5 Reinforcement of Carbon Fibre in Polymer Matrix and Its Effects

In this research, only 15 % carbon fibre particles will be extruded along ABS particles to produce a composite filament. Carbon fibre reinforced polymer is a strong and light fibre reinforced plastic. Rupinder et al. (2016) stated that the range of the application of polymer can be extended further by the reinforcement of ceramics, metals, carbon fibre and fibre glass in polymer matrix. At present time, only fee stocks used as in FDM is thermoplastic filaments. The examples of thermoplastic filaments are acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polylactide (PLA) and polyamide (PA) (Tekinalp et al. 2014). Fuda et al. (2015) revealed that one of the possible ways to increase the strength of FDM printed pure thermoplastic parts is by adding reinforced materials such as carbon fibre into plastic materials to form thermoplastic matrix carbon fibre reinforced plastic (CFRP) composites. Nowadays, CFRP are applied in various industries. The examples of application are components in automotive and endoscopic surgery.

The studies performed thus far showed that glass fibre could significantly improve the tensile strength and surface rigidity of the ABS filament (Zhong et al., 2001). Tekinalp et al. (2014) compared carbon fibre reinforced ABS composites fabricated by both compress molding and FDM by conducting tensile test on printed samples. The tensile strength and Young's modulus of the samples were measured for the comparisons. The literature review (Tekinalp et al., 2014) showed that the samples created by both FDM and compress molding methods show important increases in both tensile strength and Young's modulus when the carbon fibre content is increased.

Figure 2.10: Raw carbon fibres
(Fuda et al. (2015))

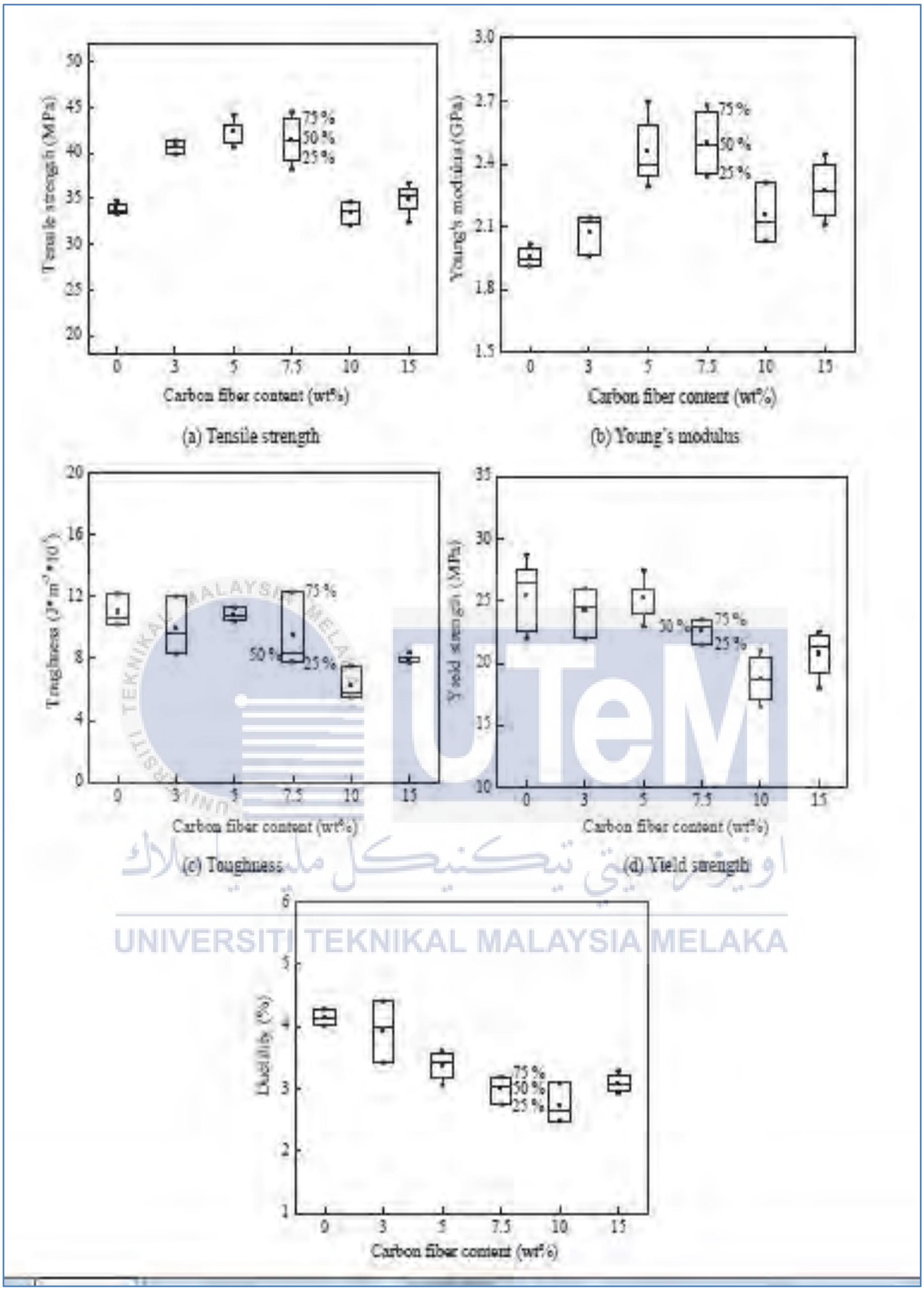


Figure 2.11: The effect of carbon fibre content on tensile properties

(Fuda et al. 2015)

2.6 Wear Test

Several studies (Rupinder et al. 2016; Vijay et al. 2012) have reported that the wear test was performed as recommended by ASTM G 99 standard under conditions of dry sliding at room temperature. This test method describes a laboratory procedure for determining the wear of materials during sliding using a pin on disk apparatus.

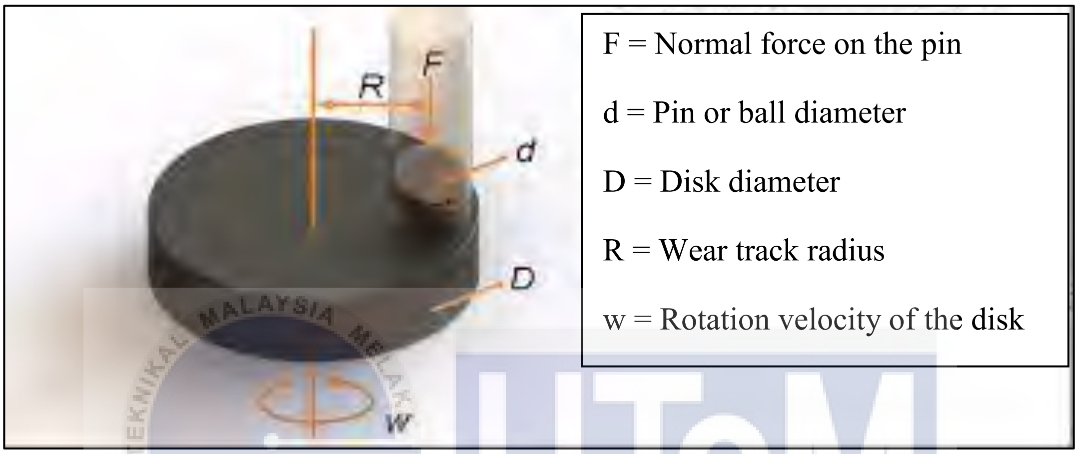


Figure 2.12: Schematic of pin on disk wear test system

(Rupinder et al. (2016))

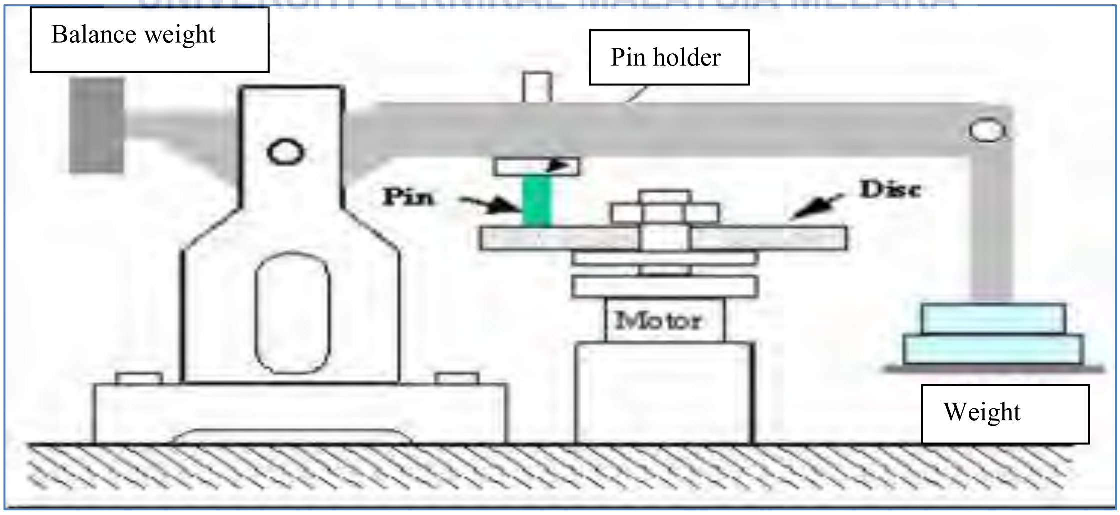


Figure 2.13: Arrangement of pin on disk apparatus

(Rupinder et al. (2016))

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will discuss about all the methodology used to conduct the study on wear behaviour of FDM printed part of carbon fibre reinforced ABS composite. The description begins with three main parts: the quantitative research, the data preparations and the experiment. The general methodology and planning during the research are shown in **figure 3.1**.

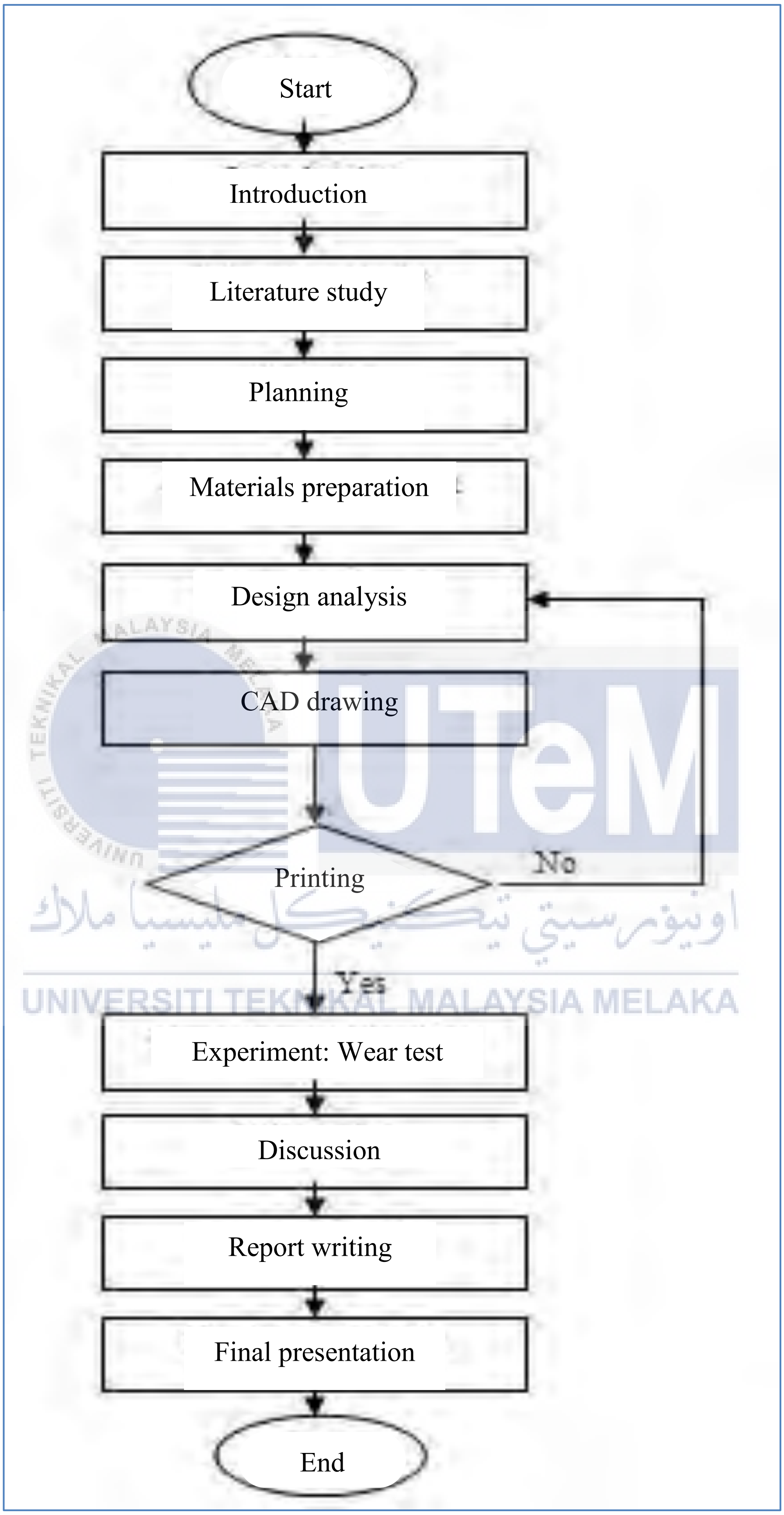


Figure 3.1: Flowchart of general methodology and planning

3.2 Quantitative Research

The first phase of the study focused on identifying the suitable test parameters, material characteristics, and test specification by conducting quantitative research. Quantitative research is the systematic empirical investigation of observable phenomena via statistical, mathematical or computational techniques (Lisa, M. 2008).

This method was carried out while researching and comparing the previous studies on this research, online journals, internet articles and books. The main purpose of conducting the quantitative research was to find the relationship between recent study and other previous studies.

3.3 Data Preparation

CATIA P3 V5R20 and FlashPrint are the main platforms for preparing the data of the test sample used in this study.

3.3.1 CATIA P3 V5R20

Computer aided three dimensional interactive application (CATIA) is a multi-platform software compatible for computer aided design (CAD), computer aided engineering (CAE) and computer aided manufacturing (CAM). CATIA was developed by the French company, Dassault Systemes. This software were used in this study to create a three dimensional model of test sample. Rupinder et al. (2016) used CATIA software to create the test sample to study the wear behaviour of FDM parts fabricated by composite material feed stock filament.

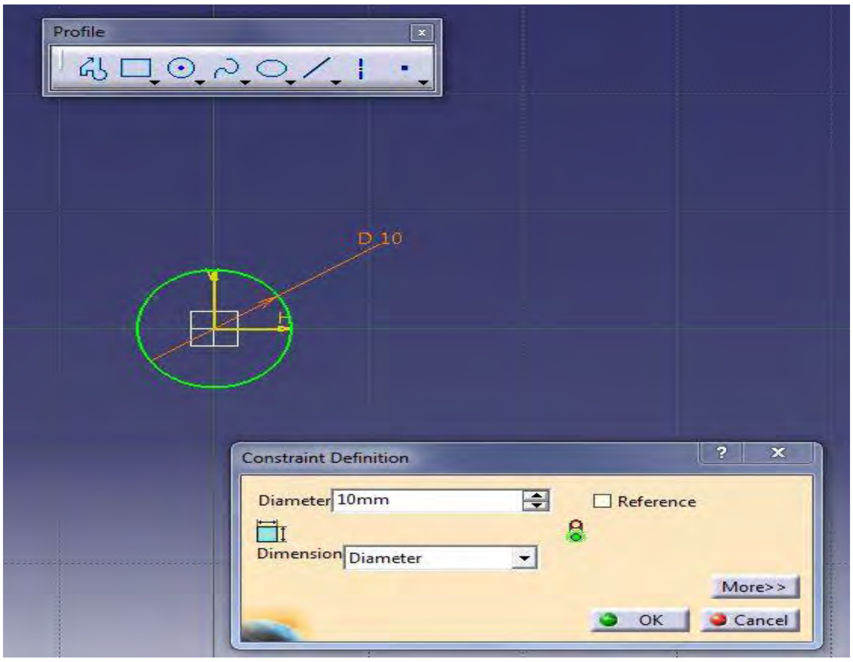


Figure 3.2: Sketching of test sample

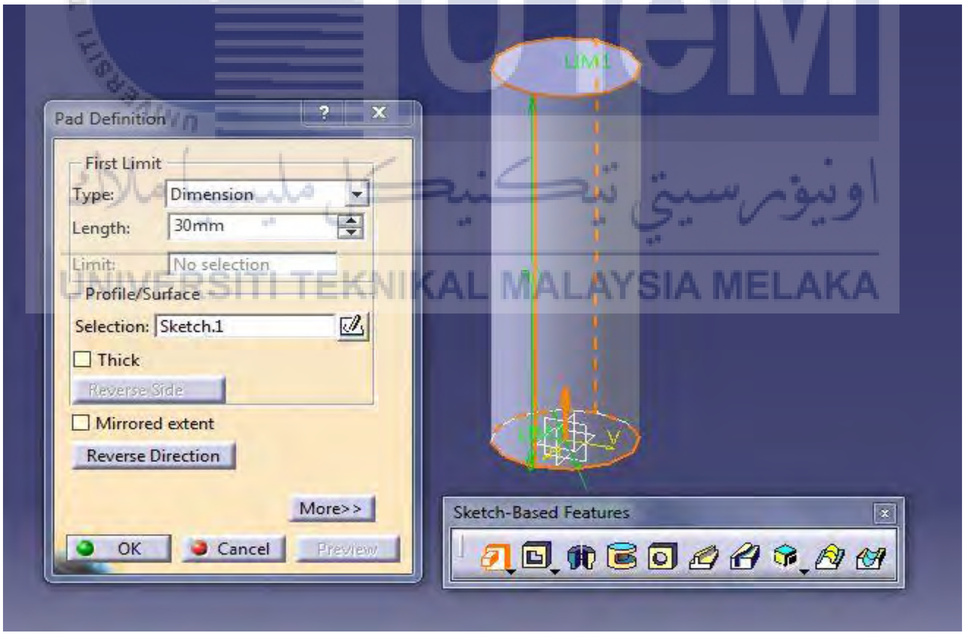


Figure 3.3: Complete 3D CAD drawing of test sample

3.3.2 FlashPrint

Three dimensional (3D) print models are typically distributed in a file format called stereolitoghraphy (STL). 3D printer slicer software is needed to convert an STL file into G-code, language which can be understood by a 3D printer.

FlashPrint is one of the 3D printer slicer software. In this study, the complete 3D CAD file in Figure 3.3 will be exported to FlashPrint software to be converted into STL file.

The parameters that will be used for all specimens are 0.25 mm layer thickness and 0° part built orientation.

3.4 Experiment: standard test method for wear testing with a pin-on-disk apparatus (ASTM G 99)

The experiment will be conducted as recommended by ASTM G 99 standard under dry sliding conditions at room temperature. The wear test will be performed with a sliding speed of 0.6 m/s, contact load of 5, 10, 15, 20, and 25 N for 3 and 5 minutes duration.

1. Immediately prior to testing, and prior to measuring or weighing, clean and dry the specimens. Take care to remove all dirt and foreign matter from the specimens. Use nonchlorinated, non-film-forming cleaning agents and solvents. Dry materials with open grains to remove all traces of the cleaning fluids that may be entrapped in the material. Steel (ferromagnetic) specimens having residual magnetism should be demagnetized. Report the methods used for cleaning.
2. Measure appropriate specimen dimensions to the nearest 2.5 µm or weigh the specimens to the nearest 0.0001 g.
3. Insert the disk securely in the holding device so that the disk is fixed perpendicular (61°) to the axis of the resolution.
4. Insert the pin specimen securely in its holder and, if necessary, adjust so that the specimen is perpendicular (61°) to the disk surface when in contact, in order to maintain the necessary contact conditions.
5. Add the proper mass to the system lever or bale to develop the selected force pressing the pin against the disk.
6. Start the motor and adjust the speed to the desired value while holding the pin specimen out of contact with the disk. Stop the motor.
7. Set the revolution counter (or equivalent) to the desired number of revolutions.
8. Begin the test with the specimens in contact under load. The test is stopped when the desired number of revolutions is achieved. Tests should not be interrupted or restarted.
9. Remove the specimens and clean off any loose wear debris. Note the existence of features on or near the wear scar such as: protrusions, displaced metal, discoloration, microcracking, or spotting.
10. Remeasure the specimen dimensions to the nearest 2.5 µm or reweigh the specimens to the nearest 0.0001 g, as appropriate.
11. Repeat the test with additional specimens to obtain sufficient data for statistically significant results.

Figure 3.4: Pin on disk procedures

(www.astm.org)

a. ***Load*** = Values of the force in Newtons at the wearing contact.

b. ***Speed*** = Relative sliding speed between the contacting surfaces in metres per second.

c. ***Distance*** = Accumulated sliding distance in meters.

d. ***Temperature*** = Temperature of one or both specimens at locations close to the wearing contact.

e. ***Atmosphere*** = Atmosphere (laboratory air, relative humidity, argon, lubricant, etc.) surrounding the wearing contact.

Figure 3.5: Wear test parameters

(www.astm.org)

3.4.1 Experimental Tables

Experiment 1

Composition: ABS

Run time: 3 minutes

Sliding speed: 286 RPM

Table 3.1: Expected result 1

Load (N)	Initial weight (g)	Final weight (g)	Weight loss (g)	Volume loss (mm^3)	Temperature (°C)	Friction force (N)	Friction coefficient	Wear rate (μm)
5								
10								
15								
20								
25								

Experiment 2

Composition: ABS

Run time: 5 minutes

Sliding speed: 286 RPM

Table 3.2: Expected result 2

Load (N)	Initial weight (g)	Final weight (g)	Weight loss (g)	Volume loss (mm^3)	Temperature (°C)	Friction force (N)	Friction coefficient	Wear rate (μm)
5								
10								
15								
20								
25								

Experiment 3

Composition: Carbon fibre reinforced ABS

Run time: 3 minutes

Sliding speed: 286 RPM

Table 3.3: Expected result 3

Load (N)	Initial weight (g)	Final weight (g)	Weight loss (g)	Volume loss (mm^3)	Temperature (°C)	Friction force (N)	Friction coefficient	Wear rate (μm)
5								
10								
15								
20								
25								

Experiment 4

Composition: Carbon fibre reinforced ABS

Run time: 5 minutes

Sliding speed: 286 RPM

Table 3.4: Expected result 4

Load (N)	Initial weight (g)	Final weight (g)	Weight loss (g)	Volume loss (mm^3)	Temperature (°C)	Friction force (N)	Friction coefficient	Wear rate (μm)
5								
10								
15								
20								
25								

Calculation and formula:

Volume loss, $V_{loss} = \frac{m_{loss}}{\rho}$

Friction coefficient, $\mu = \frac{F}{W}$

Specific wear rate, $k = \frac{V_{loss}}{WL}$

Sliding distance, $L = 2\pi \times r \times N \times t$

F = Frictional force (N)

W = Applied load (N)

L = Sliding distance (m)

r = Wear track radius (m)

N = Angular sliding speed (RPM)

T = Sliding time (min)

ρ = density (g/ mm³)

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter will discuss about the result and finding after the wear test have been carried out. The results were tabulated and presented in graphs which are according to the standard of scientific writing. The discussion and analysis of the results were referred and compared with the previous research.

4.2 Data and Result

Experiment 1

Composition: ABS
Run time: 3 minutes
Sliding speed: 286 RPM

Table 4.1: Result of Experiment 1

Load (N)	Initial weight (g)	Final weight (g)	Weight loss (g)	Volume loss (mm^3)	Temperature (°C)	Friction force (N)	Friction coefficient	Wear rate (μm)
5	2.3310	2.2727	0.0583	0.7921	23	0.5	0.100	542
10	2.2424	2.1275	0.1149	1.5300	25	0.6	0.060	733
15	2.2483	2.0762	0.1721	2.3771	26	1.2	0.080	1223
20	2.2762	2.1031	0.1731	2.3235	29	1.8	0.090	1317
25	2.2081	1.9584	0.2497	3.4205	32	2.4	0.096	1529

Experiment 2

Composition: ABS

Run time: 5 minutes

Sliding speed: 286 RPM

Table 4.2: Result of Experiment 2

Load (N)	Initial weight (g)	Final weight (g)	Weight loss (g)	Volume loss (mm³)	Temperature (°C)	Friction force (N)	Friction coefficient	Wear rate (μm)
5	2.2857	2.2191	0.0666	0.8695	22	0.9	0.1800	795
10	2.2536	2.0746	0.1790	2.4124	26	1.1	0.1100	881
15	2.2687	1.9679	0.3008	4.0160	28	2.6	0.1733	1326
20	2.2807	1.9747	0.3060	4.1860	33	2.7	0.1350	1512
25	2.2264	1.9162	0.3102	4.0923	36	3.0	0.1200	1947

Experiment 3

Composition: Carbon Fibre Reinforced ABS

Run time: 3 minutes

Sliding speed: 286 RPM

Table 4.3: Result of Experiment 3

Load (N)	Initial weight (g)	Final weight (g)	Weight loss (g)	Volume loss (mm³)	Temperature (°C)	Friction force (N)	Friction coefficient	Wear rate (μm)
5	2.2067	2.1494	0.0573	0.7936	20	0.2	0.0400	125
10	2.2354	2.1771	0.0585	0.7948	21	0.2	0.0200	518
15	2.2241	2.0623	0.1618	2.1545	22	0.5	0.0333	710
20	2.2321	2.0616	0.1705	2.2917	22	0.9	0.0450	880
25	2.2463	2.0646	0.1817	2.4925	22	1.3	0.0520	1180

Experiment 4

Composition: Carbon Fibre reinforced ABS

Run time: 5 minutes

Sliding Speed: 286 RPM

Table 4.4: Result of Experiment 4

Load (N)	Initial weight (g)	Final weight (g)	Weight loss (g)	Volume loss (mm³)	Temperature (°C)	Friction force (N)	Friction coefficient	Wear rate (μm)
5	2.2387	2.1750	0.0637	0.8960	23	0.7	0.1400	306
10	2.2615	2.1351	0.1264	1.7151	24	0.9	0.0900	558
15	2.2539	2.0130	0.2409	3.2336	25	1.8	0.1200	779
20	2.2319	1.9726	0.2593	3.5618	25	2.0	0.1000	983
25	2.2441	1.9544	0.2897	3.8068	26	2.3	0.0920	1253

4.3 Loss of Material Volume

The wear of polymers is caused by abrasion and adhesion mechanism which usually started by abrasion (Nagaraju et al., 2011). In Experiment 1 and Experiment 3, both types of samples which are the pure ABS and carbon fibre reinforced ABS were applied with varying load in 3 minutes duration (Figure 4.1). The result showed that the carbon fibre reinforced ABS specimen loss smaller amount of mass rather than the ABS specimen. Experiment 2 and Experiment 4 which were ran in 5 minutes duration also showed the same trend in Figure 4.2 except the values of material mass loss were bigger when being compared with Experiment 1 and Experiment 3.

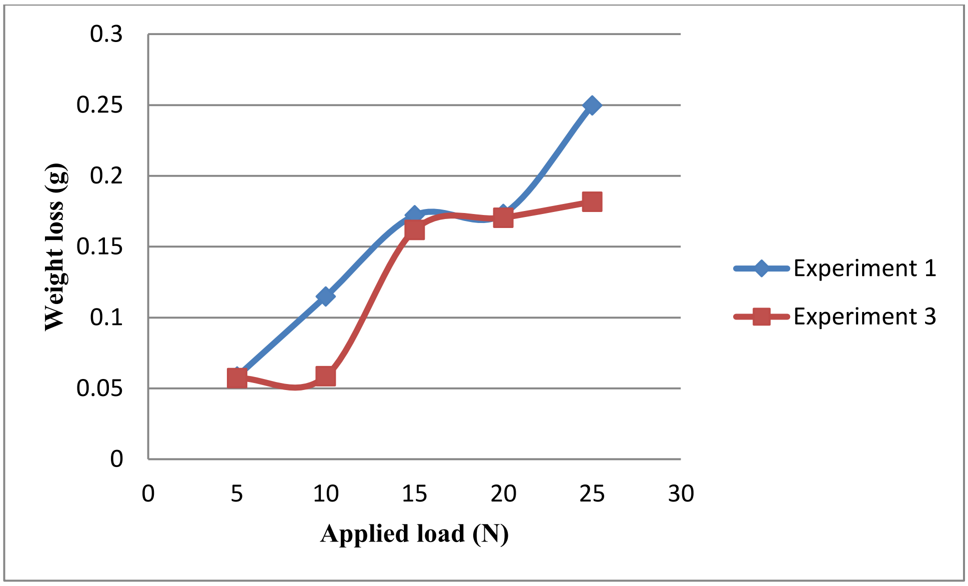


Figure 4.1: Mass loss with applied load (3 minutes run time)

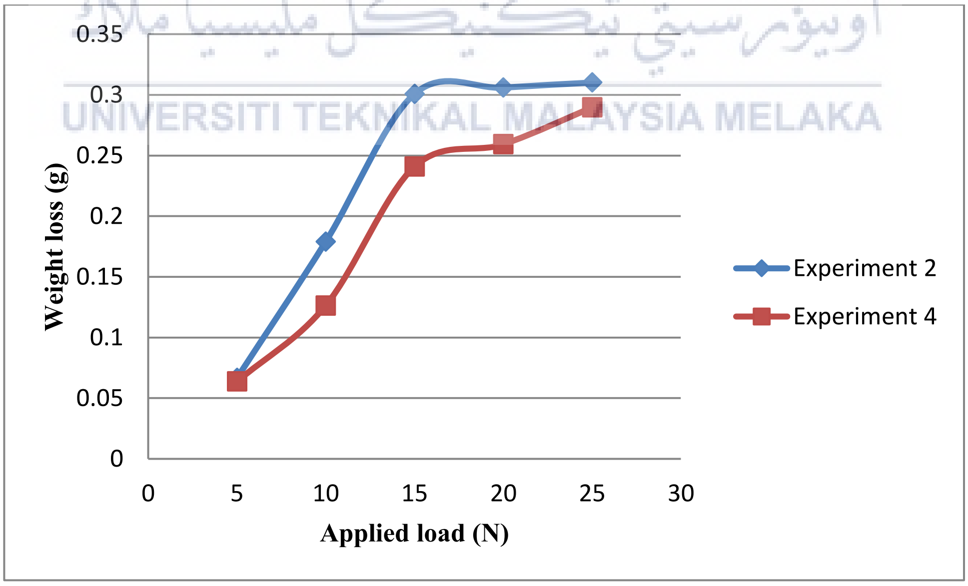


Figure 4.2: Mass loss with applied load (5 minutes run time)

According to ASTM G-99, results of mass loss were used internally in the laboratory in order to compare specimens with equivalent densities. Because of that, results of volume loss were used to measure wear so that there is no confusion caused by variations in density. All experiments showed that the higher the load applied, the higher the values of volume loss (Figure 4.3 & Figure 4.4).

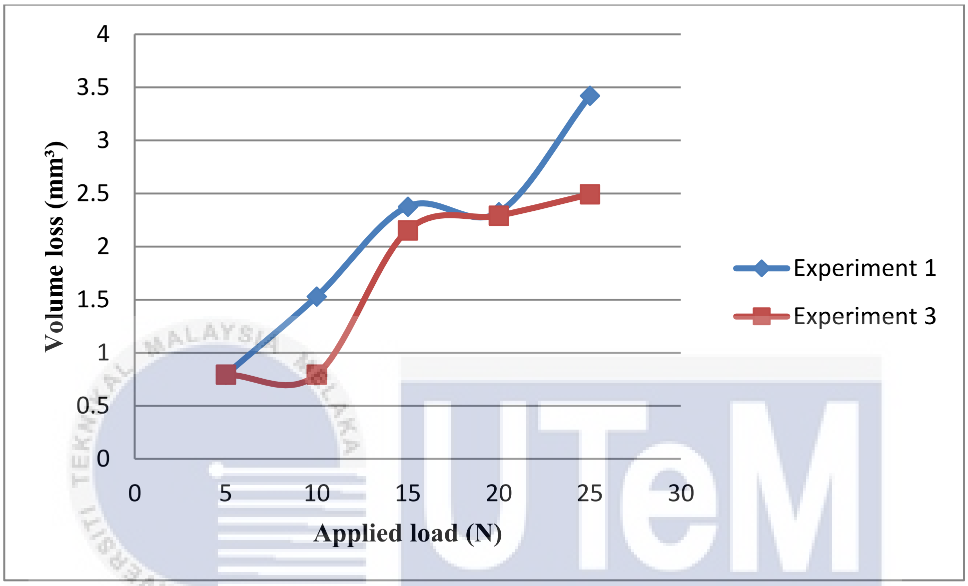


Figure 4.3: Volume loss with applied load (3 minutes run time)

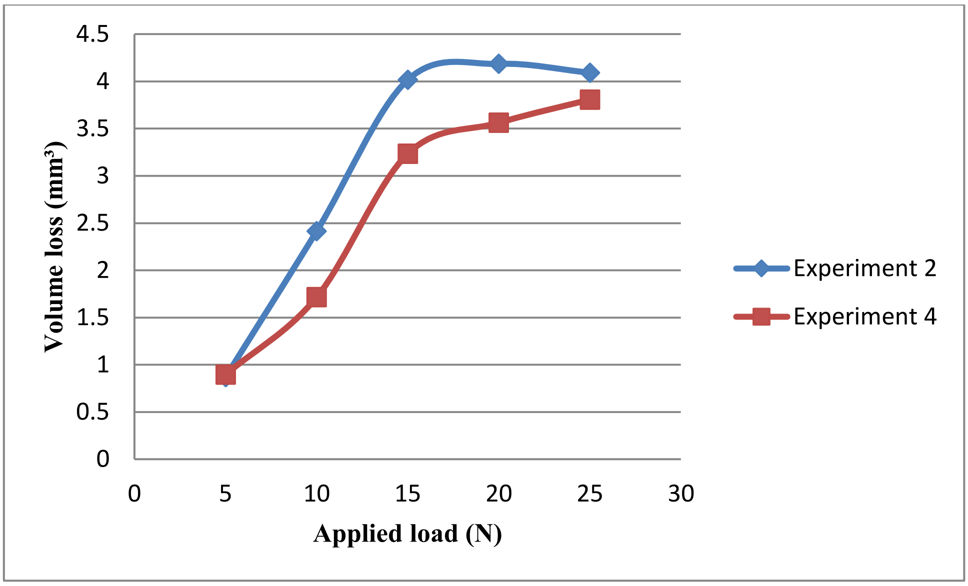


Figure 4.4: Volume loss with applied load (5 minutes run time)

Many researchers have stated that when the reinforcement of filler materials is made against polymeric materials, the wear resistance of the materials will increase (Rupinder et al., 2016). From the Archard wear equation, factors affecting wear rate are volume loss, sliding distance, and applied load. At higher values of applied load, the reinforced material started to fracture. Thus produce high values of wear rate. There are many previous researchers that state oxidation and adhesion takes place at lower loads while delamination at higher loads (Aigbodion et al., 2012). The augmentation of carbon fibre escalates abrasive properties and sliding resistance which interrupts breakdown from occurs because of the good sliding properties of carbon besides high thermal stability properties of carbon fibre (Figure 4.5 & Figure 4.6).

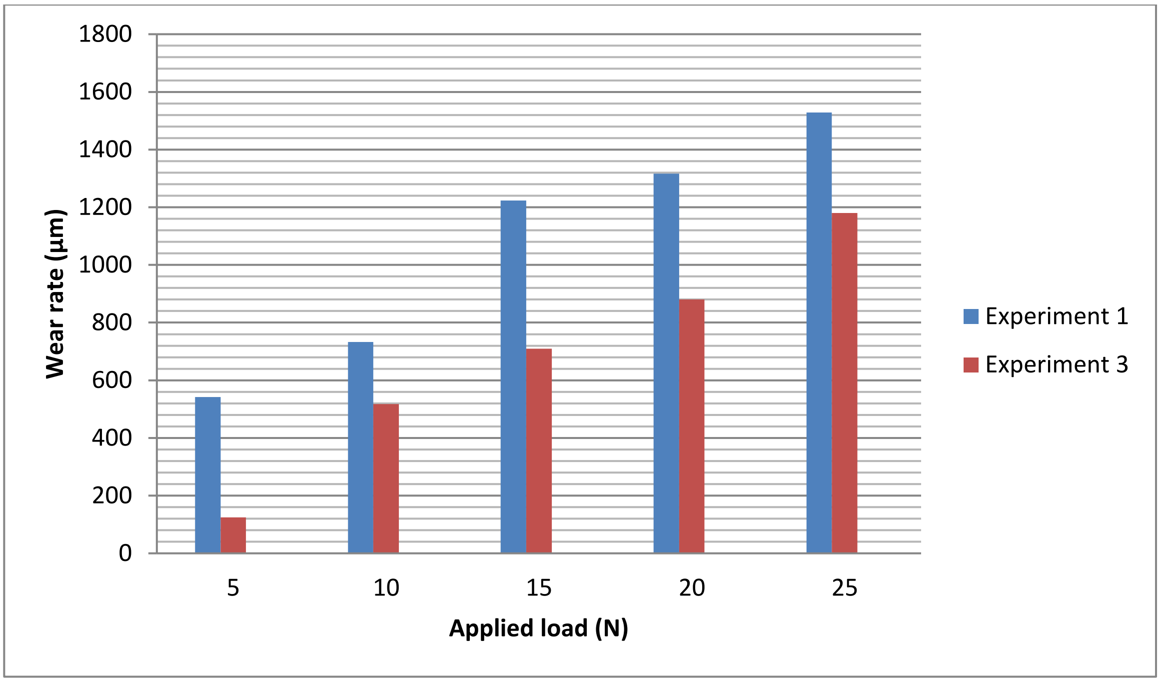


Figure 4.5: Wear rate with applied load (3 minutes run time)

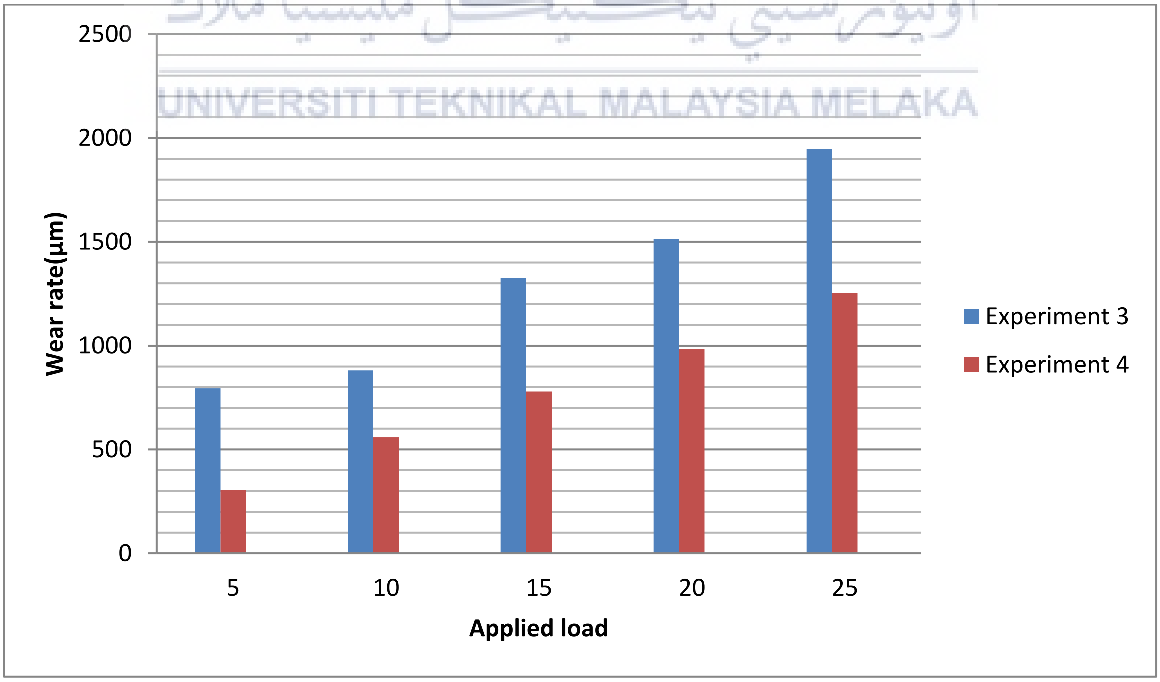


Figure 4.6: Wear rate with applied load (5 minutes run time)

4.4 Friction Force

Friction force is the force that opposes the relative motion between two objects. Dry friction is one of the several types of friction. Based on the graph, the friction force increased when the applied load and run time duration are increased. The friction force of carbon fibre reinforced polymer specimen is smaller than the friction force of pure ABS specimen. These results are due to transfer film that formed on the counterface when the specimen slides over a rough surface under dry sliding condition. The presence of the transition layers lower the friction between the surfaces (Figure 4.7 & Figure 4.8).

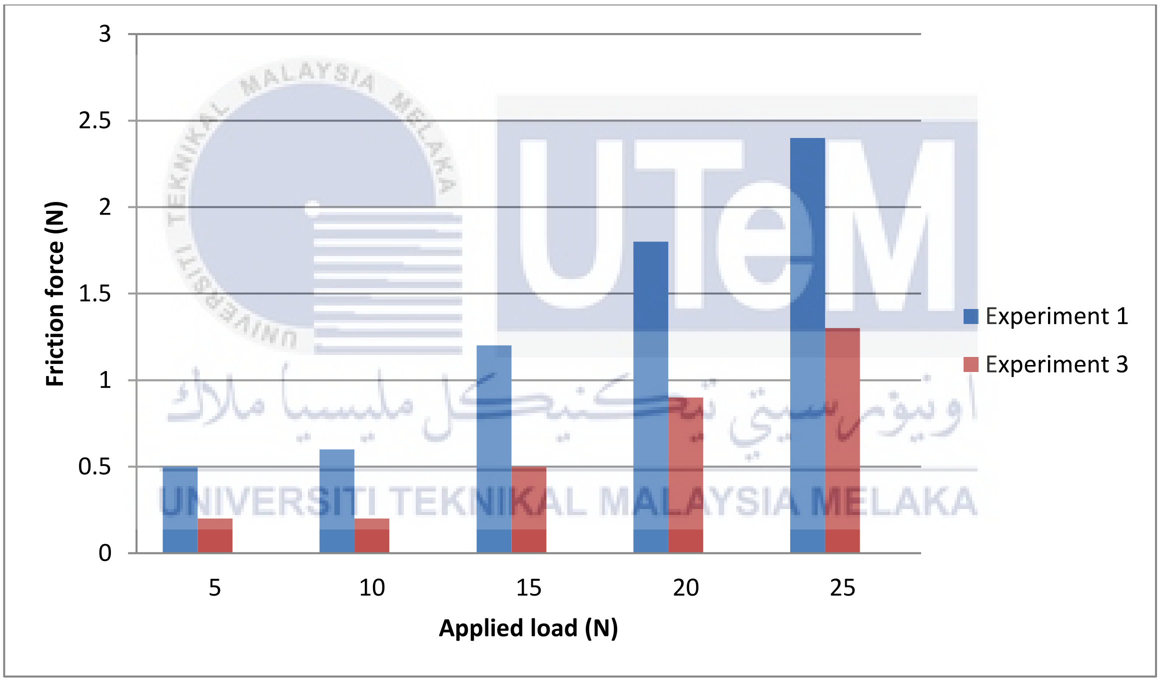


Figure 4.7: Friction force with applied load (3 minutes run time)

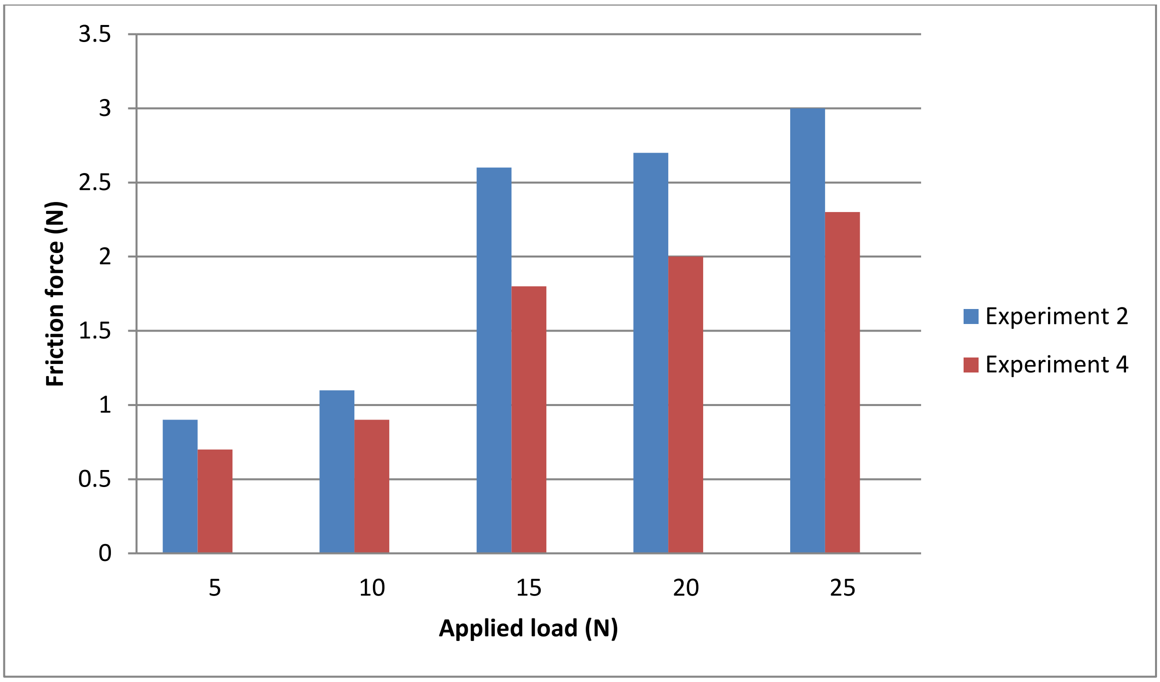


Figure 4.8: Friction force with applied load (5 minutes run time)

4.5 Coefficient of Friction

Application of filler material on polymer gives an opportunity to decrease the friction coefficient of the polymer (Friedrich et al., 2005). Previous researchers also observed that the coefficient of friction can be decreased by reinforcement of graphite in PA 6 and PA 1212 polymers and the addition of aramid fibre in PA 1010 polymer (Rupinder et al., 2016). Figure 4.9 show the difference of friction coefficient in Experiment 1 and Experiment 3. The presence of filler material in Experiment 3 which is carbon fibre managed to decrease the coefficient of friction on ABS polymer. Initially, the friction coefficient has a higher value because the specimen experienced the running-in wear state which is related to the removal of the polymer surface. Then, the wear process became stable as the transition layer is formed. Figure 4.10 showed the same trend as Figure 4.9 except higher in value of friction coefficient. The value of coefficient of friction increased as the run time is increased.

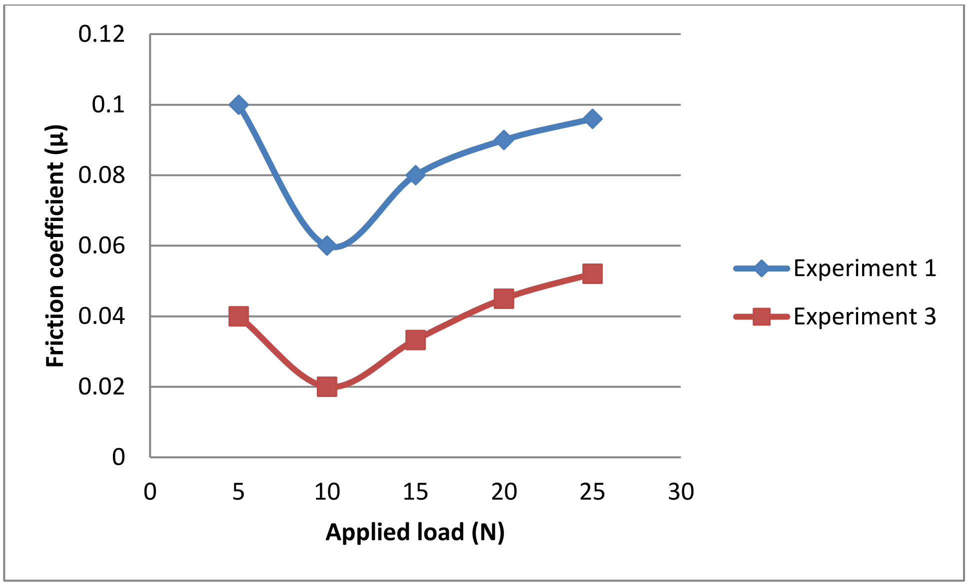


Figure 4.9: Friction coefficient with applied load (3 minutes run time)

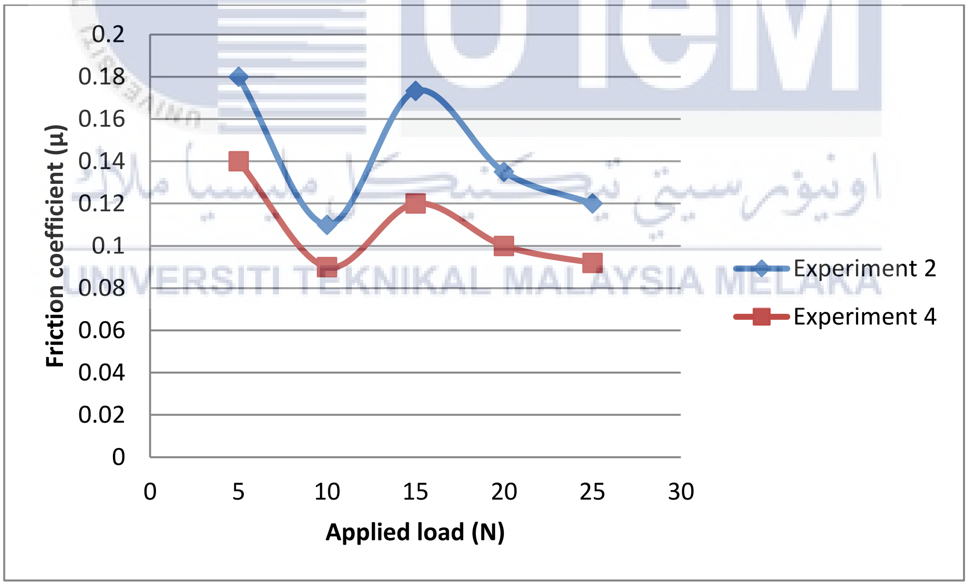


Figure 4.10: Friction coefficient with applied load (5 minutes run time)

4.6 Change of Temperature

In the experiment, the specimen temperature increased when the applied load and run time duration are increased. Rupinder (2016) stated that the heat of material constantly disintegrate from the contact surface and resulted in smaller change of temperature rise in reinforced polymer as compared to the change of temperature rise in ABS specimen. Figure 4.11 and Figure 4.12 showed that the temperature on pure ABS material specimen is higher than the temperature on carbon fibre reinforced ABS specimen. The temperature increased when the run time duration is increased. It is because the sliding distance is longer when the run time duration is increased.

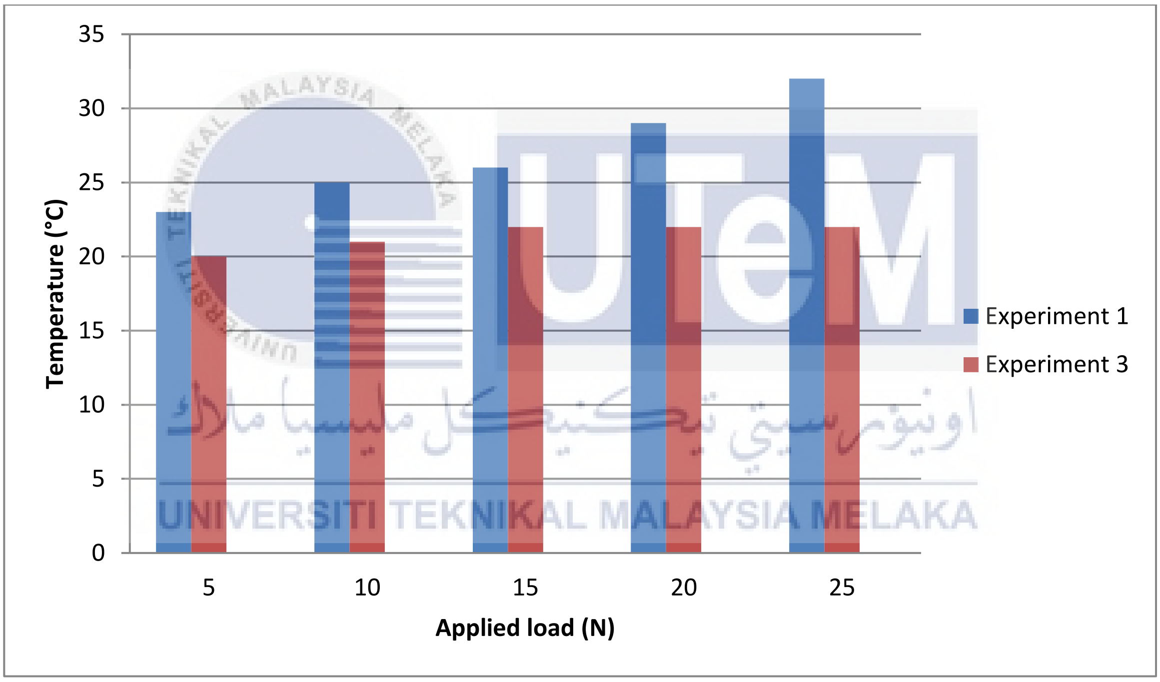


Figure 4.11: Temperature change with applied load (3 minutes run time)

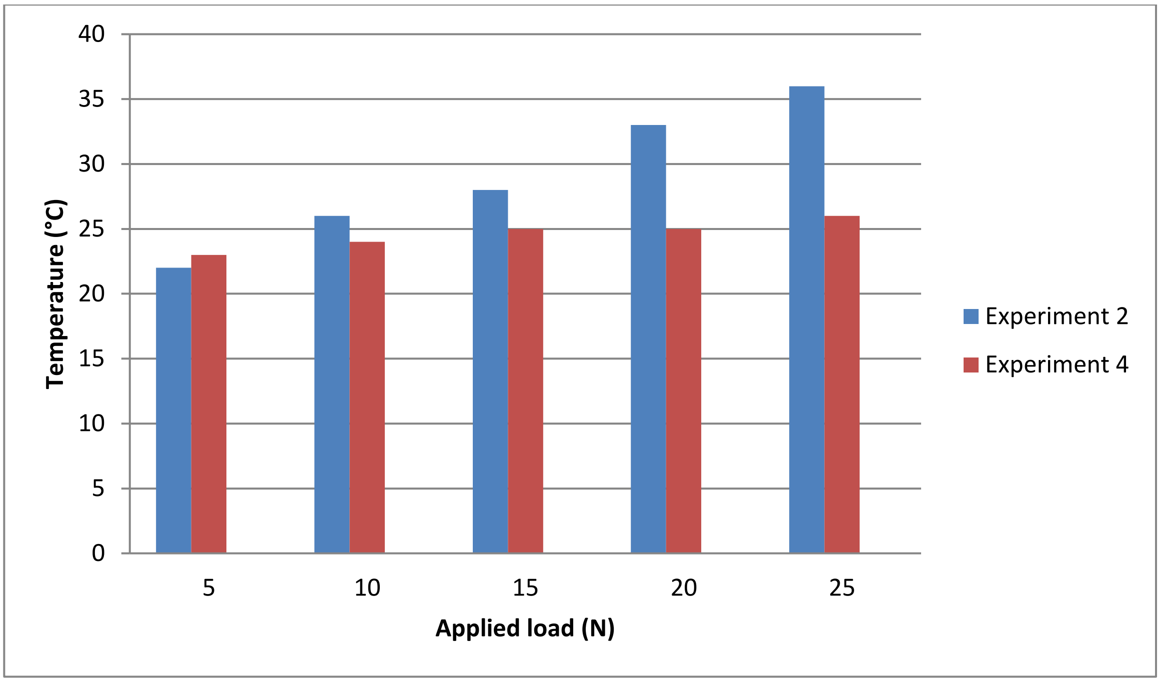


Figure 4.12: Temperature change with applied load (5 minutes run time)

4.7 Surface Analysis

When the test is being carried out, it can be seen that all specimen producing wear debris. The number of wear debris increased as the applied load and run time duration is increased. However, ABS specimen produces higher wear debris on the wear track rather than the carbon fibre reinforced ABS specimen. Generally, the surface of ABS specimen is rough. The sliding process between the surface of the specimen and rough counter surface on the sliding disk promotes abrasive wear mechanism which resulted in high loss of specimen's volume. The abrasive wear mechanism of ABS specimen is constant until the end of the experiment. For the carbon fiber reinforced ABS specimen, the wear mechanism started with abrasion. As the test continued with higher load applied and run time duration, the adhesive wear mechanism started to increase and substituted the abrasive wear mechanism. Hard and wear resistant particles of filler materials act as bearing in three-body abrasion mode (Rupinder et al., 2016). The rate of material removal in three-body abrasion is lower than the two-body abrasion mode. Figure 4.13 until Figure 4.16 show the wear track of the specimens.

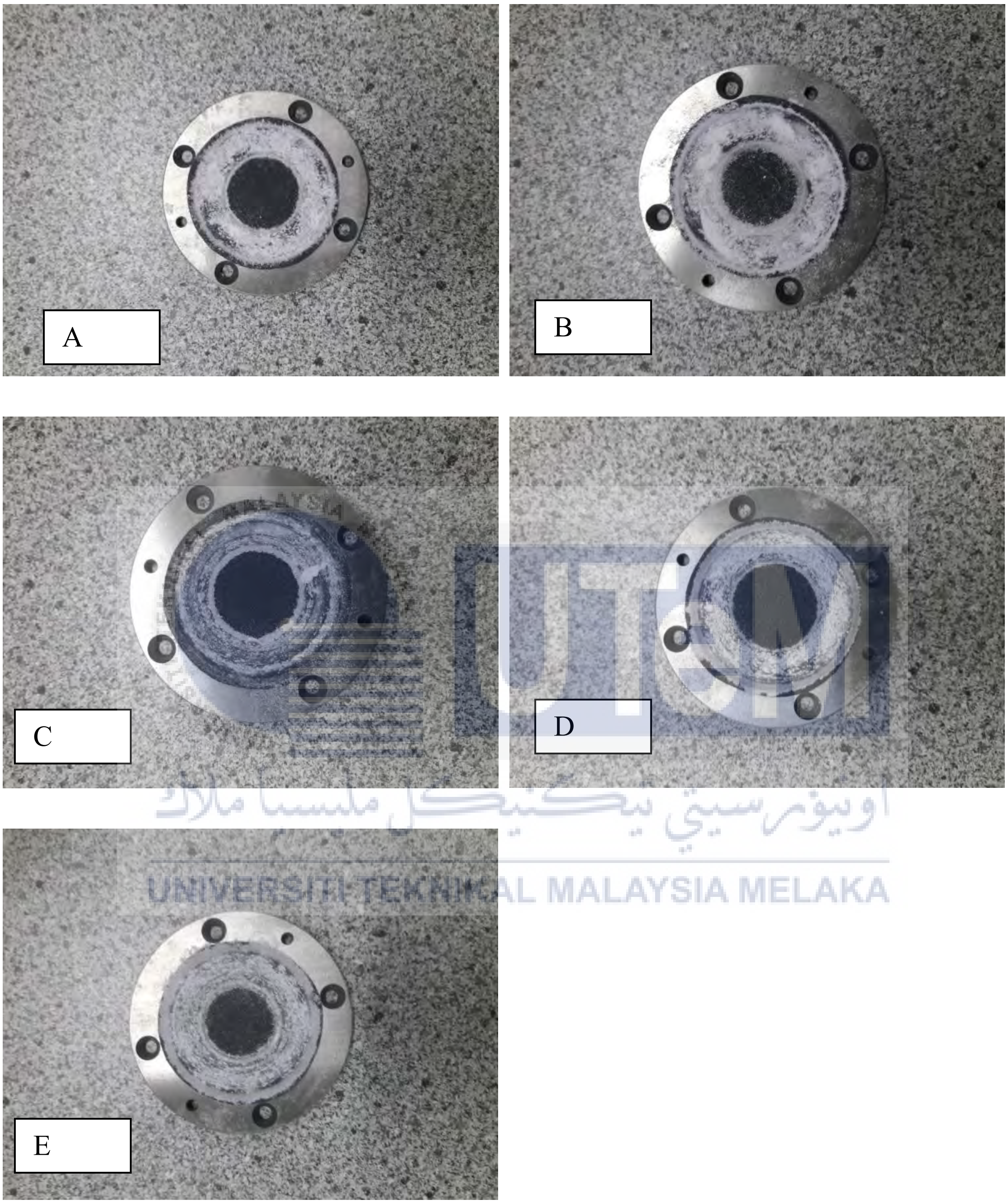


Figure 4.13: Wear track of pure ABS specimen (3 minutes run time)

Notes: A (5 N), B (10 N), C (15 N), D (20 N), E (25 N)

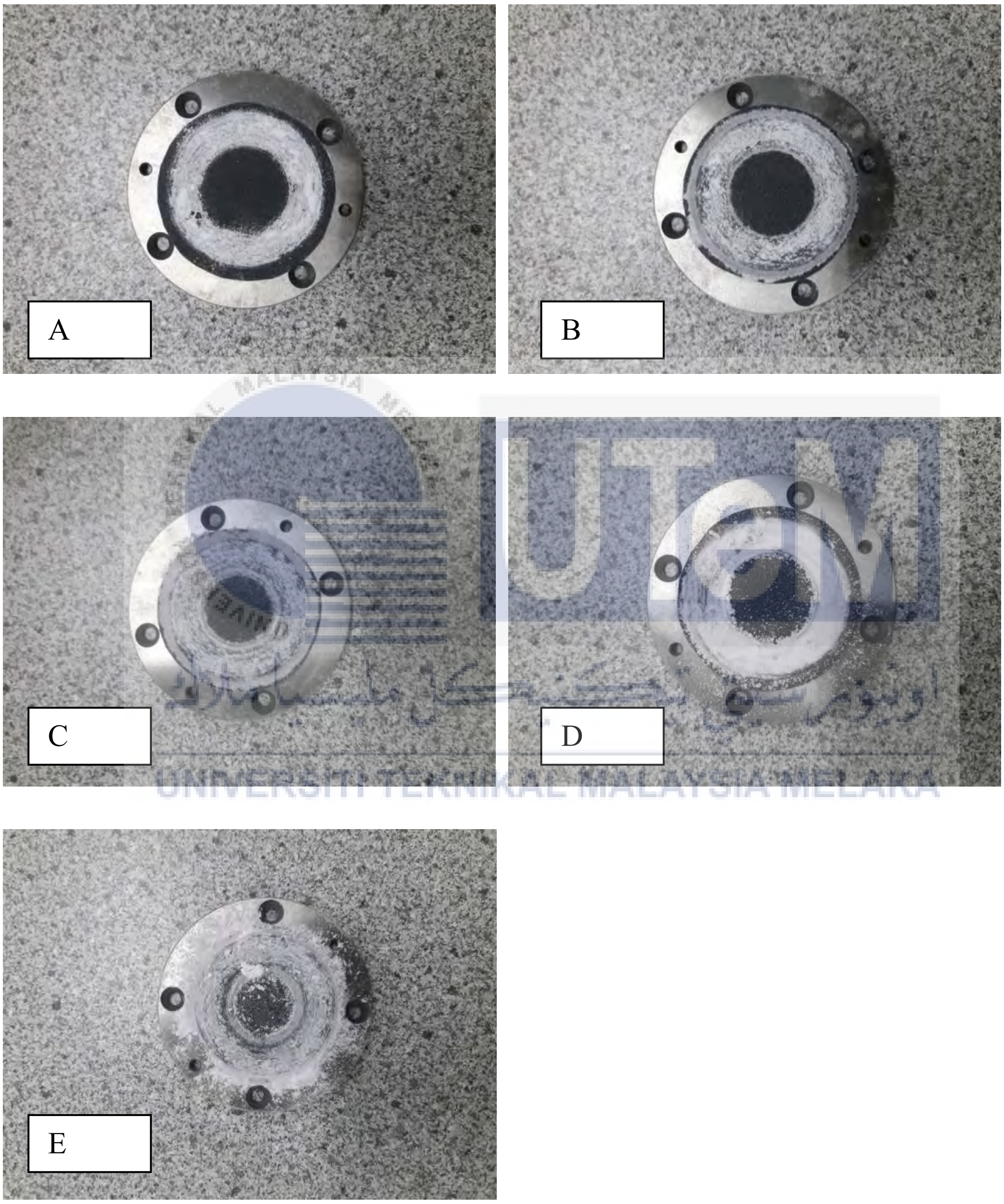


Figure 4.14: Wear track of pure ABS specimen (5 minutes run time)

Notes: A (5 N), B (10 N), C (15 N), D (20 N), E (25 N)

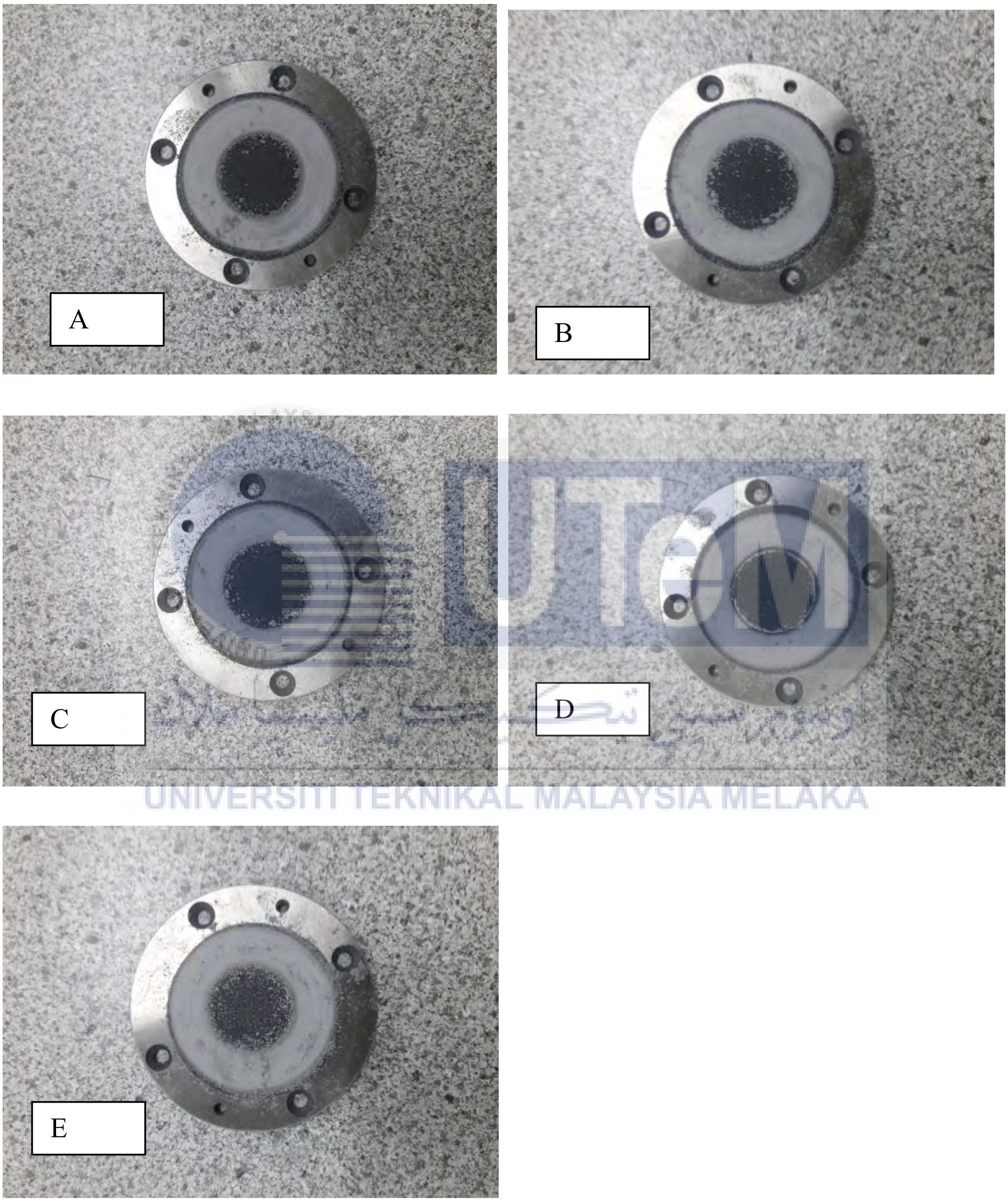


Figure 4.15: Wear track of carbon fibre reinforced ABS specimen(3 minutes run time)

Notes: A (5 N), B (10 N), C (15 N), D (20 N), E (25 N)

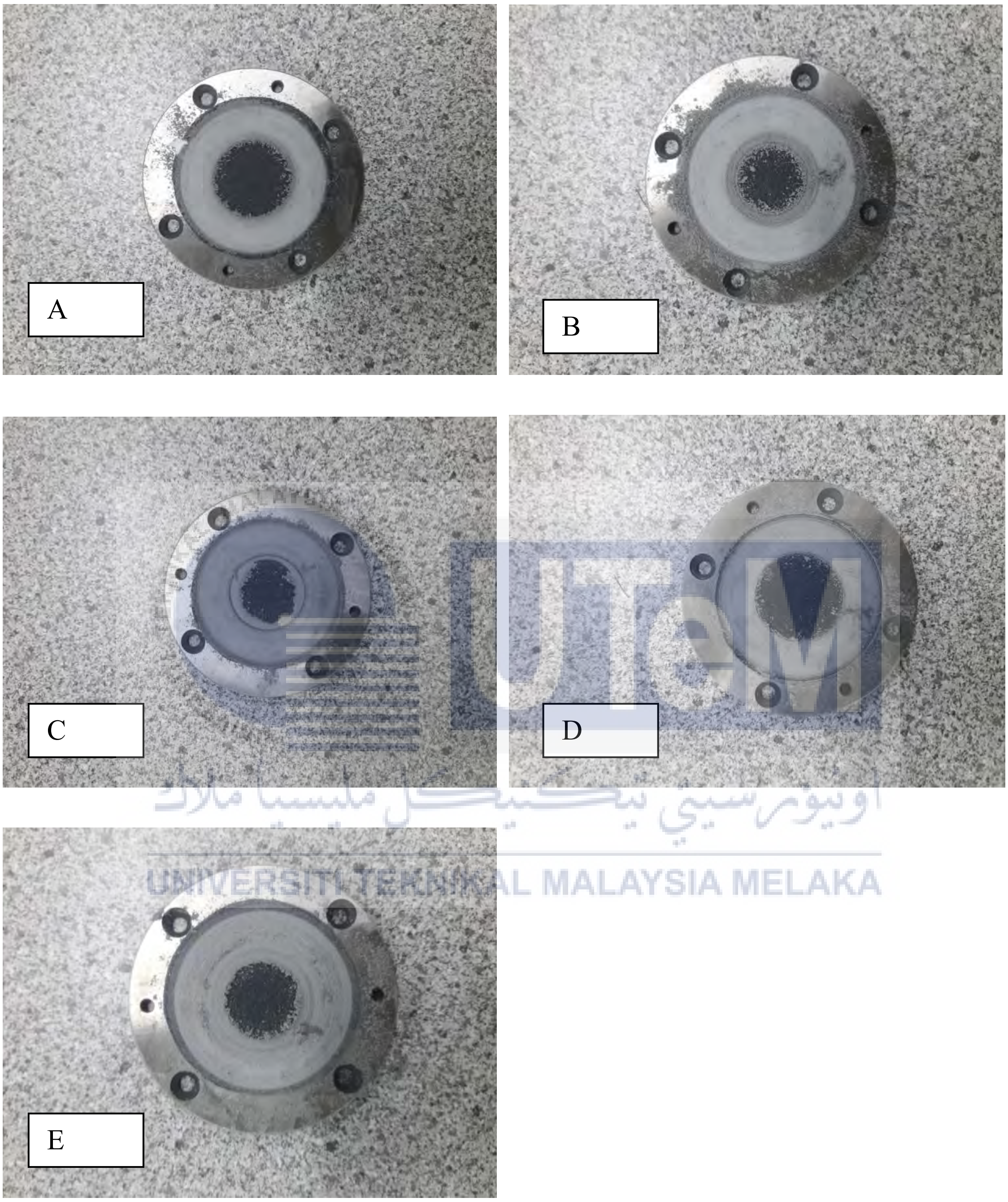


Figure 4.16: Wear track of carbon fibre reinforced ABS specimen (5 minutes run time)
Notes: A (5 N), B (10 N), C (15 N), D (20 N), E (25 N)

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Introduction

This chapter will discuss about the conclusion of the project work and some recommendation for the upcoming research. The conclusion will reveal about all the important findings that can be found throughout the research.

5.2 Conclusion

Wear behaviour of FDM printed parts of ABS and carbon fibre reinforced ABS filament were investigated and compared under dry sliding condition at room temperature. The test were carried out by using pin on disk apparatus with the parameter of 5, 10, 15, 20 and 25 N of applied load for each run time duration of 3 and 5 minutes and 0.6 m/s or 286 RPM sliding velocity.

The research found that carbon fibre reinforced ABS specimen have higher wear resistance as compared to pure ABS specimen. It is because carbon particles act as bearing in three-body abrasion mode and lower the rate of material removal of the specimen.

There are two types of wear mechanism that attribute wear loss which are abrasion and adhesion. Abrasive wear mechanism mostly occurs on pure ABS specimen while adhesion occurs on carbon fibre reinforced ABS specimen.

Pure ABS specimen has higher material loss (7%), friction force (23%), coefficient of friction (23%), temperature rise and wear rate (36%) when being compared with pure carbon fibre reinforced ABS specimen after the maximum load of 25 N is applied with constant sliding speed of 286 RPM for 5 minutes run time duration. These show that carbon fibre reinforced ABS specimen have high stability and strength when operating at high sliding velocity and long run.

The wear track images of both specimens show that pure ABS specimen have lower wear resistance, less stiffer and thermally unstable as compared to carbon fibre reinforced ABS specimen.

5.3 Recommendation

The process parameters of FDM can improve the wear behaviours on FDM printed parts. The FDM parameters used for all specimens are 0.25 mm layer thickness, 0° part built orientation and 90% density. It is highly recommend that the future studies should highlight the FDM parameters optimization on sliding wear of test specimens. Other parameters of wear test such as sliding speed and surrounding temperature should be varied on future research as both of the parameters can affect the wear behaviour of the specimens.

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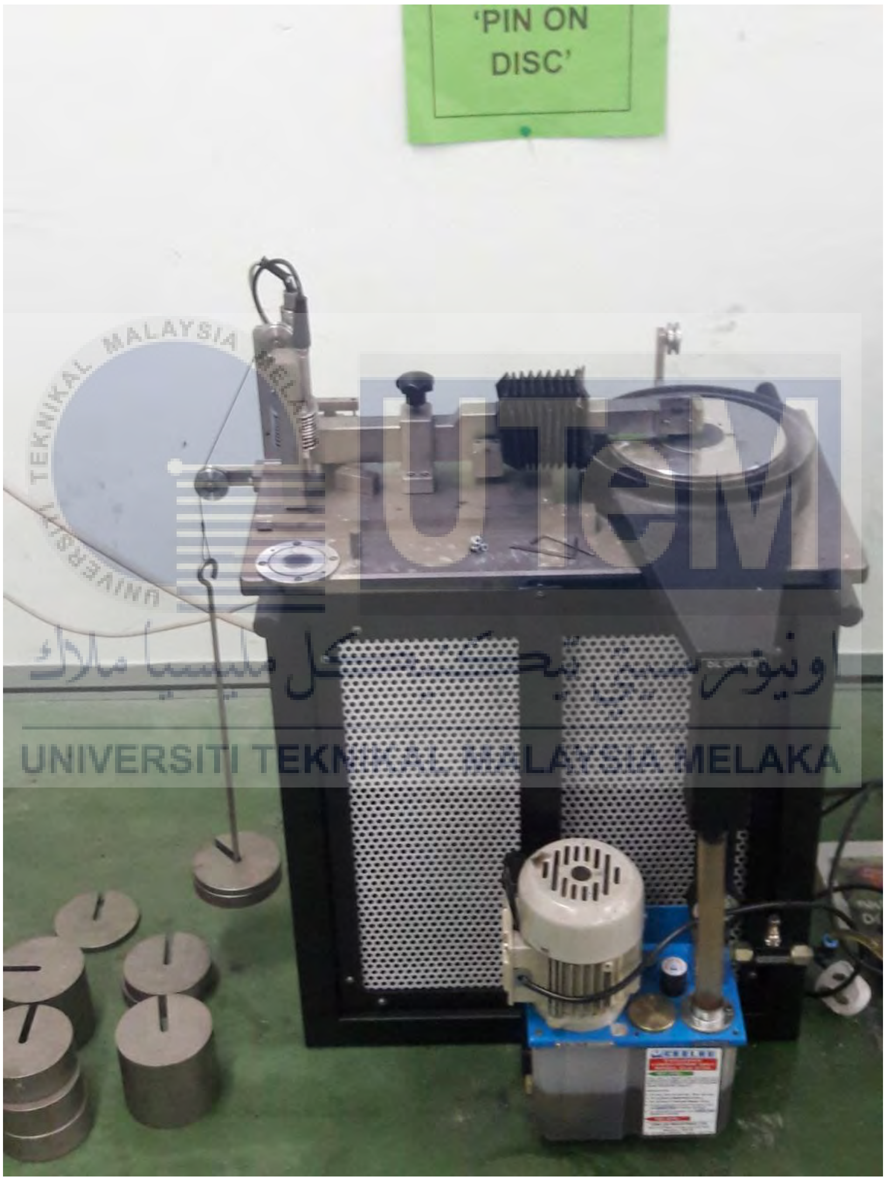
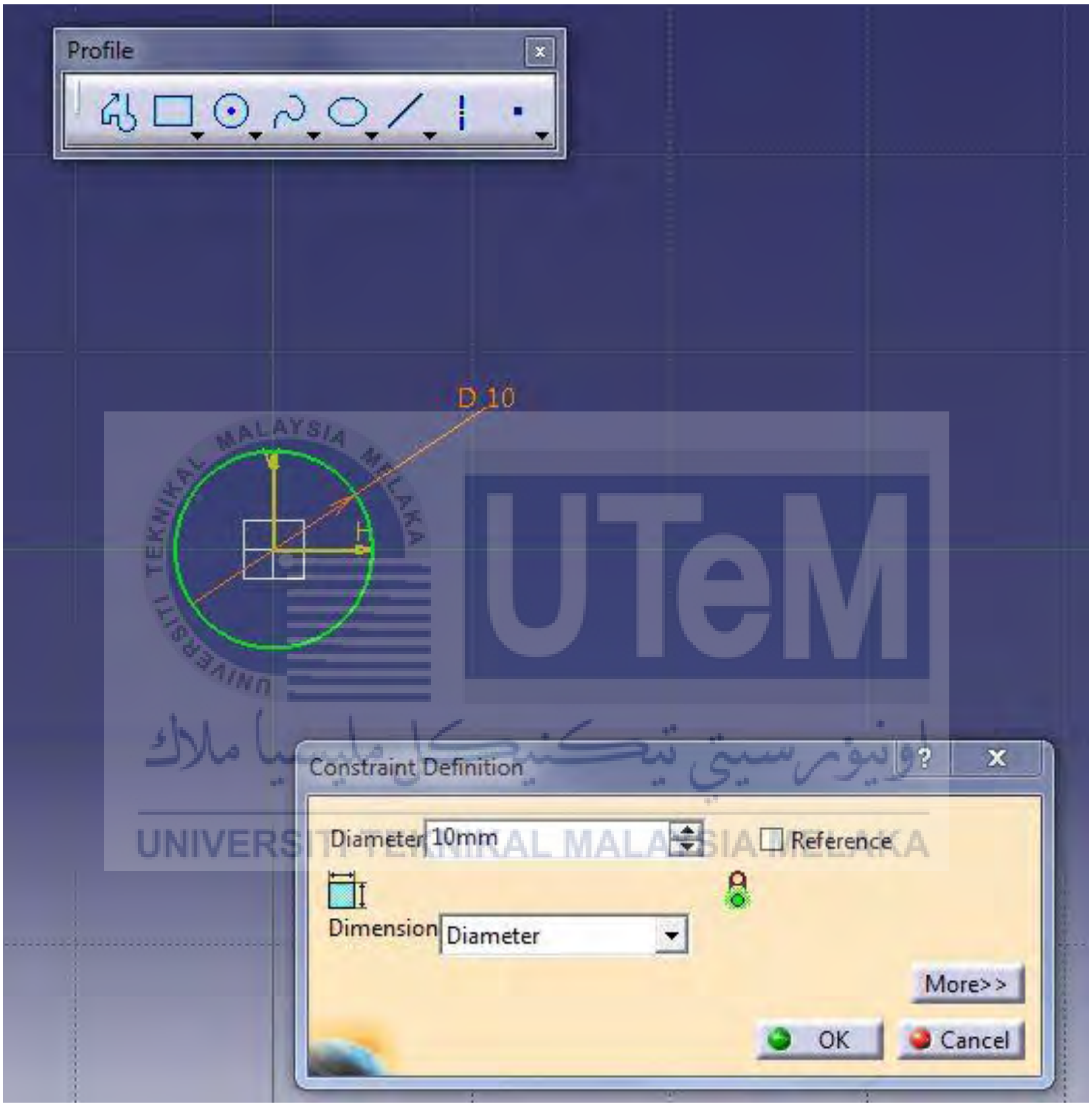
APPENDIX A



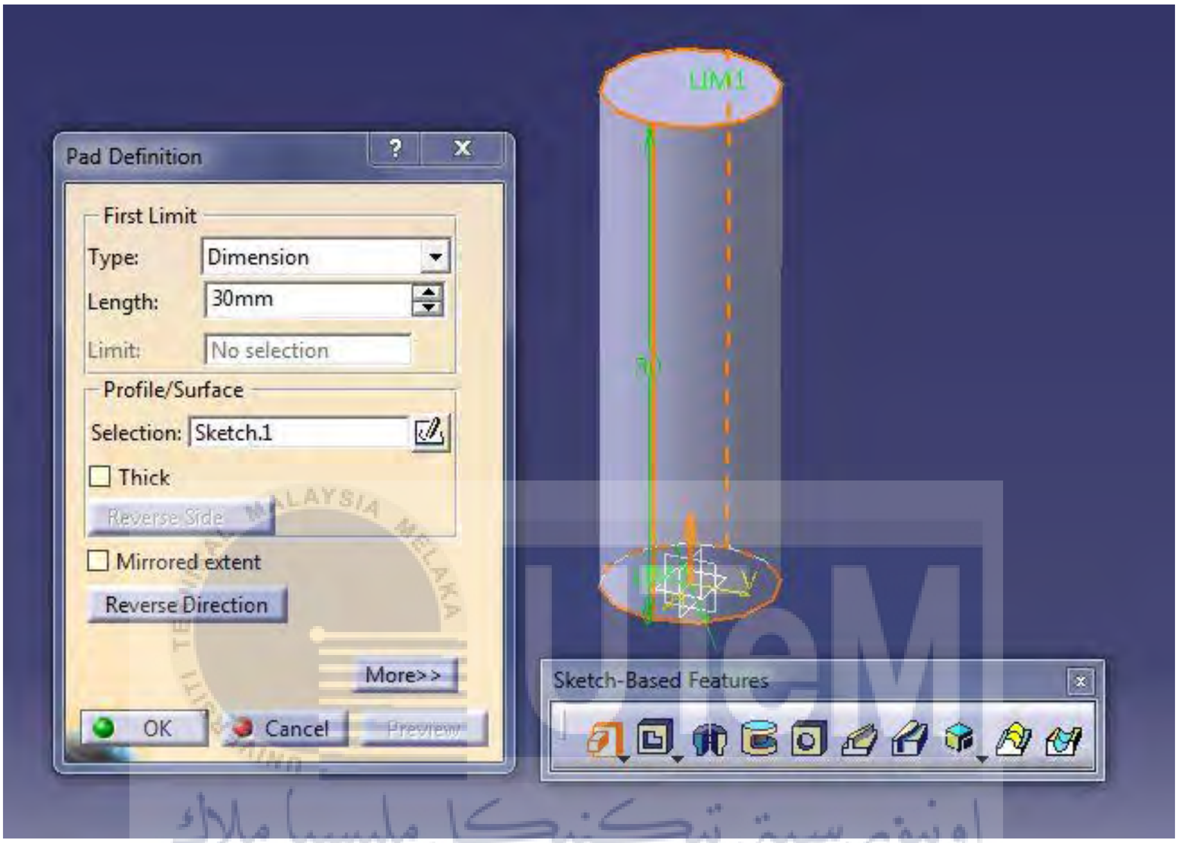
Appendix A1: Pin on disk apparatus

Appendix A2: Disk with clean abrasive surface

APPENDIX B



Appendix B1: Raw sketching of test sample



Appendix B2: Complete 3D CAD drawing of test sample