TRIBOLOGICAL PROPERTIES OF 3D PRINTED ACRYLONITRILE BUTADIENE STYRENE (ABS) UNDER DRY AND WET CONDITIONS

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A report submitted
in fulfillment of the requirement for the degree of
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DECLARATION

I declare that this project report entitled "Tribological Properties of 3D Printed Acrylonitrile Butadiene Styrene (ABS) under Dry and Wet Conditions" is the result of my own work except as cited in the references.

Signature : ....

Name : ....

Date : ....

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :. ....

Name of Supervisor : ....

Date : ....

DEDICATION

To my beloved mother and father

ABSTRACT

3D printer was used to fabricate acrylonitrile–butadiene–styrene (ABS) to identify the friction and wear. This new adaptation technology is starting to attract industry especially medical field since it has longer life span and low cost. Previous investigation focuses the influence of hardness, tensile test and temperature effect. However, the understanding regarding tribological properties need more research. It is great to identify application that suitable since ABS is one of biocompatible material. The aim for this study to compare the tribological performance between 3D printer ABS and molded ABS under dry and wet conditions. The result of coefficient of friction of both samples were taken using ball-on-disc machine. Both samples were formed in disc shape for experiment. 3D printer and molded ABS that tested under wet condition were using paraffin oil as lubrication and others parameter were set as constant such as temperature (27°C) and speed (120 rpm). Different load was applied from 20 – 40 N throughout the experiment both sample and conditions. The result shows that molded ABS has the lowest COF than 3D printer ABS under both conditions. However, specific wear rate of the experiment show 3D printer had the lowest wear compared to molded because of it has porosity to retain the fluid in 3D printer sample. As conclusion, 3D printer sample is good wear resistance compared to molded meanwhile COF improvement need further study.

ABSTRAK

Pencetak 3D digunakan untuk membuat Acrylonitrile-Butadiena-Styrene (ABS) untuk mengenal pasti geseran dan pakai. Teknologi penyesuaian baru ini mula menarik minat industri terutama bidang perubatan kerana ia mempunyai jangka hayat yang lebih lama dan kos rendah. Siasatan terdahulu mengkaji lebih banyak kepada kekerasan, ujian tegangan dan kesan suhu. Oleh itu, pemahaman tentang sifat-sifat tribologi memerlukan lebih banyak penyelidikan. Adalah baik untuk mengenal pasti aplikasi yang sesuai kerana ABS adalah salah satu bahan biokompatibel. Tujuan kajian ini untuk membandingkan prestasi tribologi antara ABS pencetak 3D dan acuan ABS di bawah keadaan kering dan basah. Hasil pengkali geseran kedua-dua sampel yang dalam bentuk cakera diambil dengan menggunakan mesin bola-pada-cakera. Pencetak 3D dan acuan ABS yang diuji di bawah keadaan basah menggunakan minyak paraffin sebagai pelinciran dan parameter lain ditetapkan sebagai tetap seperti suhu (27 ℃) dan kelajuan (120 rpm). Beban yang berbeza digunakan dari 20 - 40 N di seluruh eksperimen kedua-dua sampel dan keadaan. Hasilnya menunjukkan bahawa acuan ABS mempunyai COF terendah daripada pencetak 3D ABS di bawah kedua-dua keadaan. Walau bagaimanapun, kadar haus khusus menunjukkan percetakan 3D ABS menunjukkan haus terendah berbanding acuan ABS kerana ia mempunyai keliangan untuk mengekalkan cecair dalam sampel pencetak 3D. Sebagai kesimpulan, sampel pencetak 3D mempunyai penghalang haus yang baik berbanding dengan acuan manakala peningkatan COF memerlukan kajian lanjut.

ACKNOWLEDGEMENT

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It is a great pleasure to express my gratitude to my supervisor Associate Professor Dr. Mohd Fadzli Bin Abdollah for giving me the opportunity to do this final year project and providing his valuable guidance, motivation, suggestions and improvement throughout this research. It was a great privilege and honor to work and study under his guidance.

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LIST OF ABBREVIATIONS

ABS	Acrylonitrile-Butadiene-Styrene
FDM	Fused Deposition Modelling
CAD	Computer Aided Design
3D PRINTER	Three-Dimensional Printer
COF	Coefficient of Friction
DOE	Design of Experiment
ASTM	American Society for Testing and Materials

CHAPTER 1

INTRODUCTION

This introduction chapter provides the background of the study, problem statement, objectives, scope of study and report structure.

1.1 Background of study.

In this era of globalization, plastic polymer considers as popular material that are widely used in industry. Acrylonitrile–butadiene–styrene (ABS) is one of the engineering thermoplastic polymer that had been found the applications in many fields like automotive, aerospace, business machines, computers and telephone handsets (Sudeepan et al, 2014). The impact of resistance and toughness on mechanical properties of ABS was the main factor ABS are useful and popular in industry to reduce external or internal friction (Olivera et. al, 2016). Other than that, ABS can be manufactured by two process which is extrusion and molding (Ozcelik et al, 2010; Stansbury & Idacavage, 2016)

According to Ciocca et al (2009), the advantages of ABS that do not easily wear compared to metal makes it became popular even in medical field. The new technologies in medical world where artificial organs or joint made by plastic to replaces the damage organs is also one of the reasons why ABS has been used in medical field. Besides that, the process of manufactured are using one of the modern engineered method which is additive manufacturing or likely known as 3D printer. Additive manufacturing able to transform 3D solid drawing into a physical model without using any additional tools (Berman, 2012;

Huang et al, 2013; Weller et al, 2015). The unique of this process where layer manufactured form the part makes it more suitable for medical because of organ that had their own characteristic and this process doesn't need to be assembled can cut time if the required organs or joint need to be used as soon as possible.

Meanwhile, molded are more conventional where this process required more tools, forms, or punches in process to complete the design. The suitable parameters also played main role in the manufacture process such as compression flow rate, mold wall temperature and tensile modulus of compression molded parts to form the parts. Every parameter is parallel with each other due to the importance of each parameters and how it leads to the performance of the tribological behaviour. It is the aim of any project to know how the input parameters of the process contributes to the performance of the process in order to get an excellent product.

1.2 Problem Statement

ABS is one of the common materials that are widely used in industry. This polymer has starting to attract more industry to use it as part of their material since ABS provide more benefit with low cost and this including medical field. The adaptation of new technology such as 3D printer also attract industry to invest in this area. The fabrication ABS using 3D printed that can printed in the complex shape is one of the important criteria that attract medical field. ABS also prove to be one of the biocompatible materials that can be used as part of medical equipment. However, it has become a huge problem that friction and wear causes high loss for industry. Medical field itself require the material that has lower friction and wear that can be used in long period.

Due to this problem, the demand of research in tribological properties has increase to prove that 3D printer ABS have lower friction and wear. Reduction of friction and wear needed for industry to save cost and have longer lifespan material. Basically, previous research is focusing on the behaviour or strength of ABS instead of tribological properties. This study can help industry to stop doubtful on 3D printer ABS tribological performance.

1.3 Objective

The objective of this study as follow:

- To compare the tribological performance between 3D printer ABS and molded ABS under dry and wet conditions.

1.4 Scopes

This study focuses on tribological properties of acrylonitrile–butadiene–styrene (ABS) under wet and dry conditions. For 3D printer ABS and molded ABS, both of this was prepared in disc form for tribological test. The different load applied to disc were observed within the range of 20 N-40 N to identify the effect of friction. The paraffin oil was used as lubricant when the test for the disc conducted for wet conditions. Other parameters such as speed, ball bearing SKD-11 and temperature will not be covered in this study and these parameters are set to be constant. The tribological test was done at sliding condition according to ASTM G99-95a.

1.5 Report Structure

This report had five chapter to provide more understanding about the flow of this study. This study divided into two phase or two semesters where each semester contain different chapter. In FYP 1, the chapter covered is the primary chapter which is introduction (Chapter 1), literature review (Chapter 2) and methodology (Chapter 3). Meanwhile, FYP 2 covered results and discussion (Chapter 4) and conclusion (Chapter 5). The summarized of this whole chapter combined to achieve the objective of this study. Table 1. 1 shows the report structure for FYP 1 and FYP 2.

Table 1. 1: Report Structure

Chapter	**Content**	**Division**
1	Introduction • Consists of title, problem statement, objectives, scopes of the project and report structure.	**FYP 1**
2	Literature Review • The research based on journal which related to the scope of the study that focus on books, and journal.	
3	Methodology • The method used to conduct the experiment	
4	Result and Discussion • Collecting the data that has been gathered during conducted research and discuss the result.	**FYP 2**
5	Conclusion • Conclude the overall project and improvement can be done.	

CHAPTER 2

LITERATURE REVIEW

Literature review will be discussed in this chapter. The outline of this chapter is the theory that need to emphasized stage by stage for this study and every related topic will be discussed before starting any project analysis or study. Relevant sources like journals, articles, websites and books had been utilized well in order to script this chapter.

2.1 Additive Manufacturing

Additive manufacturing or known as 3D printer is one of the new era or revolutions that currently had potential uses in industry. The popularity of this technologies is dramatically increased in past a decade. According to Wohler's report (2014), the percentage of world sales 2014 increased up to 33% annually in past three years and this combine the sales from devices, material and services for industrial scale to consumer-based printers.

This technology that have their own uniqueness where doesn't need any mold or tools to customized product. The abilities to direct manufacturing process where 3D drawing transform into physical part is one of the factors this technology seen as one of the prospective future development. In future prospect, this technology seen as one of the big steps for every company in world to compete toward Fourth Industrial Revolutions. Thus, development of this technology is one of the successful strategic to solve the problem that currently faced by industry.

There are seven process of additive manufacturing which is binder jetting, directed energy deposition, material extrusion, material jetting, powder ped fusion, sheet lamination and vat photo-polymerization (Lee et al, 2017). Each of this process had their own characteristic that significantly helps the manufacturing fields. However, the focus on this study is material extrusion or known as fused deposition modelling where this process used to fabricate material for this study.

2.1.1 Fused Deposition Modelling (FDM)

Fused Deposition Modelling (FDM) was one of the process involve in additive manufacturing. The printed process was done layer by layer to build the object draw in CAD and transform into physical parts. This process provides a lot of benefit such as complex design part printed according to real part structure, short cycle time and save cost compared to conventional manufacturing process. Plus, engineering and industry such as aircraft, dental restorations, medical implants and automotive products still searching on its application for this technology (Mohamed, Masood, & Bhowmik, 2015). Figure 2. 1 shows the actual diagram of 3D printer that used in this study.

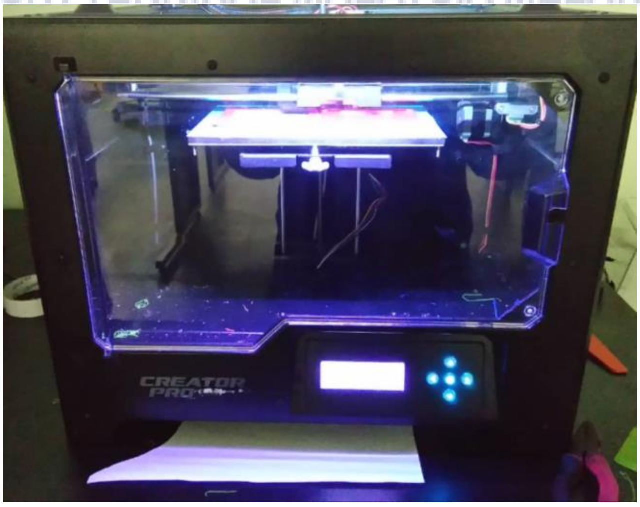


Figure 2. 1: The actual diagram of 3D printer

According to (J. Y. Lee et al., 2017), 3D printer consider as new journey on revolutions towards advanced technology. This is the beginning of technology that helps most of industry on producing the impossible part such as body part or organs. This shows the future of 3D printer in future generation to create unimaginable solutions on undefined problems. The better future in industries can be seen with the expansion on 3D printer since this technology seen as one of the easier ways to save cost and times. Figure 2. 2 shows the AM producing material that can create opportunity on advance technologies.

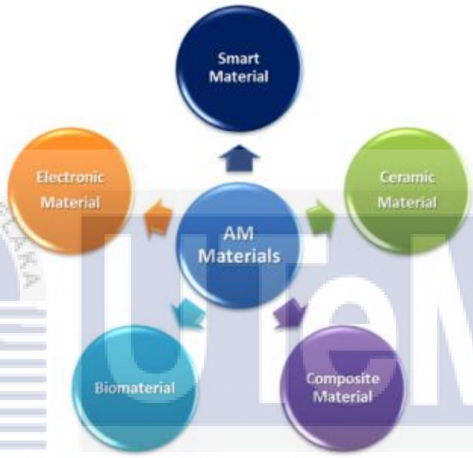


Figure 2. 2: Additive Manufacturing Material (J. Y. Lee et al., 2017).

From figure above, it shows the opportunity for local industries to expand with this technology in several areas. For example, in electronic material where FDM used to print the organic field transistor, LED and circuit that had special and sensitive characteristic in terms of application (Murr, 2016). The development of FDM seen as successful due to the ability to print the surface that flexible and transparent polymer sheets. Moreover, FDM is not only advanced technologies that suitable with current trend of 4.0 Industrial Revolutions but this technology also played major role on increasing the production that lead to more profit in company or organizations.

There are huge different between 3D printer and compression molding in terms of cost and speed. Compression molding required more time since their need the traditional process such as assemble that take times and expensive tooling involved. In addition, 3D printer might not suitable for small production but it can reduce the material waste during production (Berman, 2012). According to Petrovic et al. (2011), the material waste from production also proved that it can be recycled and reused to creating other product. This is one of the advantages to industry and one of the big reasons to choose 3D printer as part of production line.

2.1.2 FDM Applications for Biomaterial

Biomaterial is the process that involved the biological or synthetic substance that used as implant an organ, medical device and produce tissue to help body functions (Araujo Borges, Choudhury, & Zou, 2018; Ciocca et al., 2009; Daly et al., 2017; Puetzer & Bonassar, 2016). The development of 3D printer is one of benefit to medical institutes to solve problems on difficulties to find suitable donor. The advancements in biocompatible materials have empowered 3D bio-printing for useful living tissues, which can be connected regenerative medication to address the requirement for organs transplantation (Stansbury & Idacavage, 2016; Suntornnond, An, & Chua, 2017; Tack et al., 2016).

The beginning process of this technologies starts with CAD drawing in three dimensional forms before converted to stereolithography (STL) format. STL format support the CAD drawing and helping on reducing the geometry shape to keep the basic components. According to Wright (2001), the basic triangle that can be shows instead of true arcs and spline was one of the handicaps for drawn part. However, 3D printer is as yet the best decisions to embed an organ or tissue in human body to over since it can directly insert cells inside a hydrogel for fabricate, however most lithography methods require a couple of ventures to make an example of cells (Suntornnond et al., 2017)

3D printing method or FDM is used to create solid tissue engineering scaffolds (Bellini & Güçeri, 2003). Other than that, the uniqueness of 3D printer that can fabricated the tissue that had complex geometry makes this technology had a high possibility to expand in medical field since the organ and tissue itself have their own geometry. Even some of the geometry only consist of triangle but most of the characteristic still available. This combination of medical and 3D printing shows the rapid growth on research related to medical fields to create the impossible treatment and reduce the percentage of unsuccessful surgery.

2.1.3 Advantage of FDM for Biomaterials

The advantages of FDM in Biomaterials had been summarized below:

1. Daly et al, (2017) stated that the benefit of FDM is that scaffolds with coordinate pore geometries and channels size can be produce in short times. By shifting procedure parameters such as the extrusion pressure, nozzle diameter and deposition speed it had potential to print scaffolds with extensive variety of filament diameter and porosities.
2. Banis et al., (2014) found that the capacity of the framework to precisely deliver the customized platform design which is programmed scaffold architecture that will be characterized by how much the extruded framework compares to the first model.
3. Cui et al., (2017) confirmed that the FDM process in tissue engineering accomplishment is easy employment, fast printing capacity diverse biomaterial availability and good mechanical properties makes hard tissue seem possible.
4. Suntornnond, An and Chua, (2017) concluded that bioprinting has great repeatability, high accuracy, and satisfactory adaptability, which are imperative for tissue substitute manufacture and may possibly lead to organ printing.

5. (M. Lee & Wu, 2012) the lead of FDM due to high porosity because of complex design and high mechanical strength.

2.1.4 Limitation of FDM for Biomaterial

There are limitations of FDM for Biomaterial listed below to shows the discussion:

1) Geometric limitation

- Stated that FDM able to identify the complex geometries but this technology in the beginning state to identify the correct of design. This effect the geometries of object and the printer item might not have the same surface roughness.

2) Limitation to material

- Thermoplastic materials with good melt viscosity properties that are high enough to build viscosity but low enough for extrusion viscosity

3) High temperature.

- Due to high processing temperature, the inability to incorporate living cells or temperature sensitive biological agents during extrusion.

2.2 Acrylonitrile–butadiene–styrene (ABS)

ABS is one of the materials that had been used in FDM or 3D printer. This material had they own characteristic that played major roles in present and future industry in terms of its application. Most of industry start to consider plastic as one of the useful materials since plastic are cheaper and easier to handle compare to metals. According to Ciocca et al. (2009), ABS is one of the high demand materials in prototyping industry due to low cost for fabrication.

The combination of acrylonitrile, butadiene and styrene makes this material had the good durability, mechanical strength and can absorb high resistance. Each of this material have their own characteristic such as acrylonitrile provides chemical resistance and heat stability, butadiene withstands the impact strength and toughness and the styrene makes this materials inflexibility and easiness of processability (Ben Difallah, Kharrat, Dammak, & Monteil, 2012). Figure 2. 3 below shows the monomers of ABS.

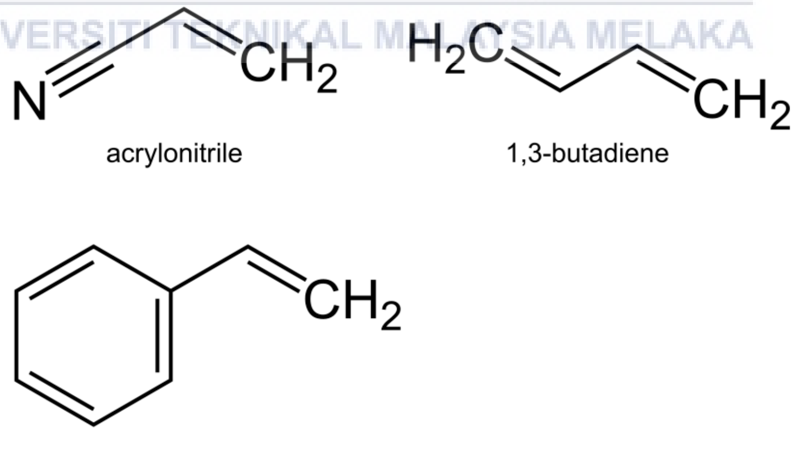


Figure 2. 3: Monomers of ABS (Olivera et al., 2016)

2.2.1 Mechanical Characteristic of ABS

The results of 3D printer ABS and mold ABS compared to find the lowest coefficient of frictions. The physical and mechanical properties show in Table 2. 1. From this table, it clarified the properties of this material and this material is one of the most chosen material for industry.

Table 2. 1: Mechanical and Physical Properties of ABS (Dimic, 2016)

Density	0.9 -1. 53 [g/cm^3]
Thermal conductivity	0.1 [W/mK]
Linear Thermal Expansion Coefficient	73.8×10^{6}[m/mK]
Tensile stress	22 [MPa]
Tensile modulus	1360 [MPa]
Tensile Elongation	6 [%]
Melting Point	230 °C

Mechanical properties might affect the results of comparisons between 3D printed and molded ABS. The density of injection molded ABS and 3D printed ABS is different and this can affect the tribological performance on how the material absorbs the lubricant to reduce friction.

2.2.2 Advantages and Limitation of ABS

The advantage of ABS (Ashraf, 2014) listed below:

a) Good impact resistance

- ABS show one of the important qualities in manufacturing industry which good impact resistance. Butadiene is one of the materials that have a good impact resistance and the combination with other improve the performance of this polymer.

b) Easy machining

- This material can be easily machining and fabricate including turning, drilling, milling, sawing, die-cutting and shearing.

c) Low cost

- Low cost is one of the biggest benefits to company to manufacture and the material don't require assemble or hard for machining.

The limitation of ABS (Anonymous, 2012) is shown below:

- Poor weatherability
- Poor solvent resistance
- Produce high smoke when burned

2.3 Possible Application of ABS

Common material that currently popular in industry due to it stability on withstand and absorb the resistance. This makes ABS are likely been chosen by industry as main material to manufacture. Moreover, this material still has more characteristic that can be explores by researcher to use in industry and currently towards Industrial Revolutions 4.0 may lead to expansion of plastic as part of life. Table 2. 2 below shows the possible application of ABS in industry.

Table 2. 2: Application of ABS in industry

Industry	Applications
Automotive (Patil, Patel, & Purohit, 2017)	Use to makes automotive body parts, dashboards, wheel covers manufacture of housings, covers and linings.
Building Material (Anonymous, 2017)	Use to build material in 3D printer instead of PLA that have lower melting point
Household Appliance (Roca & Cited, 2006)	Use for kitchen utensils, refrigerants and vacuum cleaner
Electric and Electronic Applications (Olivera et al., 2016)	Make electric enclosures and computer keyboard.
Medical Applications (M. Lee & Wu, 2012)	Use for medical equipment, mold for tissue generations.

2.4 ABS in Bioprinting and Biomaterial

The involvement of ABS in medical field still in beginning phase without any further researcher that related to human body instead of medical devices. The material itself seen as one of the suitable material that can be prepared as biomaterials and the material should had biostability, bio durability and biocompatible characteristic to use in the assemble (Evans et al., 2017). This shows that ABS categorized as biomaterial that might suitable for implant or tissue generation if further study conducted.

Moreover, ABS one of the well-known materials that had been used as mold for medical process. The application on ABS in bioprinting can be seen when the process of repairing organ involved. Mostly, ABS will be printed in the shape of organ to make easier for the doctor to repair the imaginary broken organ before real surgery which is can reduce time of operation and predict the suitable method to repair the damage organ (Cui et al., 2017). For example, ABS material used in pre-operational maxillofacial surgery where the prototype of damaged jaw bone had manufacture to check the damage jaw bone and find the solution for this surgery (Dimic, 2016).

Plus, the material use for the prototype should had the biocompatible characteristic and the properties of ABS itself that strength, rigidity and easy to be machining makes it suitable to be used. Figure 2. 4 shows the maxillofacial surgery that use ABS.

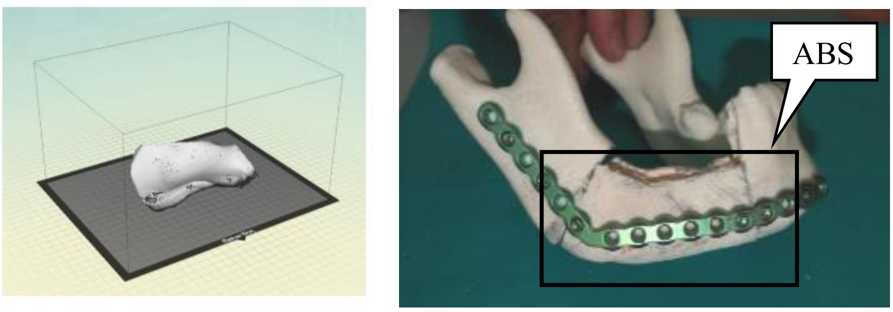


Figure 2. 4: The Maxillofacial Surgery (Dimic, 2016)

2.5 Tribological Characterization of ABS

The tribological behaviour is one of the crucial roles in this study to determine the performance of both process which is 3D printer and mold ABS. Tribological performance effected by operating parameters on this study. The investigation of most researches is focused on the effect of polymer with the incorporation of filler and there are minimal studies that involve ABS tested for tribological performances. Moreover, this study focused on ABS that was tested under wet and dry condition.

2.5.1 Effect of Operating Parameters

The main factor that had big impact on tribological performance is operating parameters. J. Sudeepan et al.(2014) investigated the friction and wear of ABS/ Zno Polymer Composite using Taguchi method where different parameters such as load, percentage of filler and speed changes. The applied load for this test was 15-35 N and the time fixed to 300 sec for each test conducted. The results as shown in Figure 2.5 that when the applied load increases, the frictional coefficient decreases due to the surface temperature of the composites elevate with the high load and the composite surfaces turn out to be delicate caused by frictional heat at the interface and cause the COF decreases. This experiment also chooses the optimal COF and Specific wear rate for this material as shown in Figure 2.6.

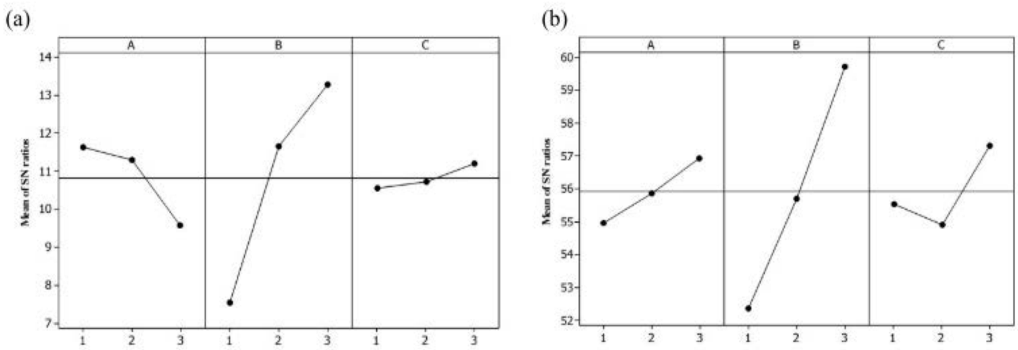


Figure 2. 5:Results of S/N ratio for COF and Specific wear rate (J. Sudeepan et al. ,2014)

Average S/N ratio for each factor level(COF)			
Level	A	B	C
1	11.623*	7.545	10.558
2	11.287	11.662	10.731
3	9.578	13.281*	11.199*
Delta	2.046	5.736	0.641
Rank	2	1	3
'*' indicates optimal process level			

Average S/N ratio for each factor level (Specific wear rate)			
Level	A	B	C
1	54.97	52.36	55.55
2	55.86	55.69	54.92
3	56.94*	59.72*	57.3*
Delta	1.96	7.36	2.38
Rank	3	1	2
'*' indicates optimal process level			

Figure 2. 6:Response table for each level of COF and Specific wear rate (J. Sudeepan et al.,2014).

Other than that, Ben Difallah et al. (2012) researched is about the mechanical and tribological response of ABS polymer matrix filled with graphic powder. The study stated that adding graphite in ABS material lower the coefficient of friction (COF) and weight. The changes of sliding cycles also effect the result in Figure 2. 7 since the more sliding cycle, the highest the coefficient of friction and addition of graphite also decreases the COF. The result gain from this research shows that by adding 7.5% of graphite into ABS can decreases the COF and loss weight. The study also found that the higher the percentage of filler, the result of wear also decreases in each distance cycles as shown in Figure 2. 8.

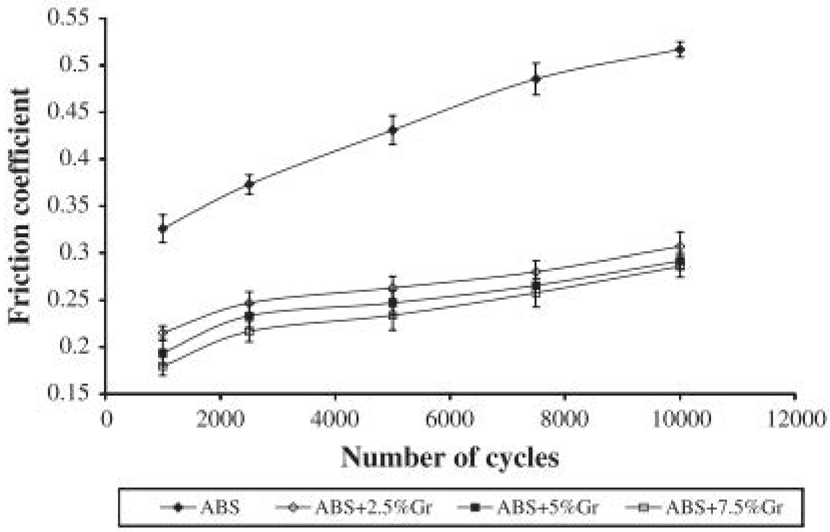


Figure 2. 7: Friction coefficient versus number of sliding cycles for ABS/graphite composites.

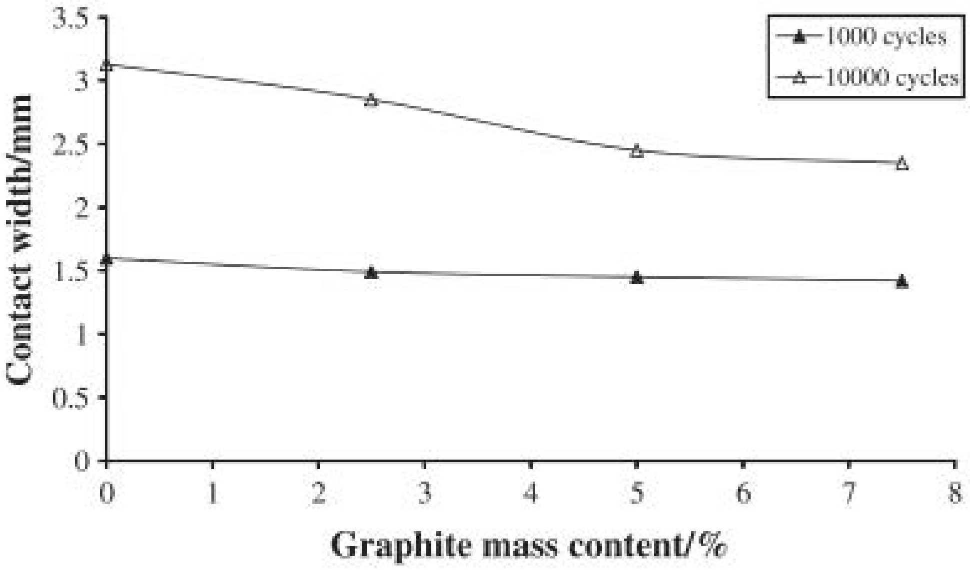


Figure 2. 8:Wear scar widths versus the graphite mass content after 1000 and 10,000 cycles for ABS/graphite composites.

(Sudeepan et al., 2014b) had studied the friction and wear properties of ABS/Kaolin polymer composites using grey relational technique. Using the optimum parameters conduct by previous study which is 35 N, speed 120 rpm and the filler is 5 wt %, For this study, the same parameter were use applied load is between 15,25 and 35 N, speed (80, 100, 120 rpm) and filler (5, 10, 15 %). ABS was combined with Kaolin powder to check the value of coefficient of friction and wear to confirm the optimum value.

Figure 2. 9 shows the optimum result obtain from previous research had the lowest coefficient of friction and wear.

From the result, it shows that different filler in each material effect the performance characteristic that will contribute the change of COF. In this experiment, it stated that load played the major role for COF graph might due to different load given different result and this experiment also stated that almost 77% shows load affect result the most. Meanwhile, there are 70% of this experiment shows that load also affect the specific wear rate for this experiment. The specific wear rate of this experiment as shown in F also increases when the parameter changes throughout the experiment.

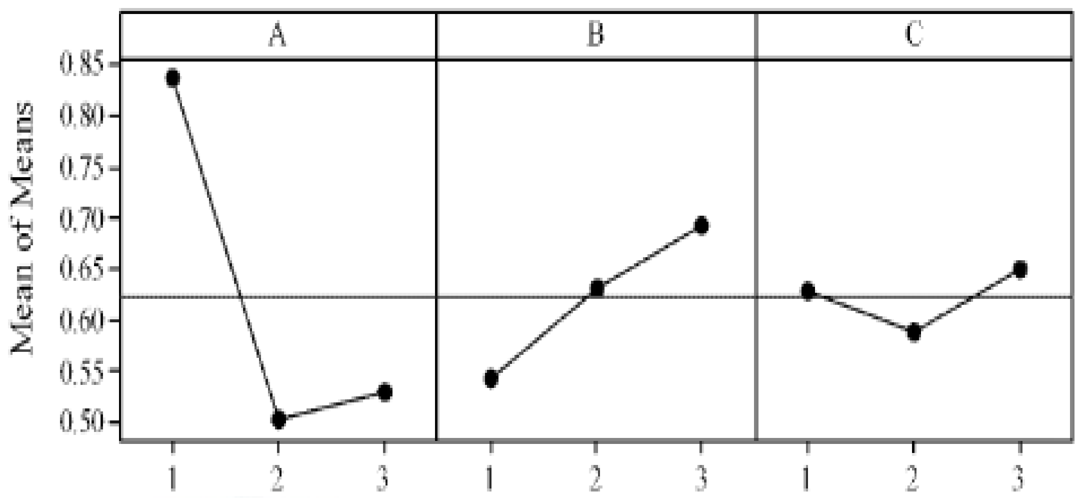


Figure 2. 9:Results of S/N ratio for COF and Specific wear rate (J. Sudeepan et al. ,2014b)

	Average S/N ratio for each factor level (Grey relational grade)		
Level	A	B	C
1	0.8358*	0.5433	0.6293
2	0.5015	0.6300	0.5878
3	0.5293	0.6933*	0.6495*
Delta	0.3343	0.1501	0.0618
Rank	1	2	3
'*' indicates optimal process level			

	Average mean for each factor level (Grey relational grade)		
Level	A	B	C
1	-1.5780*	-5.673	-4.375
2	-6.0970	-4.340	-4.971
3	-5.6740	-3.337*	-4.005*
Delta	4.5190	2.336	0.966
Rank	1	2	3
'*' indicates optimal process level			

Figure 2. 10: Response table for each level of COF and specific wear rate (J. Sudeepan et al.,2014b).

According to Araujo Borges et al., (2018), 3D printing for meniscus artificial is one of the latest technology to replace old technology. The latest technology can prevent the same problem happen in future by replacing the meniscus. This experiment was conducted by testing in several samples such as 3D printer and molded polycarbonate-urethane (PCU) and ultra-high-molecular-weight (UHMWPE). The sample was testing in ball-on-disc machine and the result of COF and wear compared to see if there is porosity in each sample. From the experiment, 3D printed PCU shows 27% less wear dept compared to the molded PCU and this proves that 3D printed retained fluid in its porosity. Figure shows the result of COF and figure shows the wear track obtained from the experiment.

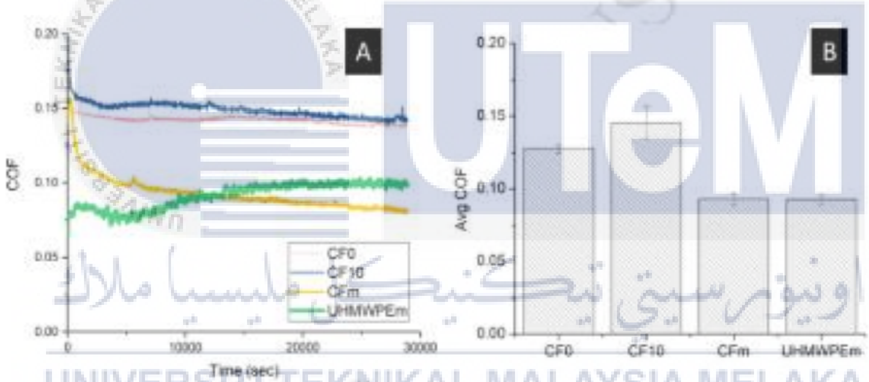


Figure 2. 11: Result of COF versus time (Arauje Borges et al.,2018)

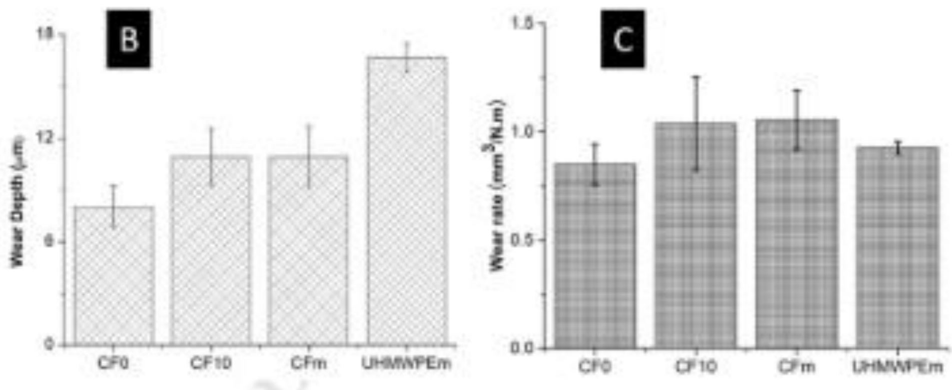


Figure 2. 12: Result of wear track (Arouje Borges et al,2018)

2.6 Mathematical Equation

For this study, there are several equations that used to calculate. The equation helps to smooth the experiment in order to achieve the target. Each of equation used is calculated from the parameter that was used to start the experiment such as speed, applied load and distance.

2.6.1 Coefficient of friction.

Friction test was carried out for testing the 3D printed ABS and molded ABS under two conditions which is dry and wet conditions. The data from tribological test recorded in computer to shows the value on the graph. From this data, coefficient of friction was calculated.

$$COF = \frac{F}{W} \tag{2.1}$$

Where,

F = frictional force (N)

W = Applied load (N)

After tribological test, the wear track diameter measured to know the disc wear after experiment.

2.6.2 Specific Wear Rate

Wear rate was calculated by using a suitable formula to identify the wear. After check under the microscope to identify the wear track radius, the value was calculated using this formula.

$$k = \frac{Vloss}{(W \times L)} \tag{2.2}$$

$$Vloss = 2\pi R \times \pi(a^2 + h^2) \quad (2.3)$$

$$h = r - \sqrt{r^2 - a^2} \quad (2.4)$$

Where k = wear rate (mm^2/Nmm)

Vloss = wear volume loss (mm),

L = sliding distance (mm),

R = wear track radius (mm),

a = wear scar radius (mm),

h = spherical cap height/wear depth (mm),

r = ball bearing radius (mm).

CHAPTER 3

METHODOLOGY

The aim for this chapter is to shows the experimental work procedure and guideline on how to conduct the study from the beginning until the end of study. This chapter also provides the equation that related to experiment that need to be calculated. All the procedure and steps were list to make better understanding on how the study conducted.

3.1 Experiment Details

This chapter covered the element needed to complete this study. There are four phase that included in this chapter which is planning phase, designing phase, conducting phase and analyzing phase. Starting from planning phase where the objective and parameter for the experiment is discussed to identify the responding variables. Secondly, the designing phase where the Design of Experiment is used to organize the results. The experiment parameters will be listed in design of experiment for better understanding on how the experiment conducted. Conducting phase is where the related procedure and experiment listed as guideline to achieve the objective of study. This phase also shows the relate equation involved and machine that will be used throughout the studies. Lastly, the analyzing phase for this experiment and this phase shows on how the result will be analyzed and compared. The data also will be validated in this phase to ensure the data is correct and follow all the guidelines.

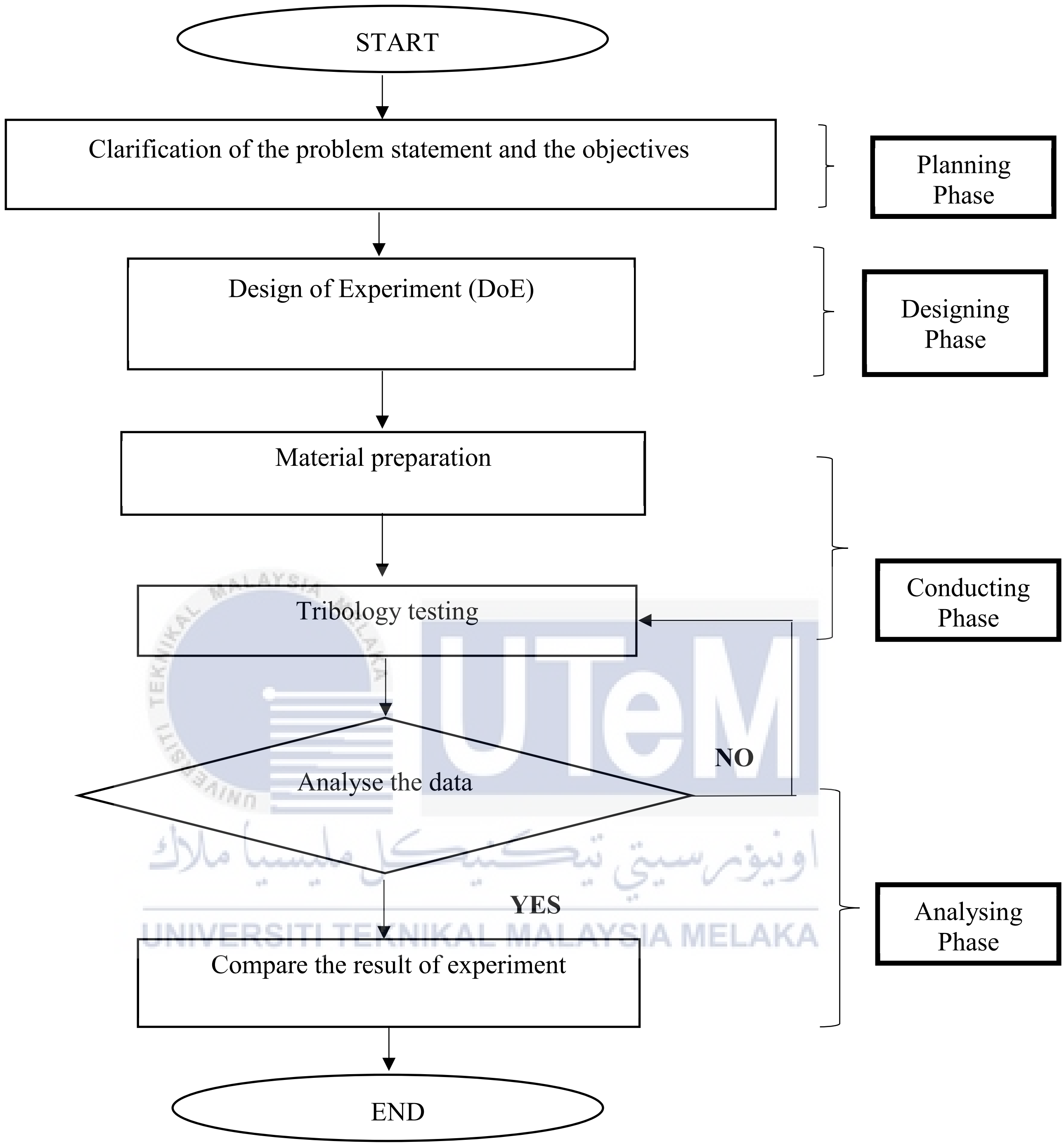


Figure 3. 1: The flow of methodology

3.2 Planning Phase

3.2.1 Clarifications on Problem Statement and Objectives.

Meniscus replacement one of the treatments that patient can choose to solve the knee problems. However, the replacement not guarantee the knee problem will not happen again and it also may lead to degenerative arthritis due to unbalanced cartilage to support the upper body. Using ABS as meniscus replacement might be prevent the problem repeated.

This study was conducted to know the abilities of ABS withstand the friction with the applied load under dry and wet conditions like our body that have body liquids. The result also shows ABS durability if the ABS can act as meniscus in human body. Furthermore, the material will be printed using 3D printer or FDM and compared to the molded ABS to check the performance of coefficient of friction.

The constant parameter that set to be constant is speed, ball bearing SKD-11, temperature and the lubricant for wet condition which is paraffin oil. The parameters change will be stated in Design of Experiment (DoE).

3.3 Designing Phase

3.3.1 Design of Experiment

This study will conduct using ABS as material that printed into disc using 3D printer and molded ABS also will be tested for comparisons. The applied load that will be used for this experiment is between 20 N ~ 35 N. The other parameters such as speed set to 120 rpm, ball bearing SKD-11 and temperature set to be room temperature which is 27°C. Eventually, the quantity of paraffin oil will not be calculated as it was added as lubricant only. Table 3. 1 shows the Design of Experiment for this study.

Table 3. 1:Design of experiment

LOAD / PARAMETERS	3D PRINTED ABS	MOLDED ABS
	DRY AND WET CONDITIONS	
20 N		
25 N		
30 N		
35 N		
40 N		

3.4 Conducting Phase

3.4.1 Sample Preparation

Sample preparation before test conducted is one of the crucial moments in this study. Parameter related to the material need to emphasis to avoid material not in good shape. This can affect the result of coefficient of friction during test. There is two process involve in preparing ABS:

a) 3D Printer or FDM

Preparation ABS in this process involved FDM machine as shown in Figure 3. 2. To identify the suitable 3D printing parameters that produced a good quality sample, a preliminary experiment was conducted and used for other samples. The density of filler to print ABS is 70% in order to ensure the disc in solid form. The nozzle temperature heated until the temperature reaches 240°C and the print bed also heated until it reaches 65°C. After turning on the machine, wait until temperatures reaches the parameter set. When the temperature reaches the parameter set, the extruder nozzle started to melt the ABS and formed it into the shape in drawing. The filler of ABS was printed layer by layer until it reaches the diameter of the disc based on the drawing in the memory card reader that already been extract using Repetier software. After the printed process done, quick evaluation to the disc had been done to ensure there is not defect occur that can affect the experiment result in ball-on-disc.

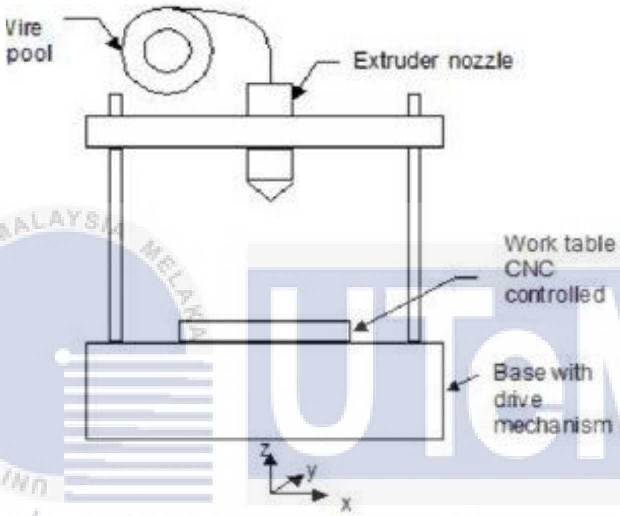


Figure 3. 2: 3D Printer

Figure 3. 3 shows the measurement of FDM sample which is 75×75×4 mm and the disc were designed using Solidwork. The disc printed from drawing that converted to STL file and slice using Lulzbort that inserted in SD card to connect with 3D printer. The size of disc was designed followed the standard size that suitable for ball-on-disc machine.

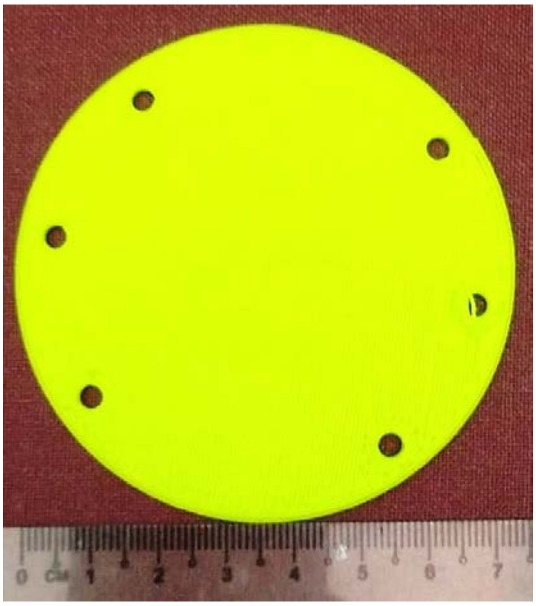


Figure 3. 3: 3D Printer Preparation

b) Mold

Due to limited material available in laboratory, the molded ABS was cut to cube shapes for several test and only one were cut to disc shape. The molded ABS that cut into disc shape will be reused for next experiment with different cubes as shown in Figure 3. 4. The test conducted only in small track in the range area of cube shape.

Figure 3. 4: Molded ABS preparation

The dimensions of cube inserted at the centre of disc is 30 × 30 mm. This material was cut used bench saw show in Figure 3. 5 and the dimension for the disc same with the 3D printer disc.

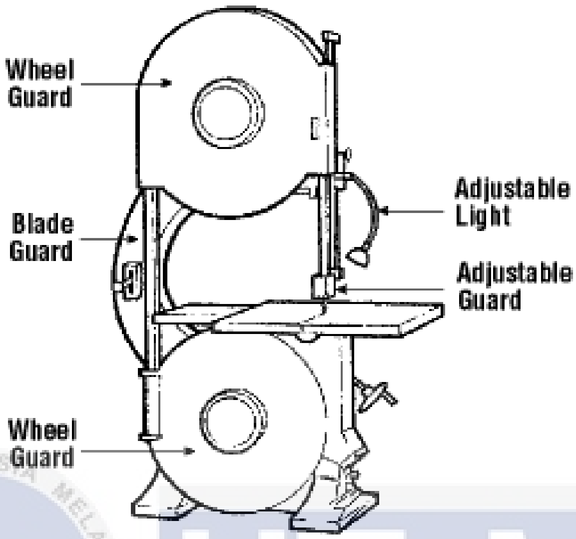
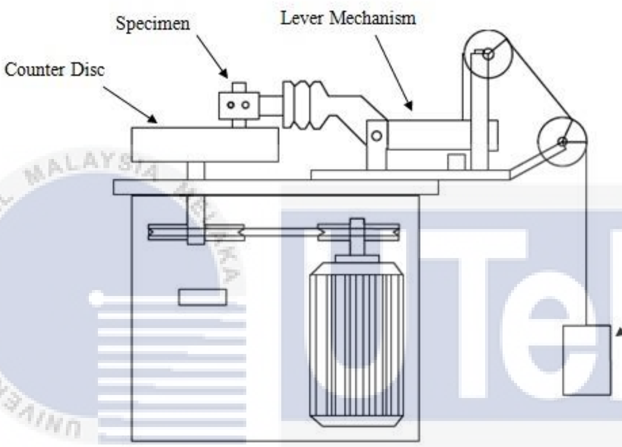


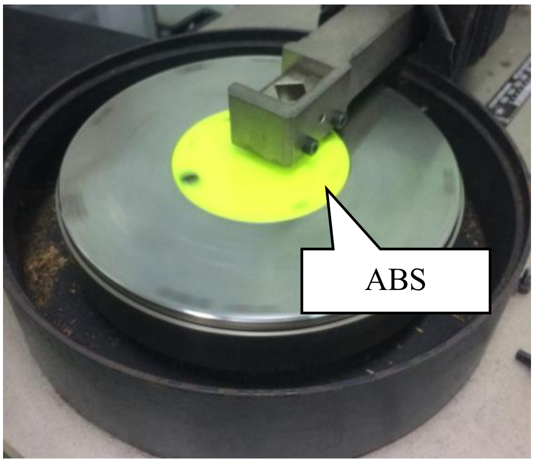
Figure 3. 5: Bench saw schematic diagram

3.4.2 Tribological Performance

The tribological testing was conducted using a ball-on-disc machine against 3D printer ABS or molded ABS. Figure 3. 6 shows the schematic diagram of ball-on-disc tribometer. The disc was wiped with paraffin oil before running the test. The machine set up based on parameter that had been decided such as different applied load and this tribological test conducts according to the ASTM G99-95a.



a) Schematic diagram of ball-on-disc



b) Actual diagram of ball-on-disc

Figure 3. 6: Ball-on-disc tribometer

The temperature for this experiment were set to room temperature which is 27℃ constants during test. The disc was test under dry and wet condition to compare the performance of coefficient of friction (COF) and 120 rpm for sliding speed that were decided based on previous research. Meanwhile, the applied load changes from 20-40 N according to ASTM F732 that were standard test method for joint prostheses. Table 3. 2 shows the detail of parameters.

Table 3. 2:The details of parameter.

Test Parameter	**Units**	**Values**
Load	N	20-40
Sliding Speed	RPM	120
Temperature	℃	27

3.5 Analysing Phase

This phase concluded the experiment results where there is certain equation that were used to determine the difference between 3D printer and molded ABS under dry and wet condition. The comparisons results were plotted in the graph for more understanding on the performance of both processes. Moreover, the result shows the best representative between samples and the averaged result of experiment represent in graph. Below is the equation used for this study:

a) Time

Time were calculated using other parameters to determine the time taken for test running.

$$t = \frac{D}{2\pi r N} \tag{3.1}$$

$$t = \frac{1000}{2\pi(37.5)(120)}$$

Where,

t = time taken for the test run (sec)

D = sliding distance (m),

r = the radius of disc (m)

N = speed (rpm)

b) Coefficient of friction

The result of tribological test was calculated to find the coefficient of friction based on equation 3.3

$$COF = \frac{F}{(20,25,30,35,40)}$$

Where,

F = frictional force (N)

W = applied load (N).

c) Wear

Wear were calculated using the formula from equation. There is certain value was fixed for the whole experiment such as:

- Sliding distance = 902.46m
- Wear track radius = 20 mm
- Ball bearing radius = 12.7 mm
- Applied load = (20,25,30,35,40) N

$$k = \frac{Vloss}{(W \times 906.42)}$$

$$Vloss = 2\pi R \times \pi(a^2 + h^2)$$

$$h = r - \sqrt{r^2 - a^2}$$

where

k = wear rate (mm/Nmm),

Vloss = wear volume loss (mm),

L = sliding distance (mm),

R = wear track radius (mm),

a = wear scar radius (mm),

h = spherical cap height/wear depth (mm),

r = ball bearing radius (mm).

d) Radius scar Track by Using Portable 3D Non-contact Profilometer

After test running on ball-on-disc, the wear scar radius needed to calculate the specific wear rate. This portable 3D Non-contact profilometer was using to identify the scar radius in both samples. Figure 3.7 shows the portable 3D Non-Contact Profilometer.

Figure 3. 7: Portable Non-contact Profilometer

CHAPTER 4

RESULT AND DISCUSSION

This chapter focuses on the experimental result of this project and discussion on how the result affect the study conducted. The comparisons data between condition to be discussed throughout research. The chapter discussed more detailed the result after the steps of experiment were followed according to methodology.

4.1 Tribological Properties

4.1.1 Coefficient of Friction of ABS under Wet condition.

i. 3D Printer

Figure 4. 1 shows the result of coefficient of friction 3D Printer ABS under wet condition. This experiment shows the different result of different load was applied during the experiment running. The constant parameter was applied such as speed (120 rpm), paraffin oil act as lubricant and sliding distance. The results for 3D Printer ABS under wet condition can be conclude that the lowest load (20N) has the lowest coefficient of friction compare to others. The trend of this graph shows that the COF increase at the beginning and stabilize around halfway of testing. The stabilize region were taken to identify the average coefficient of friction for ABS 3D printer. As you increase the load the roughness deformed and spread, so the area of contact increases. The force divided to the whole area is roughly the yield pressure, which is a material property and roughly constant, so you end up with the real area of contact roughly proportional to the load.

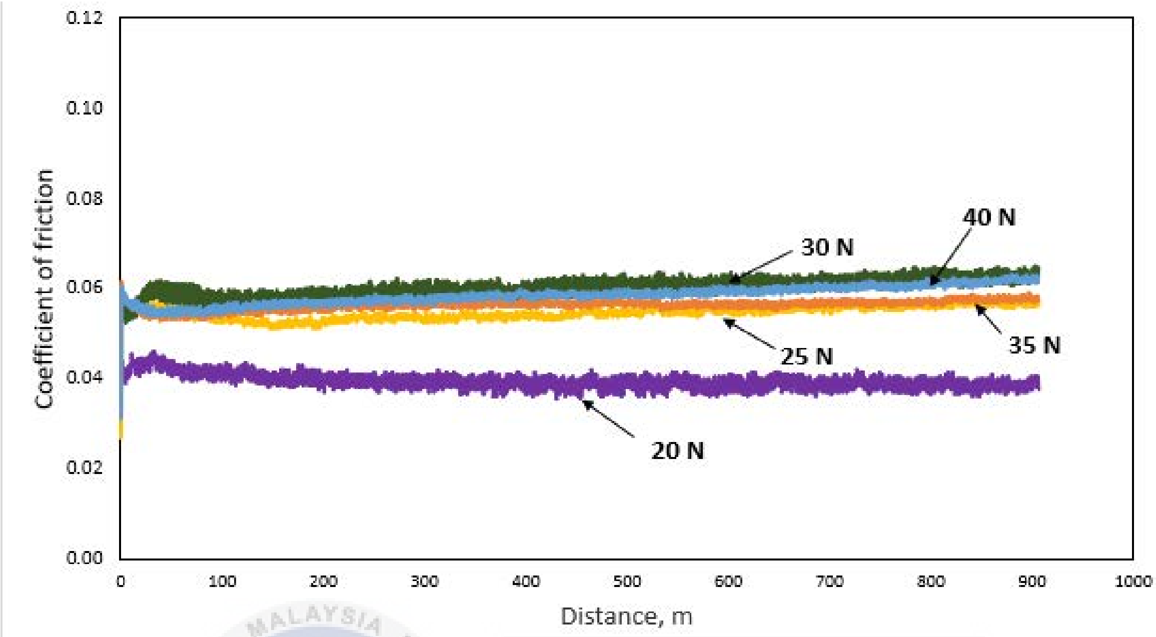


Figure 4. 1: Graph of coefficient of friction versus sliding distance for 3D printer ABS under wet condition.

According to Araujo Borges et al. (2018), the COF presenting decreasing trend after certain period possibly due to absorption of solution that were put in sample as lubrication. The greater average result as shown in might due the higher surface roughness of 3D printed samples. The importance of the result is the stable region where the average coefficient of friction was taken and the result of COF within the range.

(Majd et al., 2017) stated that the increased of COF were expected for this experiment where the meniscus tissue was replaced with PCU. The high average of COF might due to not enough interstitial fluid weeps out the surface of material and fluid not able to create thick fluid film to reduce the COF. However, the result of COF slightly different to the range of value compared to the previous research.

Figure 4. 2 shows the result of average COF for 3D printer ABS under wet condition. The result obtained from the experiment still within the range that mention in (Majd et al.,

2017) which is 0.05 until 0.09. The increasing trend of COF were affected by load applied in this experiment to the disc and the result shows the highest COF of this experiment is 30 N. The phenomena could be explained due to uneven distribution of paraffin oil into the disc and the lubrication not absorbed properly to the 3D sample. Table 4.1 shows the average value of COF for ABS 3D printer under wet condition.

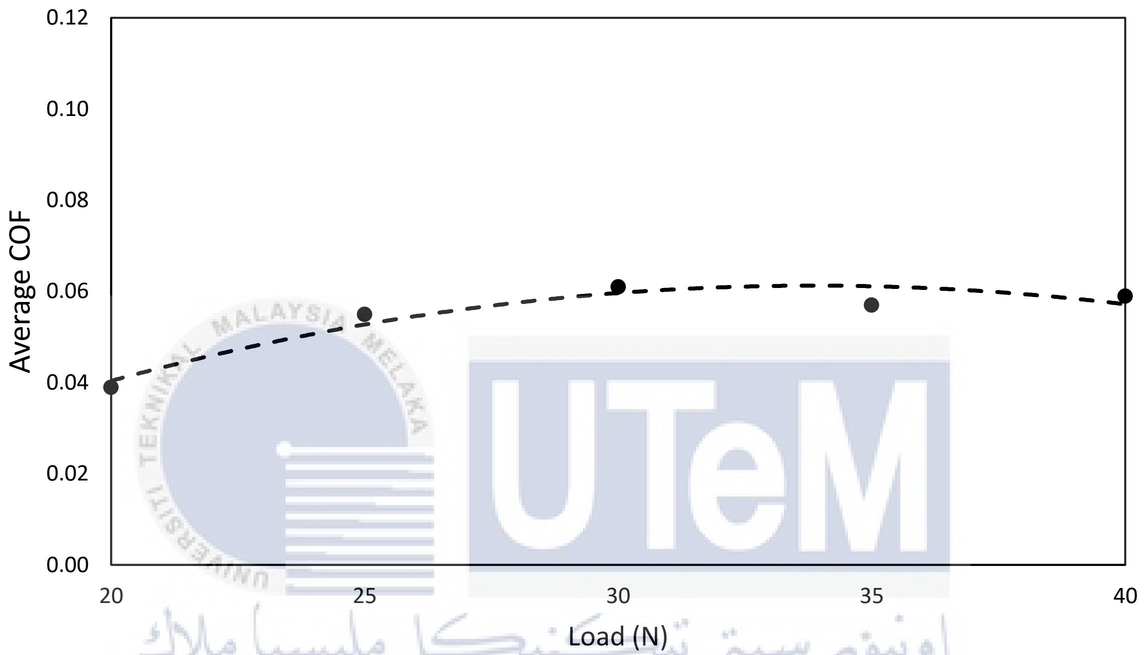


Figure 4. 2: Graph of average COF versus load for 3D printer ABS under wet condition.

Table 4. 1: Average value of COF for 3D printer ABS under wet condition.

Load (N)	COF
20	0.039
25	0.055
30	0.061
35	0.057
40	0.059

ii. Molded

Figure 4.3 shows the graph of COF versus distance molded ABS under wet conditions. This molded ABS was tested on ball-on-disc machine with same parameter using for ABS 3D printer. The lubrication was also included during this experiment which is paraffin oil. The trend for this graph shows that there is fluctuation at the beginning of the graph where the value of coefficient of friction increases. After several minutes test was running, it shows the trend of the graph tremendously decreasing and this behaviour was observed throughout the experiment. The graph stabilizes when it reaches 200m after test running until the end of experiment.

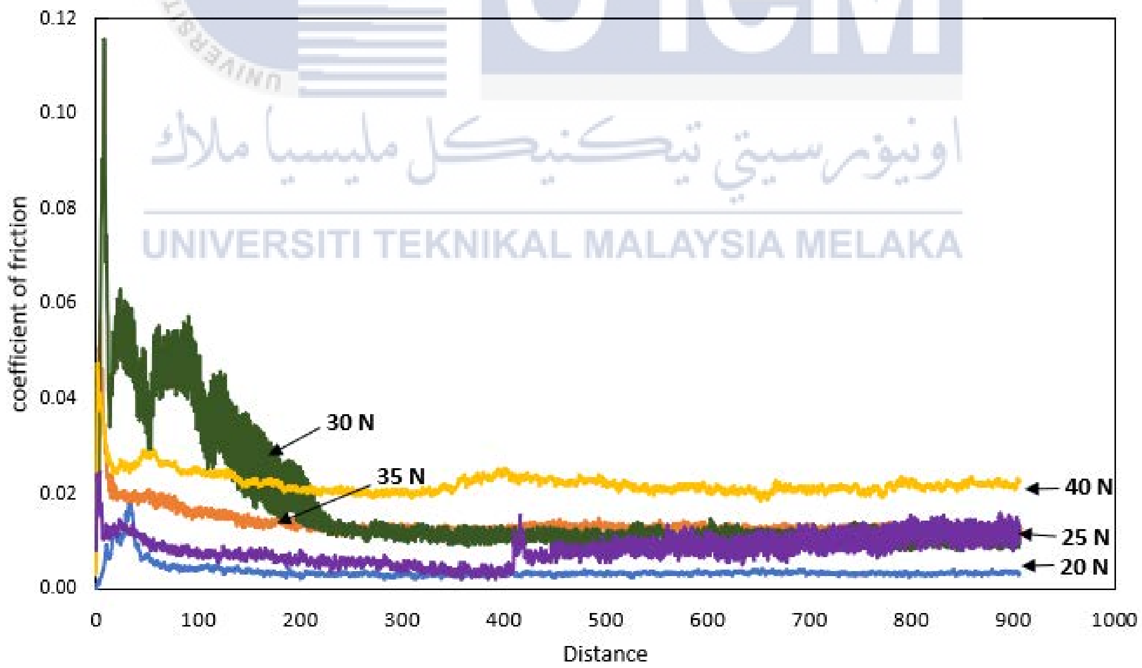


Figure 4. 3: Graph of coefficient of friction versus sliding distance for molded ABS under wet condition.

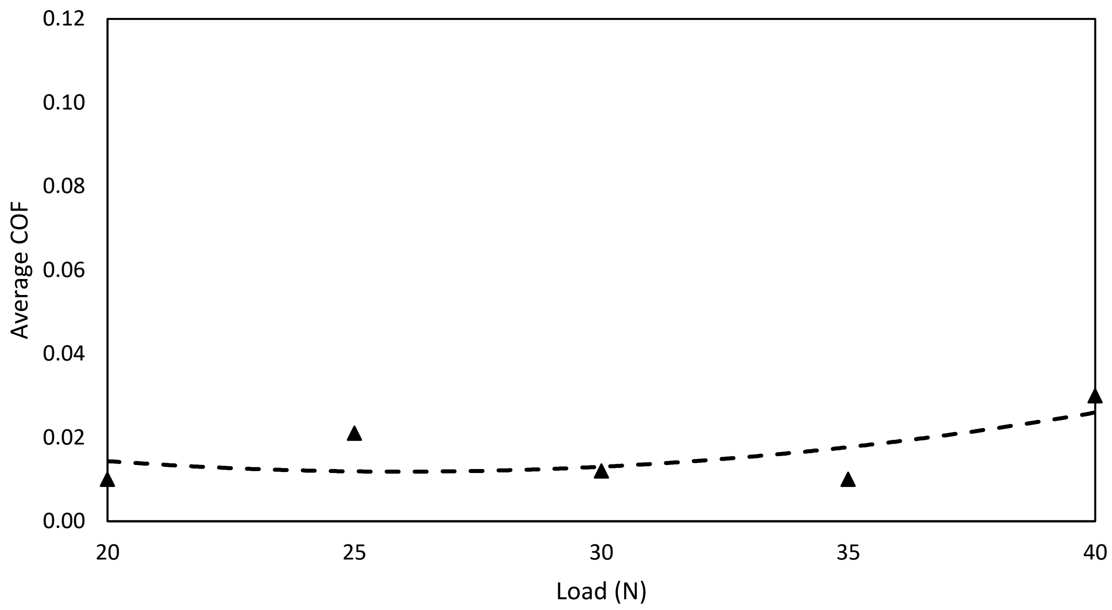


Figure 4. 4: Graph of average COF versus load for molded ABS under wet condition.

The graph of average COF versus load as shown in figure 4.4. The trend show increasing of COF for molded ABS. The range of COF for different load within 0.01 to 0.04 as shown in table.

Table 4. 2: Average value of COF for molded ABS under wet condition

Load (N)	COF
20	0.01
25	0.021
30	0.012
35	0.01
40	0.03

4.1.2 Coefficient of Friction of ABS under Dry Condition.

i. 3D Printer

The graph shows the result of experiment of ABS 3D printer under dry conditions. Based on the graph, it tends to increase at the beginning of test due to no lubrication were provided for this experiment. The experiment started to stable at 400 – 500 m until the end of experiment. The applied load has minimum effects to the result of graph whereas shows the highest the load the lowest the friction. The result of experiment for 35N and 40N shows decreasing COF at the end of experiment due to disc surface defect after running for 700 meters. The absent of lubricant in the disc during running test effects the performance of material and the result of COF were slightly disturb due to the unexpected worn layer in disc.

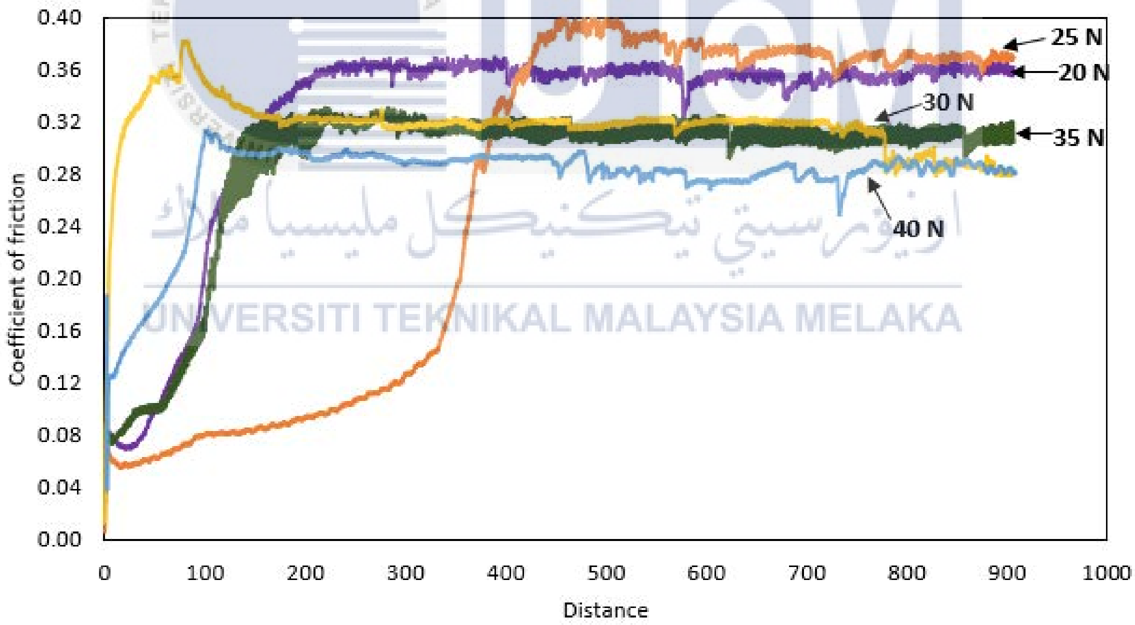


Figure 4. 5: Graph of coefficient of friction versus sliding distance for 3D printer ABS under dry condition.

Sudeepan et al.,(2014a) have investigated that COF decreases when the high load was applied to the surface because of surface temperature increases during contact and surface contact become soft caused by frictional heat. This phenomenon causes reduction of COF when higher load was applied during the experiment. Due to high speed, the roller and sample produce shear action that acts as thin layer which formed at interface. Then, frictional contact played major role where its accumulated debris and when it reaches the certain amount of rotation, friction will be at steady state condition. In this case, the rotational speed and applied load increases lead to lowest coefficient of friction for dry condition.

Kolluri et al. (2007) found out that COF decreasing when applied load increasing and proving that contact between two surfaces can lead adhesive and abrasive wear. This wear leas to accumulated debris that happen due to contact between two surfaces. Meanwhile, Zhang et al. (2009) also stated that this finding was consistence since the observation from the study shows that coefficient of friction decreasing when the environmental temperature increasing. The adhesive resin that was used in the experiment makes the COF decrease as the temperature increases throughout the experiment process. This similar observation from several study that were conducted proves that COF decreasing when temperature and applied load increasing.

The result of average COF of 3D printer under dry condition as shown in figure 4.6 The applied load of 40 N has the lowest coefficient of friction compare to others. The surface contact between 3D printer and ball bearing leading to accumulated debris that reduces the value of COF. The beginning of the process shows tremendous increases value of COF before it reaches steady state and start to decrease. Table 4.2 shows the average value of COF for 3D printer under dry condition.

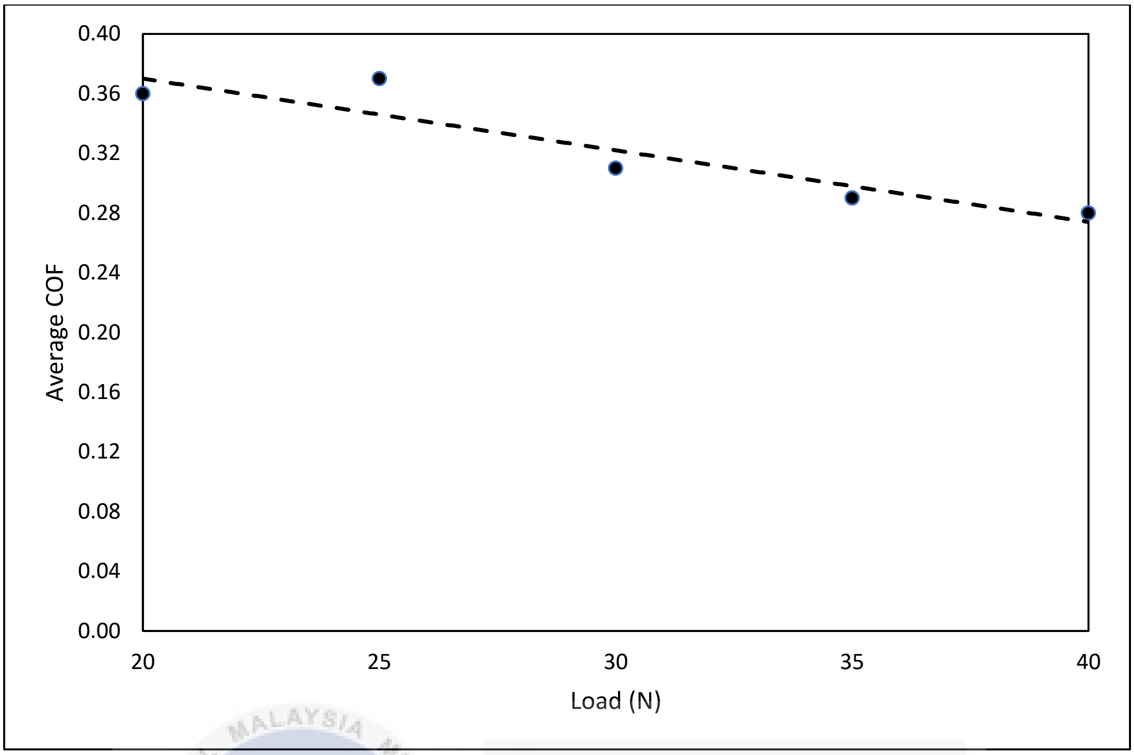


Figure 4. 6: Graph of average COF versus load for 3D printer ABS under dry condition.

Table 4. 3: Average value of COF for 3D printer ABS under dry condition

Load (N)	COF
20	0.36
25	0.37
30	0.31
35	0.29
40	0.28

ii- Molded

The test conducted for molded ABS under dry condition using same parameter without any lubrication. The result of this experiment shows the same phenomenon happen during 3D printer ABS under wet condition running. Based on Figure 4. 7, there is different trend for each applied load to the molded ABS. For 20 N and 30 N, the beginning of experiment shows the graph increases before it reaches the steady region until the end of experiment. Meanwhile, others applied load shows continuous increases before reaches the steady region until the end of experiment. There wear occur at the middle of experiment for 30 and 40 N due to no lubrication using for this sample.

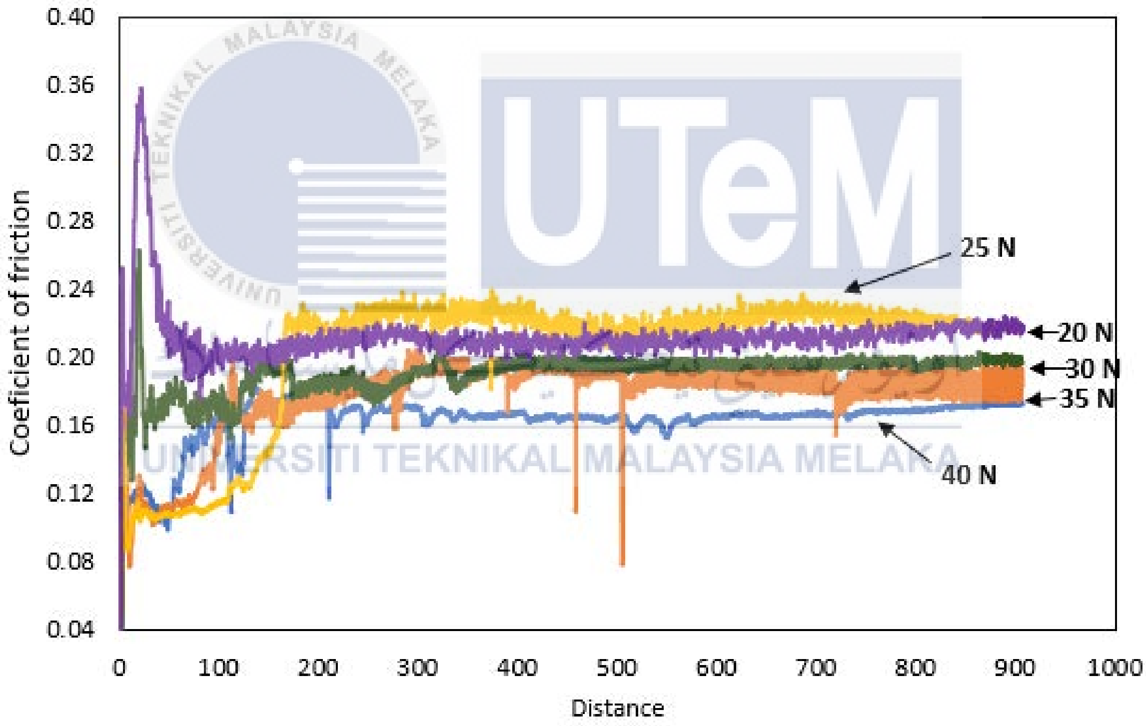


Figure 4. 7: Graph of coefficient of friction versus sliding distance for molded ABS under dry condition.

The result in Figure 4. 8 for average COF versus load shows that the trend was decreasing when the load applied increasing. The observation for this test same with dry condition for 3D printer ABS where the contact between surface produce accumulated debris that leading to reduction of COF.

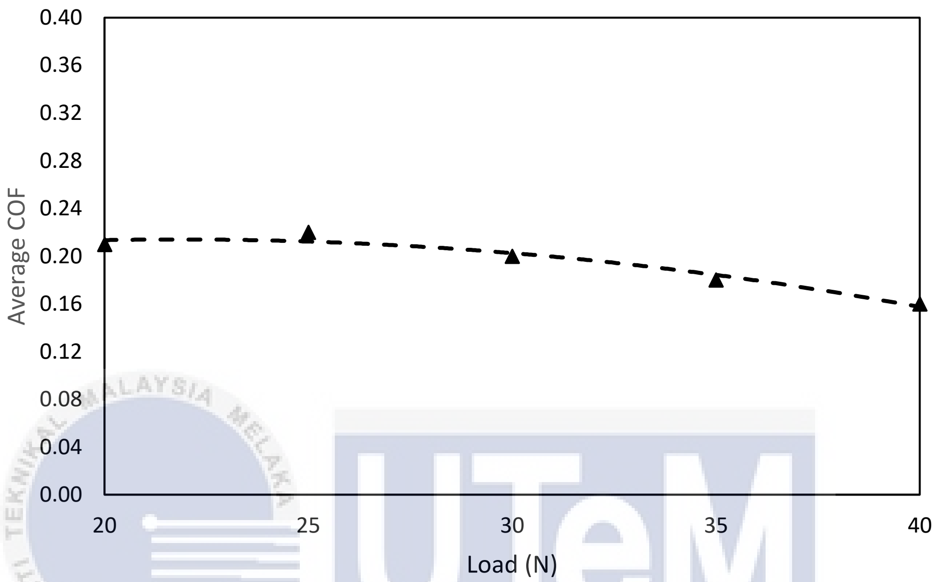


Figure 4. 8: Graph of average COF versus load for molded ABS under dry condition.

Table 4. 2: Average value of COF for molded ABS under dry condition.

Load	COF
20	0.21
25	0.22
30	0.20
35	0.18
40	0.16

4.1.3 Comparison Coefficient of Friction for 3D Printer and Molded ABS.

i- Wet conditions

Based on the graph, the result of average COF between 3D printer and ABS molded shows the increasing trend for COF versus load. The range COF for ABS 3D printer are within 0.04 to 0.06 which higher that COF of molded ABS. The range for molded ABS is within 0.01 to 0.03. From this experiment, the result still within the range and this prove that 3D printer has fast action to obtain the result. Figure shows the result of comparisons average COF between 3D printer and molded ABS.

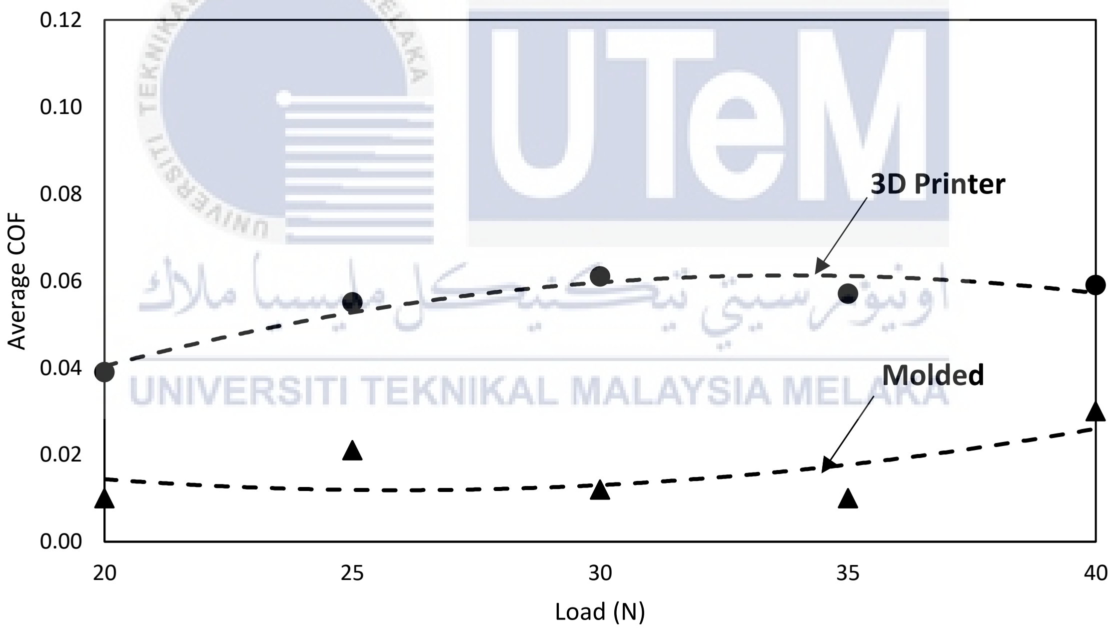


Figure 4. 9: Comparisons average COF between 3D printer and molded ABS under wet condition.

ii- Dry conditions.

Figure shows that the result of average COF between 3D printer and molded ABS under dry condition. The average of COF was decreasing when the applied load increasing. As discussed, the contact between surface during experiment causes by sliding effect the COF value. This experiment was conducted without lubrication also one of the important factors the value COF high compared to wet condition.

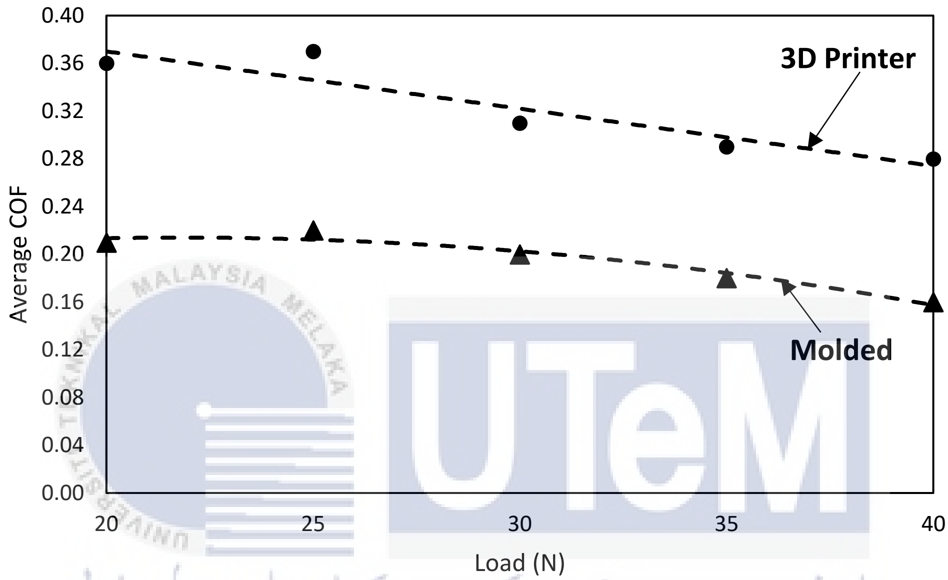


Figure 4. 10: Comparisons average COF between 3D printer and molded ABS under dry condition.

4.2 Wear mechanism

4.2.1 Specific Wear Rate for ABS under wet condition.

i. 3D Printer

The graph in Figure 4. 11 shows the wear rate for 3D printer under wet condition. The wear scar radius was taken using portable 3D Non-contact Profilometer. The result of specific wear rate was calculated using Equation 2. Based on the graph, the trend of wear scar diameter increasing when the higher load was applied. The range of the wear rate for this condition is within 0.8×10^{-6} to 2.2×10^{-6} mm^3/Nmm.

Based on Araujo Borges et al., (2018), 3D printed sample has the lowest wear depth compare to other sample. This is might due to lubrication behaviour inside the 3D printer that has porosity. As part of 3D printer mechanical characteristic which are wear resistance, mechanically strong and able to provide lubrication during the sliding.

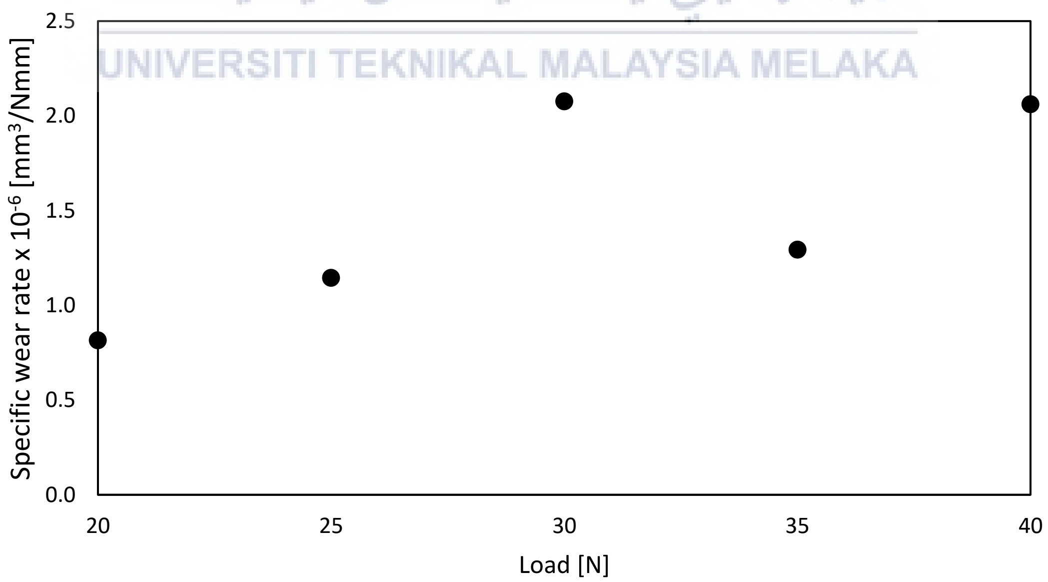


Figure 4. 11: Specific wear rate of 3D printed ABS under wet condition.

ii. Molded

The graph shows that specific wear rate affected by the value of COF. For applied load 25 N has the highest COF and it is also have the highest wear.(Ben Difallah et al., 2012) study about ABS filled with graphic powder. The wear mechanism can be seen where more graphic powder was added to ABS. Thus, the highest wear rate also shows the smooth surface and there is debris in sample. Figure 4. 13 shows the result of wear track for molded ABS under wet condition.

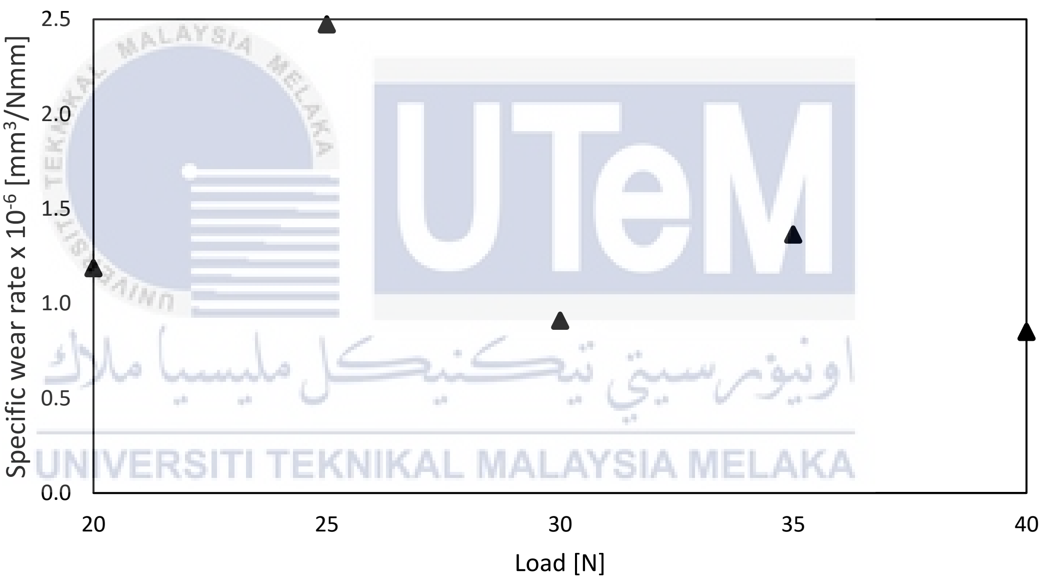


Figure 4. 12: Specific wear rate of molded ABS under wet condition.

4.2.2 Specific Wear Rate for ABS under dry conditions

i. 3D Printer

Figure 4. 13 shows the specific wear rate of the 3D printer ABS and tested under dry condition. From the experiment, it shows that the lubricant and applied load effect the result of wear. According to Unal, Mimaroglu, Kadioglu, & Ekiz (2004), the wear rate will increases due to the critical surface energy of the polymer. The result for the experiment also stated that when the load increase without lubricant, the wear also increases until it reaches certain limit the polymer can afford. It is also stated that the sliding speed is one of the factors that influence the value of wear rate.

Based on (Xiong & Ge, 2001), the COF and sliding distance might affect the wear track in dry condition during experiment. This experiment compared the friction and wear for different types of condition which is under dry condition and wet condition but different lubricant. Thus, the highest wear was sample under dry conditions due to no lubricant were used. The high wear rate also might due to some flakes from sample that had been transferred to surface during experiment. The increasing load resulting decrease the COF due to contact between surface but repeated of friction force leading to wear surface layer where causes the fatigue happens.

Meanwhile, the worn surface of the composite for dry condition worse than the composites with lubricant. Jia, Zhou, Gao, & Chen, (2003) stated that dry conditions has higher worn surface compared to water lubricant for the test. Water lubricant has lowest worn surface due to polymer matrix combines the fiber well and absorbing water lubricant decrease wear.

The same rules were applied for this graph where the decreasing COF where increasing lead to increasing of wear. This phenomenon happens due to certain friction force can be supported by molded ABS. Thus, the continuous friction force to the molded ABS surface influence the wear rate value during the experiment.

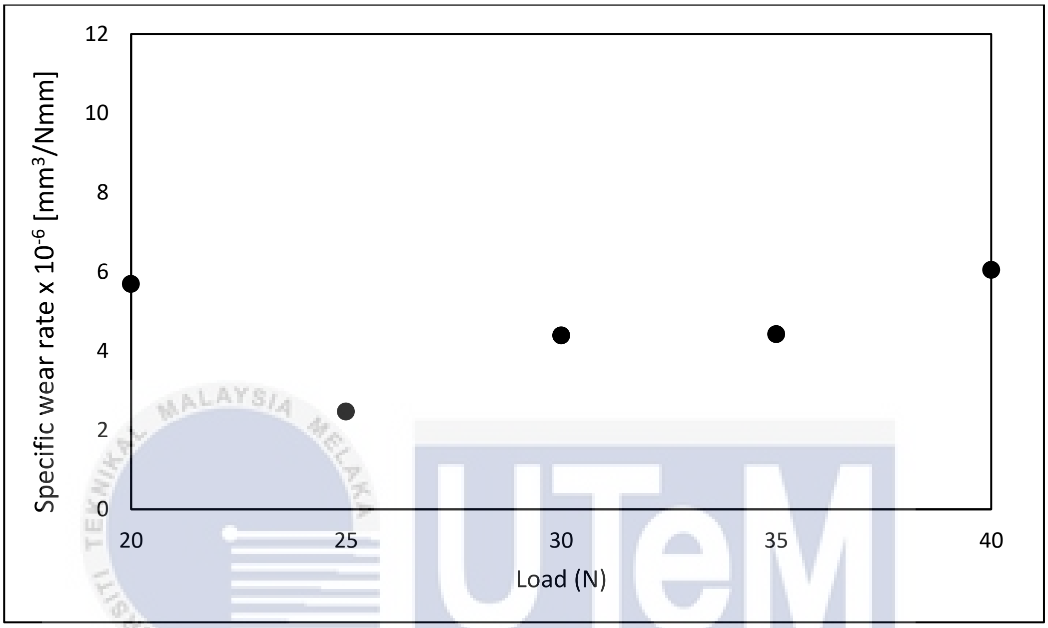


Figure 4. 13: Specific wear rate for 3D printer ABS under dry condition.

ii. Molded

Figure 4. 14 shows the result of specific wear rate of molded ABS under dry condition. When COF increases, the specific wear rate also increases due to surface energy of the polymer (Unal et al., 2004). As shown in graph, 40 N has the lowest wear compared to others due to COF for load 40 N also lowest which is 0.16. The experiment was conducted under dry condition where the possibility for surface to worn is high because there is no lubrication in the sample. Thus, molded ABS cannot absorb humidity and use it as natural lubricant to reduce the specific wear rate.

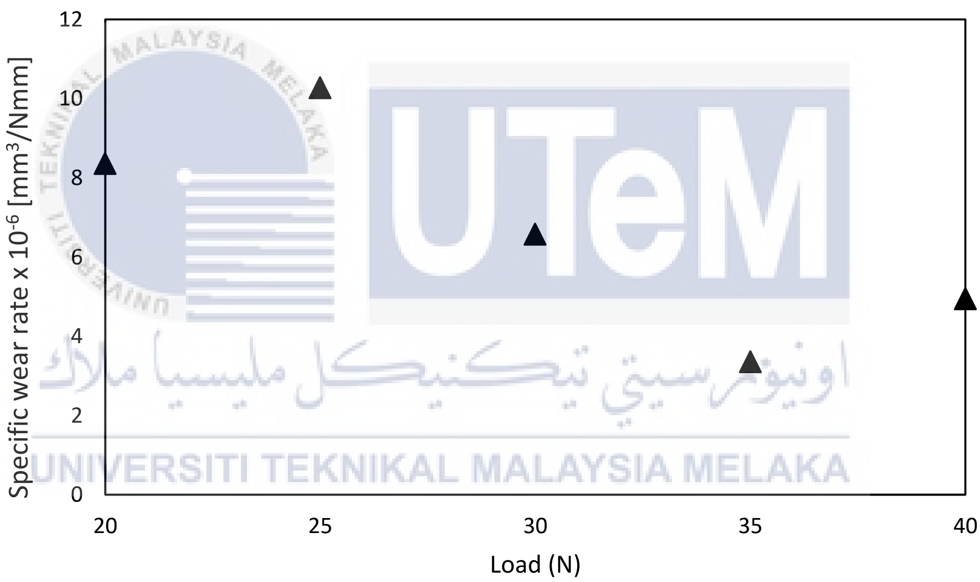


Figure 4. 14: Specific wear rate of molded ABS under dry conditions.

4.2.3 Comparison Specific Wear Rate for 3D Printer and Molded ABS.

i. Wet conditions.

The comparisons between 3D printer and molded Abs under wet condition as shown in figure 4. 15. The wear track result doesn't show any big difference between 3D printer and molded ABS even though the COF value of 3D printer is higher than molded. This proves that 3D printer sample has porosity that absorb the lubrication. According to Araujo Borges et al., (2018), 3D printer has porosity where the porous retained and releases the fluid during movement of body. It is also act as separation boundary between surface. The result of this specific wear rate shows that 3D printer ABS has wear resistance.

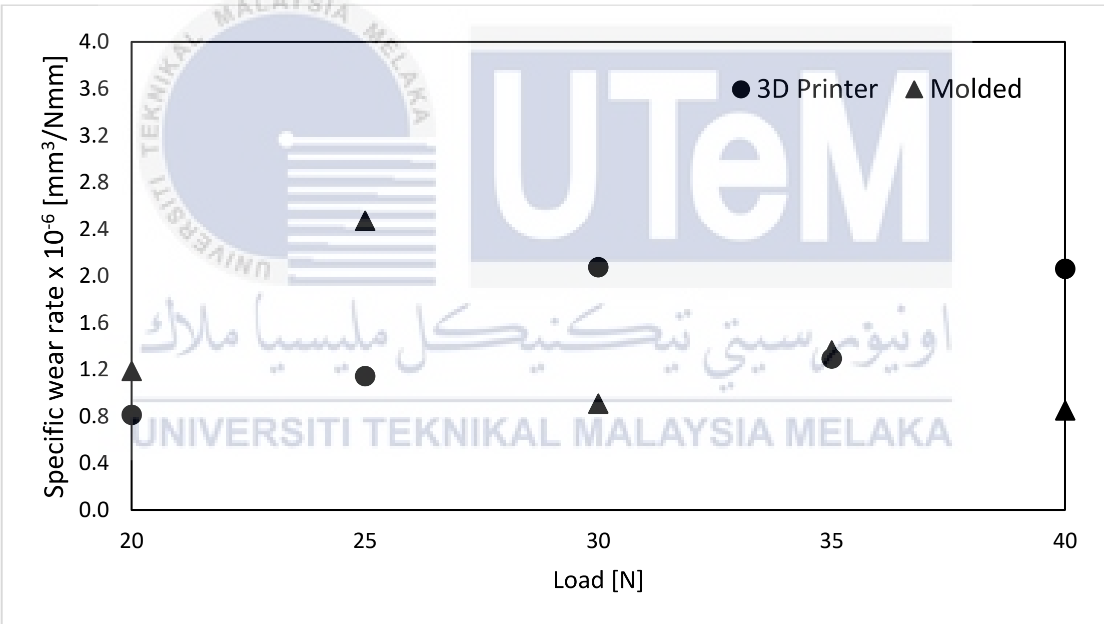


Figure 4. 15: Comparisons specific wear rate 3D Printer and molded ABS under wet conditions.

ii. Dry Conditions.

Figure 4.16 shows the comparisons between 3D printer ABS and molded ABS under dry condition. The graph shows that 3D printer ABS has lower specific wear rate compared to molded specific wear rate. This due to ABS mechanical characteristic itself where ABS wear resistance. The reduction of wear also supported by the fabrication of ABS that used 3D printer. By using 3D printer, ABS were printed layer by layer where there is porosity to help reduce the wear instead of molded.

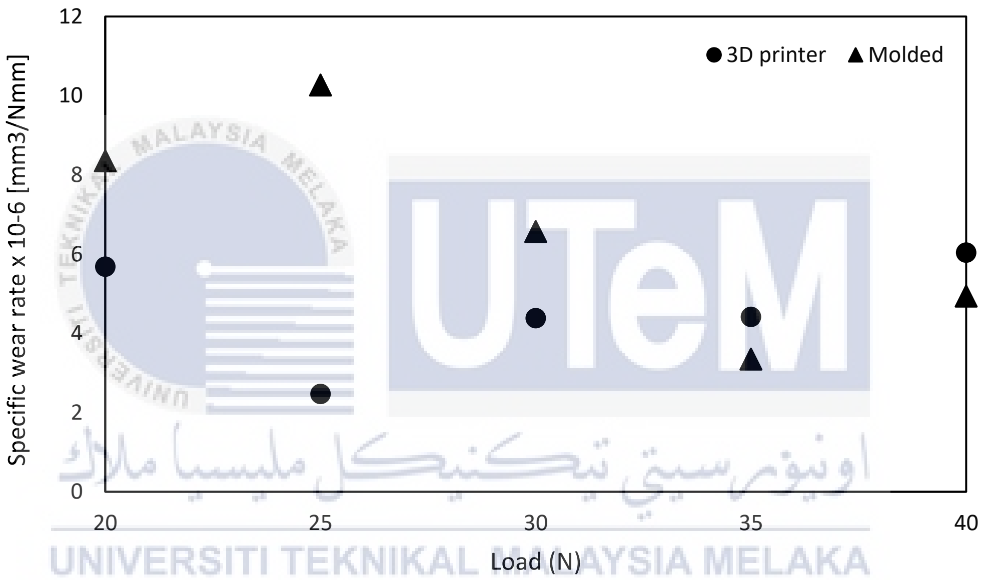


Figure 4. 16: Comparisons Specific wear rate 3D Printer and molded ABS under wet conditions.

CHAPTER 5

CONCLUSIONS

The main focuses of this chapter are to conclude the result of entire experiment and choose the best result as final decision. Suggestion for future improvement to achieve a better the result in future.

5.1 Conclusion

The purpose of this study is to identify the tribological performance between 3D printer and molded ABS. The good performance on COF and wear proves that 3D printer ABS able to have smooth surface that can be widely used in industry especially medical field. The result of COF and wear can be obtained from ball-on-disc experiment where can identify that 3D printer ABS get a better result than molded ABS.

The coefficient of friction of 3D printer and molded ABS under wet condition shows that 3D printer ABS has the highest COF compared to molded. This might due molded ABS has smooth surface that reduce the friction when two metal collide together. However, the specific wear rate 3D printer ABS show slightly difference compared to molded ABS. This proves that 3D printer ABS have porosity that retained the lubrication throughout the experiment. The porosity absorbed lubricant and helps protect both surface from wear.

Next, the coefficient of friction of 3D printer and molded ABS under dry condition. From previous research stated that ABS under dry condition has higher COF and wear but the range of this result still acceptable to be used. From this experiment, 3D printer ABS have the highest COF due to no lubrication was used at ball-on-disc machine. The specific wear rate result shows difference outcomes where molded ABS has higher wear compared to 3D printer ABS. The surface of the molded ABS also wear due to continuous friction heat were supplied. In summary, this research found that 3D printer that has better performance of reduce the wear even though the COF result still high.

5.2 Future Recommendation

Based on result of this research, there is few suggestions for improvement in future:

1. Lubrication is one of the important aspects that effect the value of COF. In future, the different oil can be used as lubricant to test the tribological performance of 3D printer ABS.
2. Combining other substance to explore more on behaviour of 3D printer ABS for tribological performances. The lack of studies about ABS friction performance need to be focuses on.
3. Changing the parameter such as sliding distance, temperature and speed to investigate the effect of tribological performance during wet and dry conditions.

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APPENDICES

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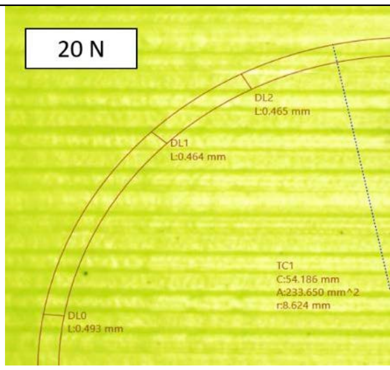
<td>
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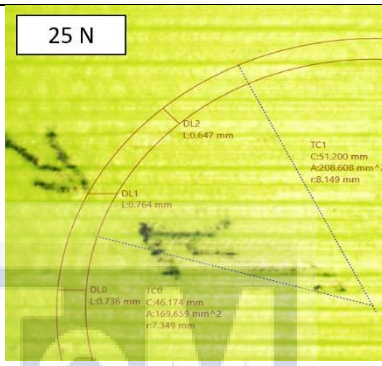
<td>
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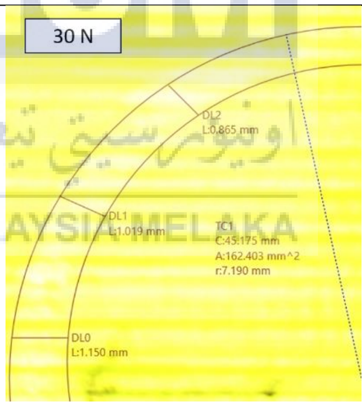
<td>
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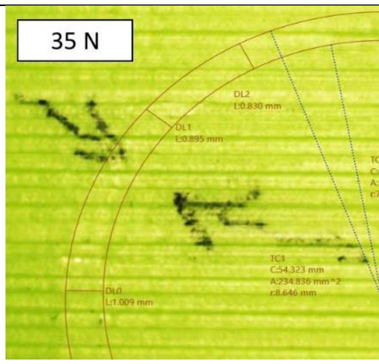
<td>
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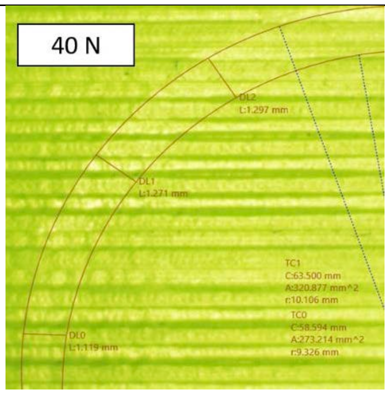
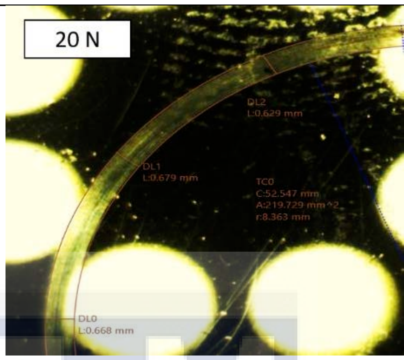
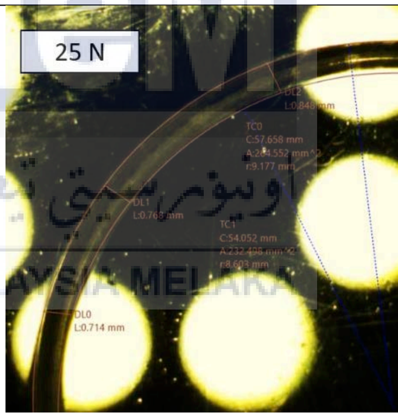
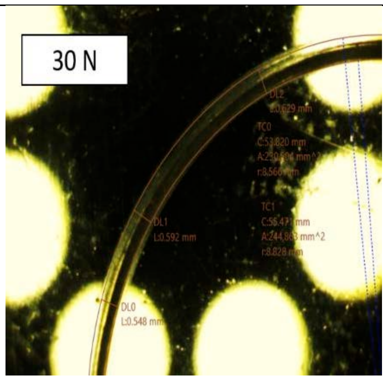
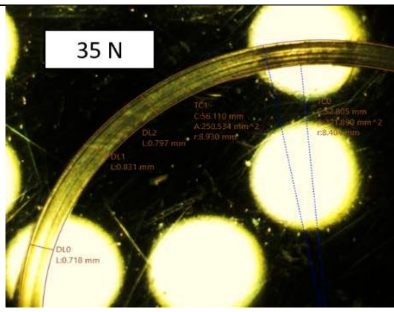
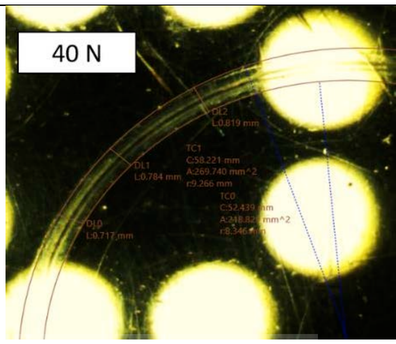
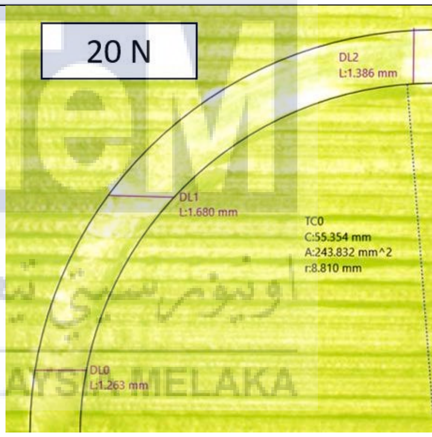
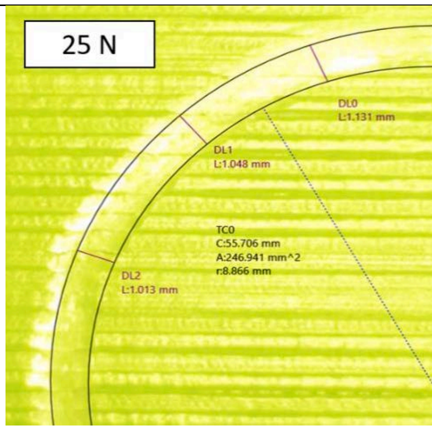
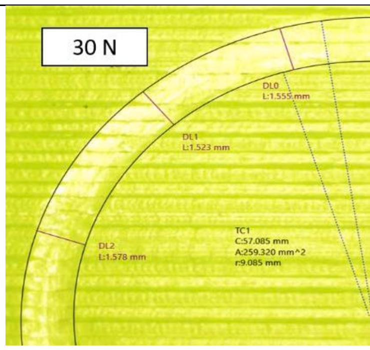
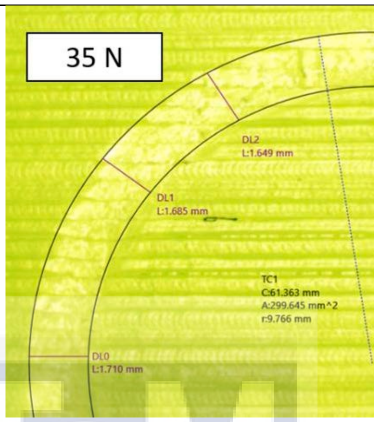
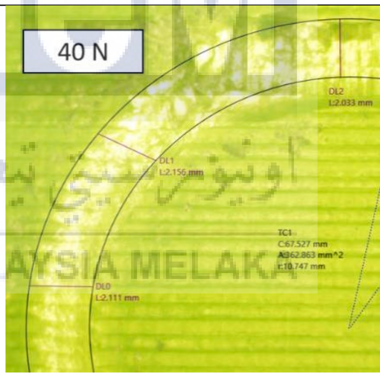
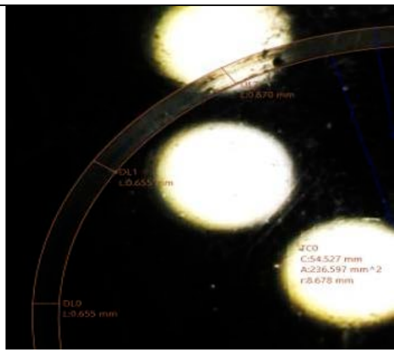
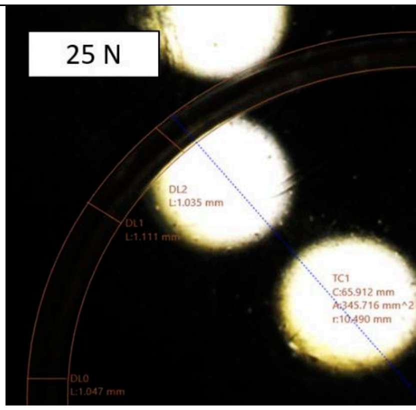
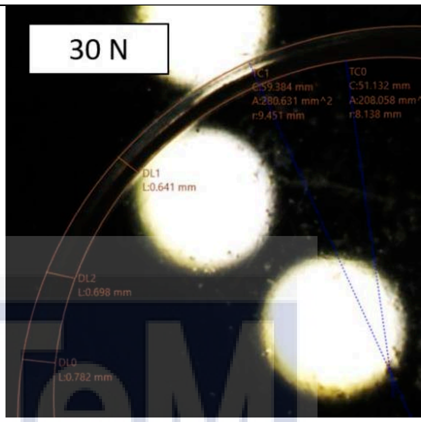
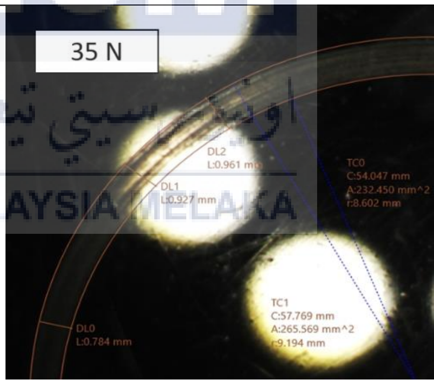
APPENDIX 5: **3D Printer ABS Wet Condition**	
APPENDIX 6: **Molded ABS Wet Condition**	
APPENDIX 7: **Molded ABS Wet Condition**	
APPENDIX 8: **Molded ABS Wet Condition**	

APPENDIX 9: **Molded ABS Wet Condition**	
APPENDIX 10: **Molded ABS Wet Condition**	
APPENDIX 11: **3D Printer Dry Condition**	
APPENDIX 12: **3D Printer Dry Condition**	

APPENDIX 13: **3D Printer Dry Condition**	
APPENDIX 14: **3D Printer Dry Condition**	
APPENDIX 15: **3D Printer Dry Condition**	
APPENDIX 16: **Molded ABS Dry Condition**	

APPENDIX 17: **Molded ABS Dry Condition**	
APPENDIX 18: **Molded ABS Dry Condition**	
APPENDIX 19: **Molded ABS Dry Condition**	
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