OPTIMIZATION OF TRIBO-PERFORMANCE OF 3D-PRINTED ABS WITH INTERNAL STRUCTURE FORMATION FOR PRODUCTION OF AUTOMOTIVE BEARING

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A report submitted in fulfillment of the requirements for the

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DECLARATION

I declare that this project report entitled “Optimization of Tribo-performance of 3D-printed ABS with internal structure formation for production of automotive bearing” is the result of my work except as cited in 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 Mechanical Engineering

Signature :.................................

Supervisor's Name :.................................

Date :.................................

DEDICATION

This report is dedicated to my beloved parents, family members, lecturers, and friends who've been with me throughout a fantastic journey of my academic life. We pray to Allah Almighty for the health and forgiveness of our parents who have given us a lot but claimed nothing.

ABSTRACT

In this paper, the objective to determine the optimized printing parameters of 3D-printed ABS for new automotive bearing formulation using the Taguchi Method. Therefore, the design of experiments was conducted for the analysis of the influence of the printing parameters such as layer height, pattern, and nozzle temperature on the coefficient of friction (COF). The results of the pin-on-disc test were used to characterize the main factors affecting COF by the Analysis of Variance (ANOVA) method Taguchi’s parametric design is the effective tool for robust design it offers a simple and systematic qualitative optimal design to a relatively low cost. However, the Design of Experiments (DOE) is the key element for achieving high quality at low cost and COF. The Taguchi method is used to find optimum process parameters in the production process of 3D-printed ABS for new automotive bearings. In the experiment, the value of the layer height is 0.1, 0.2 and 0.3 while the temperature is 225°C, 230°C and 235°C and with three different patterns which is rectilinear, concentric and hilbert was used. Experimental results show that the layer height of the printing parameters is the most significant printing parameter for COF followed by pattern and nozzle temperature in the specified test range.

ABSTRAK

Dalam kajian ini, objektifnya adalah untuk mengenal pasti cara mengoptimumkan penggunaan parameter percetakan tiga dimensibagi bahan Acrylonitrile butadiene styrene (ABS) untuk menghasilkan galas automotif yang baru dengan menggunakan kaedah Taguchi. Oleh itu, reka bentuk experiment ini dilalukan dengan menganalisis printing parameter seperti ketinggian lapisan, corak, suhu muncung pada mesin pencetak tiga dimensi keatas pekali geseran (COF). Keputusan daripada experiment pin-on-disc digunakan untuk mengkategorikan factor-faktor utama yang dipengaruhi oleh pekali geseran melalui Analysis of Variance (ANOVA) di dalam kaedah Taguchi di mana parametric design dalam kaedah ini adalah cara yang efektif untuk mendapatkan reka bentuk yang bagus dan menawarkan cara yang mudah serta sistematik dengan melibatkan kos yang rendah. Reka bentuk experiment adalah elemen yang penting untuk mendapatkan kualiti yang bagus dengan kos dan pekali geseran (COF) yang rendah. Kaedah Taguchi digunakan untuk mencari parameter proses yang optimum dalam penghasilan 3D-printed ABS untuk galas automotif yang baru. Dalam experiment ini, nilai ketinggian lapisan adalah 0.1, 0.2 dan 0.3 manakala suhu muncung pula bersamaan 225°C, 230°C dan 235°C *serta bagi corak mempunyai tiga variasi iaitu rectilinear, concentric dan hilbert telah digunakan. Keputusan experiment menunjukkan bahawa ketinggian lapisan adalah faktor yang paling mempengaruhi pekali geseran (COF) diikuti dengan faktor corak dan suhu muncung.*

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LIST OF ABBREVIATIONS

COF	-	Coefficient of Friction
FDM	-	Fused Deposition Modeling
FFF	-	Fused Filament Manufacturing
FLM	-	Fused Layer Manufacturing
PEI	-	Polyetherimide
PC	-	Polycarbonate
PPSF	-	Polyphenylsulfone
PLA	-	Polylactic Acid
PA	-	Polyammide
PVDF	-	Polyvinylidene Fluoride
HIPS	-	High-Impact Polystyrene
CAD	-	Computer-aided Design
ME	-	Modelling Extrusion
AM	-	Additive Manufacturing
ASTM	-	American Society of Testing and Materials
ABS	-	Acrylonitrile butadiene styrene

LIST OF SYMBOLS

D	-	Distance of slide, m
r	-	Radius wear track, m
N	-	Sliding speed, rpm
t	-	Time, min & sec
F	-	Frictional force, N
W	-	Applied load, N
V_{loss}	-	Volume loss, mm^3
k	-	Specific wear rate, mm^3/N.mm
a	-	Wear scar radius, mm
h	-	Wear depth, mm
L	-	Sliding distance, mm

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Tribology is the concept of the science and engineering of dynamic surfaces in relative motion. The Tribology study includes the application of the principles of lubrication, friction, and wear. It is highly interdisciplinary and has been used in many academic fields such as physics, chemistry, mathematics, biology, material sciences, and engineering. The importance of tribological properties for economic reasons are the same as technological development reason. There is various wear of patterns like erosion, fatigue, and abrasion which caused by damages of contact surfaces (Zmitrowicz, 2006). Ignorance of tribological phenomena and less effectiveness of programs of research to manage this situation cause a tremendous waste of resources.

Fused deposition modeling (FDM), also known as fused filament manufacturing (FFF), fused layer manufacturing (FLM), extrusion modeling (ME) or 3D printing is one of the most popular additive manufacturing (AM) processes used in the manufacture of prototypes and functional parts in common extrusion-based engineering plastics, the material being "selectively dispensed via a nozzle or orifice" (Iso, 2015).

The study of printing parameters and tribological properties of 3D-printed ABS material is most important because different parameters and tribological properties provide different types of properties in the materials ' mechanical behavior, friction, and wear due to different combinations of factors. This project will focus on investigating the optimum printing parameters that affect the coefficient of friction (COF) and wear of 3D-printed ABS material by varying three different factors: layer height, printing pattern, and temperature of the nozzle. The outcome of this project will provide ABS material with better and suitable printing parameters for the lowest coefficient of friction and wear.

1.2 Problem Statement

A bearing is a moving device that supports the movement of rotation between a stationary part and a rotating part. In the automotive industry, carbon steel, stainless steel, chrome steel, brass, aluminum, tungsten carbide, and plastic are used in many types of bearing materials. Compared to acrylonitrile butadiene styrene (ABS) material, these common material bearings are more expensive, a higher coefficient of friction and wear. It is part of the category of thermoplastic polymer made by polymerizing styrene and acrylonitrile with polybutadiene. This is a material commonly used in 3D printing for personal, industrial, and household uses primarily fused deposition modeling (FDM) or 3D printers for fused filament manufacturing (FFF). These ABS materials have great, lightweight plastic properties, good impact strength, resistance to abrasion, and affordable.

Therefore, this project focuses on optimized printing parameters of 3D-printed ABS material for a new automotive bearing to design a lower cost, friction coefficient, and wear bearing using ABS materials.

1.3 Objective

The objective of this study is to determine the optimized printing parameters of 3D-printed ABS for new automotive bearing formulation using the Taguchi Method.

1.4 Scope

The study covers the development of specimen of 3D-printed ABS with internal structure formation for production of automotive bearing with different parameters using fused deposition modelling (FDM), also known as fused layer manufacturing (FLM), modelling extrusion (ME), fused filament fabrication or 3D printing. This study focuses on friction and wears properties using the ASTM standard ball-on-disk tribometer with fixed temperature, speed, and time parameters. In this study, which is layer height, pattern, and nozzle temperature, three independent factors that have been considered.

1.5 General Methodology

1.5.1 Flowchart

This section explains how to carry out this project to achieve the goals of this project, such as correctly processing, identifying, analyzing data, and information. The project methodology is summarized in the flowchart below in Figure 1.1.

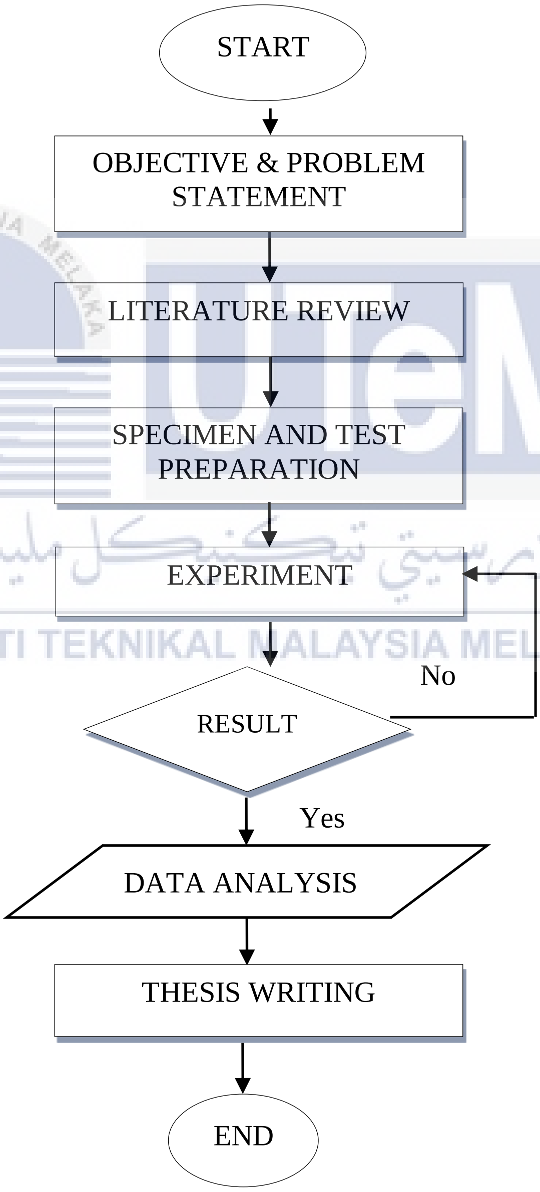


Figure 1.1: Flowchart of the methodology

Based on Figure 1.1, the first process is the selection of the project title followed by the identification of the problem statement and title-based objectives, which is to optimize the printing parameters for friction and wear analysis of fused deposition modeling (FDM) 3D-printed ABS.

Next is the research and journal literature review, which is data from the literature review of existing projects, journals, articles, and other resources on this project. Another step is the sample preparation and testing, the materials used acrylonitrile butadiene styrene (ABS) material and the testing uses a pin-on-disk device at room temperature under the dry sliding condition.

After that, the results of the testing process were obtained. The result will be recorded in writing and figure. Analyses how to optimize printing parameters for the lowest friction coefficient (COF) and wear of ABS material for the result analysis. Finally, the report writing process includes relevant information and data on the work of the project based on the format

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

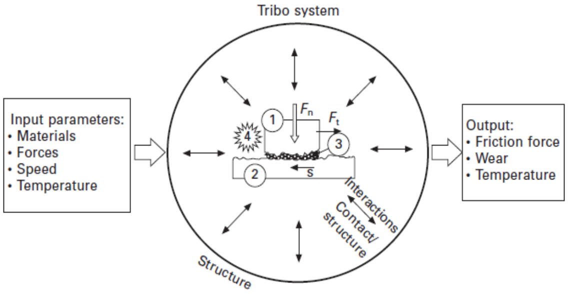
Previous research and sources from journals, reports, articles, books, and websites will be evaluated in this chapter to discover the information related to this study. The purpose of this chapter is to generate a guideline to complete this project from previous knowledge and ideas. Besides, all the information is selected under this study's objectives. Some information on tribological studies, 3D printing technologies, and materials, the Taguchi method of optimization, and pin-on-disk testing is required to achieve the objectives of this study.

For this chapter, the entire section is arranged as follows, which is the second section on tribological studies explains Section 2.2. Section 2.3 will continue to discuss 3D printing technology while Section 2.4 will explain 3D printing materials. The following section 2.5 describes the method of optimization and Section 2.6 clarifies the potential applications in this study of the 3D-printed ABS materials.

2.2 Tribology study

Tribology is the study of the science and engineering of interacting surfaces in relative motion, a phenomenon that affects our lives in various ways every day. It includes the study and application of the principles of friction, lubrication, and wear. The term tribology is based on the Greek word for rubbing which is introduced by Peter Jost in 1966 and it was officially published in Jost Report. Generally, the tribological study includes three main components which are friction, wear, and lubrication. Friction is the resistance to relative motion while wear is the loss of material due to that motion and lubrication is the use of a fluid to reduce friction and wear of materials.

The industrial growth rapidly because of the growth of technology led to the needed for a better understanding of tribology. (Lyon, 2011) stated that the study of mechanisms of tribology needs to be done to understand this field and improves the technology. The mechanisms mostly machine elements such as bearings, clutches, gears, cables, and human joints. The mechanisms are operated which require forces, speeds, temperature, etc., act on the moving object form the output of friction force, wear, and temperature. The important objective of tribology is to optimize moving systems functionally, economically as well as ecologically.



4.1 The various components of the tribosystem: 1 and 2 are the two first bodies; 3 is the interfacial body or third body; 4 represents the environment (Fn: normal force, Ft: tangential force, S: sliding speed) (Czichos, 1978).

Figure 2.1: The key elements of a tribology system from Lyon, (2011)

2.3 3D Printing Technologies

Additive manufacturing, also known as 3D printing, is a group of processes that create items by applying the material in layers that correspond to successive 3D model cross-sections unlike traditional processes of machining, casting and forging, where the material is extracted from a stock product (subtractive manufacturing) or poured into a mold and formed by dies, presses, and hammers. Rapid prototyping was the first method developed in the 1980s to create a three-dimensional layer-by-layer object using computer-aided design (CAD) to produce models and prototype parts. Plastics and metal alloys are the most commonly used materials for 3D printing, but they can work on almost anything from concrete to living tissue.

There are some advantages of 3D printing, which is capable of creating any shape that can fit within the volume of its construction. For example, in other manufacturing processes such as milling, each new part or part design change requires the manufacture of a new mold, tool, die, or jig to create a new part. The design can be fed into slicer software with 3D printing, any necessary supports can be added and then printed with less or no change in the physical machinery or equipment compared to conventional production. Besides, 3D printing is faster than injection molding and subtractive production. Faster design and prototype production, longer time to iterate the prototype, and find the product-market fit before competitors. The costs of machine operation, materials, and manufacturing for 3D printing are significantly cheaper than other alternative production methods, such as injection molding.

Many of the existing fast prototyping or 3D printing technologies on the market (Wang and Zhang 2012) are based on a similar layer manufacturing approach. First, a 3D computer-aided design (CAD) file is sliced into a stack of two-dimensional flat layers. These layers are made by a 3D printing machine and stacked one after the other to create a part. Nowadays, many different 3D printing processes can be categorized into seven types: vat photopolymerization, material jetting, binder jetting, power bed fusion, material extrusion, direct energy deposition, and sheet lamination.

The advantages and disadvantages associated with each process and equipment usually include parameters such as speed, cost, versatility with respect to feedstock material, geometric limitations, and tolerances, as well as the mechanical and appearance properties of products such as surface, strength, and color. According to the American Society of Testing and Materials (ASTM), the additive manufacturing technology is classified as shown in Table 2.1.

Table 2.1: The additive manufacturing technologies from I. Gibson, D. W. Rosen, (2015)

Process categories	**Technology**	**Materials**
Binder Jetting	3D Printing Ink-jetting S-Print M-Print	Metal Polymer Ceramic
Direct Energy Deposition	Direct Metal Deposition Laser Deposition Laser Consolidation Electron Beam Direct Melting	Metal: powder and wire
Material extrusion	Fused Deposition Modeling	Polymer

Material Jetting	Polyject Ink-jetting Thermojet	Photopolymer Wax
Powder bed fusion	Selective Laser Sintering Selective Laser Melting Electron Beam Melting	Metal Polymer Ceramic
Sheet lamination	Ultrasonic Consolidation Laminated Object Manufacture	Hybrids Metallic Ceramic
Vat photopolymerization	Stereolithography Digital Light Processing	Photopolymer Ceramic

2.3.1 Fused Deposition Modeling

Fused Deposition Modeling (FDM) also known as Fused Filament Manufacturing (FFF), Modeling Extrusion (ME), Fused Layer Manufacturing (FLM), or 3D Printing is a layer additive manufacturing (AM) process that uses a continuous filament of thermoplastic material by fused depositing. In the 1980s, the Fused Deposition Manufacturing Principle is trademarked by Stratasys Inc. and the similar term is Fused Filament Manufacturing (FFF). The filament is fed from a large coil through a moving and extruded through the tip of the nozzle to print one cross-section of the desired object, and then moves up vertically to repeat the process for a new layer until the printed shape has been completed. The speed of extruder head can be controlled whether to stop or start deposition and form an interrupted plane without stringing or dribbling between sections.

The most common material used for printing in a molded deposition is acrylonitrile butadiene styrene (ABS), a thermoplastic used to produce many products on the market, such as canoes, bricks, and protective headgear. Fused deposition modeling (FDM) machines are also printed in other thermoplastics, such as polycarbonate (PC) or polyetherimide (PEI). Support materials are usually water-soluble wax or brittle thermoplastics, such as polyphenylsulfone (PPSF). Also, the advantages of fused deposition modeling (FDM) are low cost and user-friendly compared to other traditional methods of producing objects. Consistent and accurate geometric structures and a wide variety of thermoplastics also provide some of the advantages of fused deposition modelling (FDM).

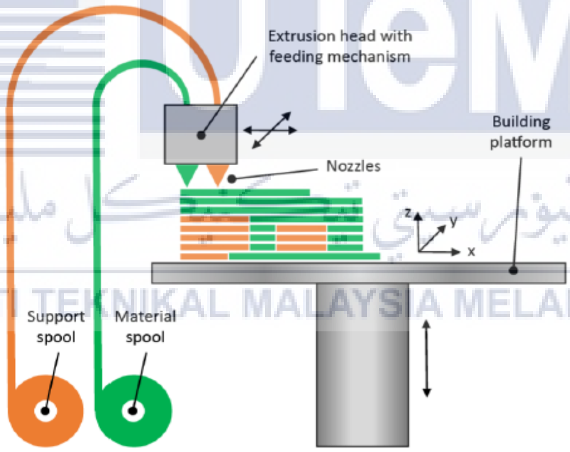


Figure 2.2: Scheme of the FDM process from Calignano et al., (2017)

2.4 3D Printing Materials

Additive manufacturing or 3D printing is a process of creating three-dimensional solid objects from a computer-aided design (CAD) model using additive processes, unlike traditional machining, casting and forging processes where the product is extracted from stock (subtractive manufacturing) or formed and molded by dies, presses, and hammers. In 3D printing, many materials are used: acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), high-impact polystyrene (HIPS), polycarbonate (PC), polyammide (PA), polyvinylidene fluoride (PVDF), polyetheretherketone (PEEK) and polyetherimide (PEI). An opaque thermoplastic polymer is commonly used for injection molding for ABS or acrylonitrile butadiene styrene. This thermoplastic engineering is an impact-resistant and amorphous polymer, consisting of three acrylonitrile, butadiene, and styrene monomers. Acrylonitrile is a synthetic monomer produced from propylene and ammonia that contributes to the stability of the heat and chemical resistance of ABS. Butadiene is then produced from steam crackers as a by-product of ethylene production, and the component provides ABS polymer itself with toughness, impact, and strength. For styrene is produced through ethylbenzene dehydrogenation and provides ABS plastic with rigidity and processability.

Generally, the mechanical properties of ABS are toughness, durable, slightly flexible, and impact resistance. It is capable of producing ABS plastic that normally operates with a hot end that is the heated part that melts the plastic before it is forced out of the nozzle at a temperature of around 210-250 ° C. Since then, the 3D printer enables ABS to be processed automatically through a heated printing bed to avoid cracking or warping of printed materials. Besides, the cost of ABS materials is the lowest of polylactic acid (PLA) and polyvinyl alcohol (PVA) filaments and was the most popular 3D printing material. It also has high tensile strength, high physical impact resistance, and chemical corrosion that can withstand heavy-duty and adverse environmental conditions.

The process temperature for 3D printing material is shown in Table 2.4. The temperatures of the materials differ according to the composition of the specific material. The higher the temperature of the extrusion, the lower the viscosity, i.e. the material flows more easily, and the higher the rate of deposition can be used (Calignano et al., 2017).

Table 2.2: Common processing temperature for different FDM materials

Materials	**Extrusion temperature [°C]**	**Bed temperature [°C]**
PLA	175 – 220	60 – 90
ABS	230 – 260	80 – 100
HIPS	220 – 250	80 – 110
PC	290 – 315	110 – 130
PA	240 – 280	100 – 120
PVDF	210 – 215	120 – 125
PEEK	360 – 400	110 – 120
PEI	330 – 360	110 – 160

2.5 Optimization method

Industries are involved in a variety of activities, including developing new models, updating previous ones, sustaining, monitoring and enhancing existing processes, and more. Experimentation is a frequent task in these activities to measure and analyze outputs, and for this purpose engineers or researchers use many tools, such as statistics, analytical models, and others. The purpose of industry experiments in today's era is essentially optimization and robust design analysis (RDA, which makes the system less sensitive to variations in uncontrollable noise factors or, in other words, to make the system robust).

Design of experiment (DOE) is the name given to the methods used to direct the collection of experiments to be carried out efficiently. In general, the system analysis can be expressed as the study of the relationships between cause and effect, which can be accomplished by drawing inferences from a small number of samples. And one of its most important objectives is to model efficient and cost-effective sampling experiments and provide an adequate qualitative database.

Experiment development has been successfully applied in a variety of fields such as agriculture (improved crop yields have resulted in grain surpluses), the petrochemical industry (for highly efficient oil refineries) and Japanese automotive manufacturing (giving them a large market share for their vehicles), and its application area continues to spread and produce optimized performance. These developments are partly due to the successful implementation of the experiment design. The reason for using the experiment design is to conduct valid and effective experiments that produce quantitative results and support sound decision-making.

2.5.1 Taguchi method

Taguchi designed a special set of general designs for factory experiments covering a wide range of applications. These are orthogonal collections of measures, variables, and thresholds for each orthogonal range of different designs. Using these arrays helps to determine the number of experiments needed for a set of factors. When a fixed number of rates are involved for all variables and the interaction is negligible, regular orthogonal arrays should satisfy most experimental design needs. The Taguchi approach effectively addresses the problems of compacting experimental design by making the orthogonal arrays reflecting the potential experimental situation and a standard procedure for evaluating the experimental outcome (Chen et al., 2008).

Taguchi method is a theory built based on optimization by experiment design, in which experiments will be carried out and the importance of performance is very critical in disciplining the way to produce a product and to investigate complex problems (Roy, 1990). This method has certainly established cost-effective ways of exploring and finding alternatives in the development and handling of problems. The activities started by brainstorming the performance characteristics and design parameters that are important to the product or processes, designing and performing the tests, evaluating the results to determine the optimum conditions, and finally carrying out the confirmation test in the optimum condition.

Moreover, the group methodology and brainstorming process in project optimization are very much in line with the performance of the design experiments as knowledge and information on variables are derived synergistically in deriving the value from the Taguchi method (Roy, 1990). The preliminary understanding of the entire process will help to plan the experiment and select the critical factors to be tested so that the number of experiments can be determined and time can be estimated efficiently. The Taguchi process emphasizes having to perform the least number of experiments. The concepts in the Taguchi method are why greater experimentation is required since it can be performed more efficiently and productively. The Taguchi method is complemented by the use of quantitative process control methods, the number of factors to be monitored, and which factors were most important and dominant were quantified by measuring the variability that each variable contributes. The statistical techniques used in the visualization of variation and mean are used to bring the Taguchi methodology into effect and reality successfully.

Besides that, the Taguchi method will provide data on which variables are important to monitor and which levels are appropriate for setting performance characteristics on target, this will include the application of quantitative quality control to ensure that system efficiency is preserved in line with anticipated variations and objectives. The flexible design approach used by Taguchi would require wider manufacturing tolerances, components, or materials of lower grades and a wider operating environment (Phadke, 2008). It is a method of achieving and storing goods that are more efficient and robust. The advantage of increased design quality can be seen when the item was manufactured and entered the consumer in the market. The results of minimal variation reduction when produced with the optimal combination of factors result in inconsistent performance with desirable quality characteristics. Significantly, according to (Phadke,2008), the advantages of implementing the Taguchi method are the reduction of process variability, reduction of fatal errors, reduction of process time, the transition from study to manufacturing and adaptation to a more specific technology.

Furthermore, the Taguchi method is an efficient problem-solving technique that can improve product and process development and system quality with minimal experimental time and cost efficiency (Lakshminarayanan and Balasubramaniam, 2008). Taguchi's parameter design has proven to be the most powerful stage for process optimization of all three stages of the offline quality engineering system (system design, parameter design, and tolerance design) (Antony et al., 2001). The Taguchi method technique uses partial factorial experiments where the number of combinations of measures is limited to a special set for the specified application.

Taguchi's parameter design has proven to be the most powerful stage for process optimization of all three stages of the offline quality engineering system (system design, parameter design, and tolerance design) (Antony et al., 2001). The Taguchi method technique uses partial factorial experiments where the number of combinations of measures is limited to a special set for the specified application. The special set is made up of orthogonal arrays that will determine the minimum and the feasible number of experiments required for a given set of factors. Table 2.5 shows the total number of experiments and the possible number of factors. The orthogonal array developed by Taguchi only works well if the calculated value objective has minimal interaction between variables that are independent and linear. The optimum condition could still be reached, while communication between factors occurs.

Table 2.3: Taguchi’s L9 Design with 3-Levels and 3 Factors

A	**B**	**C**
1	1	1
1	2	2
1	3	3
2	1	3
2	2	2
2	3	1
3	1	2
3	2	1
3	3	3

2.6 The Applications of the 3D-printed ABS material

ABS is used widely in 3D printing (Acrylonitrile Butadiene Styrene). The material has significant properties that make it a great option, such as its strength and the fact that it is lightweight as well as being able to handle many different chemicals. ABS product is also recyclable, meaning that by producing less waste, it is better for the environment than some other plastics. Moreover, ABS material comes with a wide range of applications and devices, making it a very strong 3D printing material. It is available in every conceivable color, while it is white in the raw color. It is used with a printer of fused deposition modelling (FDM).

Eventually, ABS material is often the preferred choice for pipes and fittings compared to metals and other plastics, since that it is easier to install, lighter in weight and will not suffer from corrosion or rotting, especially in cases where waste is collected. ABS is more durable than PVC and resistant to impacts and breakage in low-temperature conditions.

Besides, the application of 3D-printed ABS material is used for the automotive industry because one of ABS's main characteristics is the fact that it is lightweight and is lighter than many other plastics. Consequently, cars with ABS plastic components built in some way are often lighter by as much as 10 percent in weight, which makes vehicles more fuel-efficient. It is commonly used on dashboards, wheel covers and body parts due to how it can withstand low temperatures, strength, and surface hard enough to resist scratching.

Figure 2.3: The dashboards of a car using ABS material from Yangzhou Chengsen Plastics Co., Ltd (2019)

Besides that, ABS material is one of the most common choices when it comes to the production of household appliances, such as vacuum cleaners. It is enabling the production of robust and durable components that cannot be contained in other plastics and can be manufactured in a wide range of colors. This prevents scratching due to the strength of the ABS content and is more than able to handle heavy use.

Figure 2.4: Portable vacuum of 3D-printed ABS material from Javelin Technologies Inc (2020)

2.7 Summary

Based on the literature review discussed in this section, the study of tribology is important for many industrial applications. For example, in traditional applications, sliding surfaces or interfaces occur in most mechanical components and are critical to the energy efficiency and maximum life expectancy of these components such as bearings and gears. Furthermore, 3D printing technology uses is fused deposition modelling (FDM) because of the low cost and user-friendly compared to other traditional methods of producing objects. Consistent and accurate geometric structures and a wide variety of thermoplastics also provide some of the advantages of fused deposition modelling (FDM).

Moreover, the material of 3D printing is ABS which is uses in this study because the mechanical properties of ABS are toughness, durable, slightly flexible, and impact resistance. The optimization method uses is Taguchi method because Taguchi's parameter design has proven to be the most powerful stage for process optimization of all three stages of the offline quality engineering system (system design, parameter design, and tolerance design) (Antony et al., 2001).

CHAPTER 3

METHODOLOGY

3.1 Introduction

This study aims to use pin-on-disk to investigate the tribological properties of 3D-printed ABS material. This chapter describes the method used to obtain the desired results in this project. The total functional flow is to demonstrate the order as shown in Figure 3.1 to experiment.

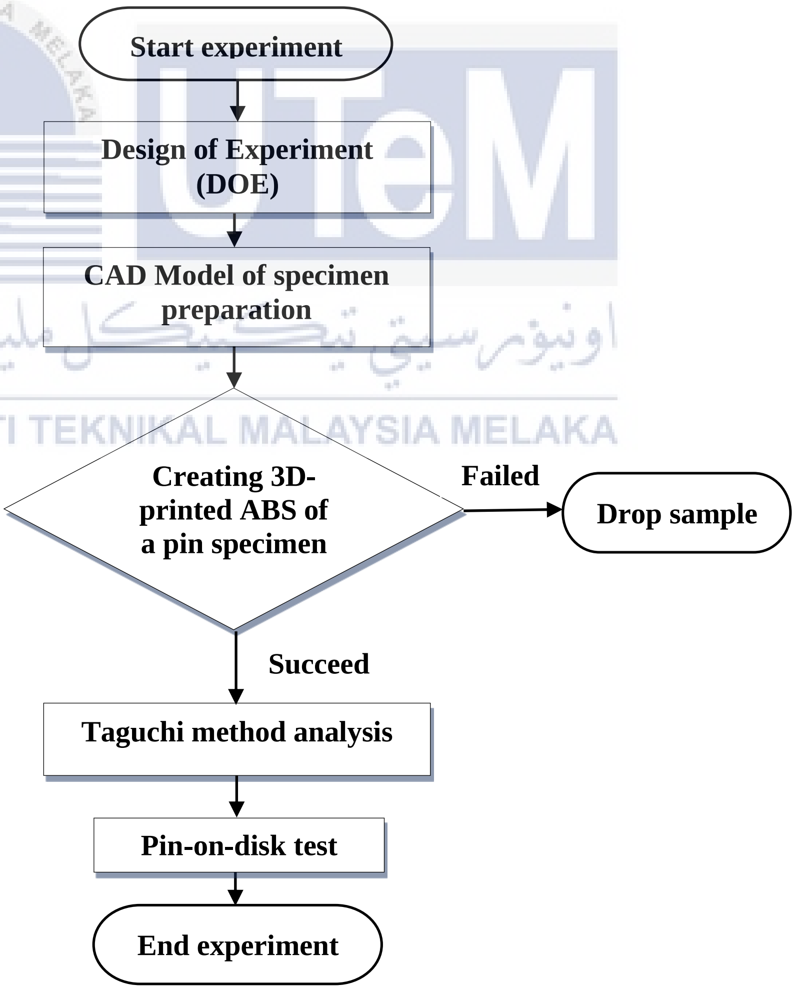


Figure 3.1: Flow chart of the experiment

3.2 Sample preparation

The process begins with drawing a 3D pin model (10 mm diameter and 20 mm height) using SolidWorks code saved as an STL file format as shown in Figure 3.2. The FlashForge Creator Pro 3 slicing program version 3.21 managed and modified all printing parameters. Then all samples are printed on the FlashForge Creator Pro build platform center with 100% infill density.

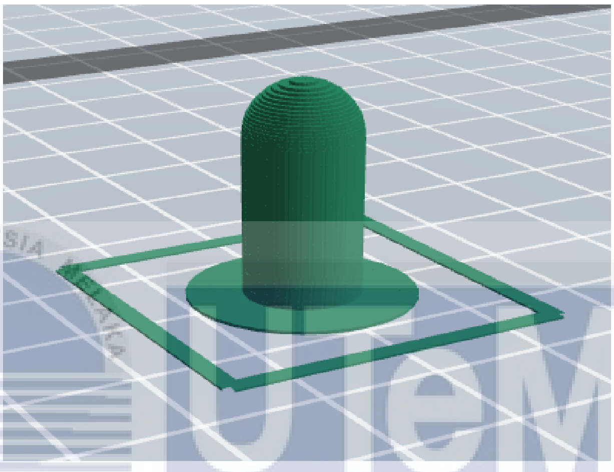


Figure 3.2: Model of a pin specimen

3.3 Taguchi method

The Taguchi test method model was used in this project to estimate the relative role of device parameters across the output of FDM parts on the ground. Taguchi method uses a unique set of arrays called orthogonal arrays to determine how to perform the minimum number of experiments, giving full data on all factors affecting the parameters of the output. In this study, the full factor orthogonal array design of L9 (three levels-three factors) was initially selected based on the number of FDM variable parameters and the number of settings or levels.

Table 3.1 shows the preferred process parameters that interrupt the performance of FDM components and their rates. The L9 orthogonal array is shown in Table 3.2.

Table 3.1: The variable parameters of 3D-printed ABS material

Parameter	Level 1	Level 2	Level 3
Layer height, H (mm) – Factor 1	0.10	0.13	0.15
Nozzle temperature, T (°C) – Factor 2	225	230	235
Pattern, P – Factor 3	Rectilinear	Concentric	Hilbert

Table 3.2: L9 orthogonal array

Experiment	Factor 1	Factor 2	Factor 3
1	0.10	225	Rectilinear
2	0.10	230	Concentric
3	0.10	235	Hilbert
4	0.13	230	Rectilinear
5	0.13	235	Concentric
6	0.13	225	Hilbert
7	0.15	235	Rectilinear
8	0.15	225	Concentric
9	0.15	230	Hilbert

3.4 Friction and wear test

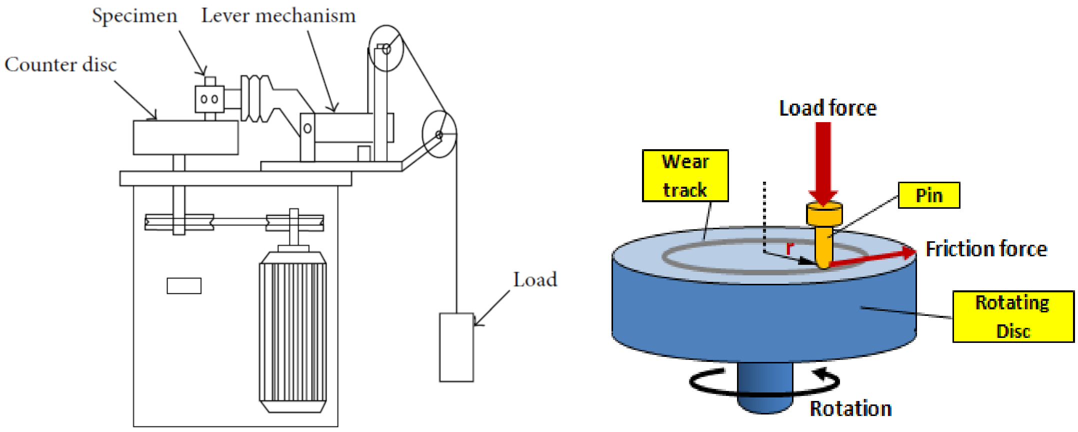


Figure 3.3: Schematic diagram of a pin-on-disc tribometer from Chauhan & Dass, (2013)

The sliding test was carried out following the ASTM G99 Standard Test Method for Wear Testing with Pin-on-Disk Apparatus. The first step needed for the test is to weigh the specimen, and then the disc and the 3D-pin specimen were cleaned with acetone before and after the test to prevent debris from entering the specimen surface. After that, the disc will be positioned firmly with the screw to ensure the touch conditions during the experiment are not moved. The 3D-pin specimen was placed on the tester arm vertically at one end, then mounted at a different diameter of the track and the track diameter used for this experiment was 20 mm and 40 mm.

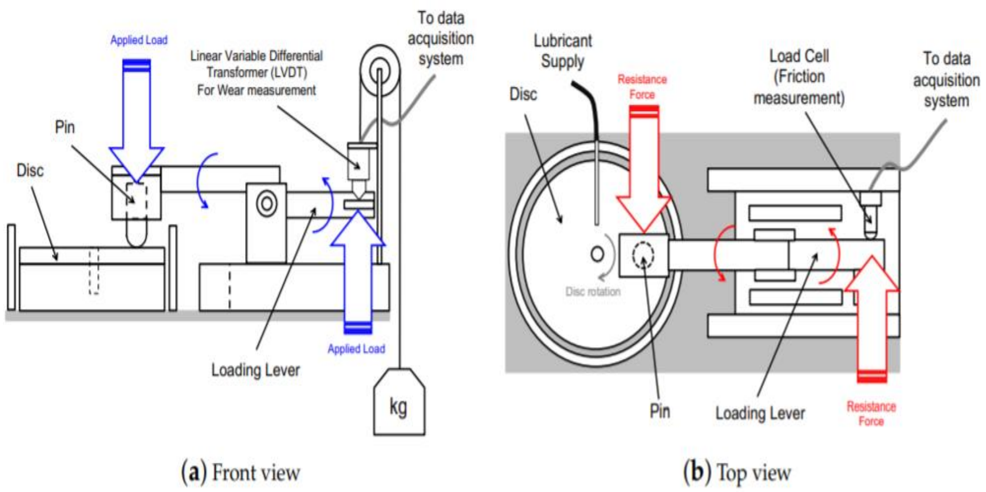


Figure 3.4: Schematic diagram illustrating the friction test using the pin-on-disc tribometer from Chong et al., (2019)

All tests were conducted at a constant 600 rpm sliding speed, 39.24 N applied load, and 800 m constant sliding distance. The parameters for this experiment were shown in Table 3.3 below and the time needed for each test was calculated using equation 3.2;

$$D = 2\pi rNt \tag{3.1}$$

$$t = \frac{D}{2\pi rN} \tag{3.2}$$

Where, t is the time required in minute, D is the sliding distance measured in m, r is radius wear track in m, and N is the sliding speed in rpm.

Table 3.3: Testing parameters used for the pin-on-disc test

Parameter	**Value**
Sliding speed [rpm]	600 rpm
Sliding distance [m]	800 m
Applied load [N]	39.24 N
Wear track diameter [mm]	20 mm and 40 mm

For track diameter = 20mm, the radius track = 10mm = 0.010m;

$$t = \frac{800}{2\pi(0.010)(600)}$$

$$t = 21 \text{ min } 22 \text{ sec}$$

For track diameter = 40mm, the radius track = 20mm = 0.020m;

$$t = \frac{800}{2\pi(0.020)(600)}$$

$$t = 10 \text{ min } 6 \text{ sec}$$

Table 3.4: Time for each test corresponds to wear track diameter

Track diameter, mm	Track radius, m	Time required
20	0.01	21 min 22 sec
40	0.02	10 min 6 sec

The PC data logging method was used to calculate the friction coefficient (COF) and frictional strength. For finding the COF and wear frequency, k, there are some essential equations. The general equations as shown below are equations 3.3, 3.4 and 3.5;

$$COF = \frac{F}{W} \tag{3.3}$$

Where F is the frictional force in N and W is the applied load in N

$$Vloss = 2\pi R \times (a2 + h2) \tag{3.4}$$

Where $Vloss$ is the volume loss in mm^3, R is the wear track radius in mm, a is the wear scar radius in mm and h is the wear depth in mm

$$k = \frac{\text{Vloss}}{W \times L} \tag{3.5}$$

Where k is the specific wear rate in mm^3/N.mm, W is the applied load in N and L is the sliding distance in mm.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter discusses the results obtained from the experiment which contains the coefficient of friction from the different parameters of the specimens. Specific calculations are performed to obtain the coefficient of friction of the specimens. All the data will be analyzed and if there are failures occurred during the test, the solutions will be explained. This chapter is divided into two sections. Section 4.2 operates the experimental parameters, such as the testing parameter of specimens and design of experiment (DOE) approach. Section 4.3 focuses on the coefficient of friction analysis for three different specimens while Section 4.4 explains about signal/noise ratio, Section 4.5 describes on analysis of variance (ANOVA) and Section 4.6 continues with a normal probability plot.

4.2 Experimental data

4.2.1 Testing parameter of the specimens

Table 4.1: Testing parameter for pin-on-disc test

Testing Parameter	Values
Sliding speed (RPM)	600
Sliding distance (m)	800
Applied load (N)	39.24
Temperature (°C)	27

4.2.2 Design of Experiment (DOE) Approach

To save time and material costs involved in the experiment, a lower number of experiments is required. The Taguchi method is therefore adopted. Experiments are carried out based on the combination levels indicated by the L9 orthogonal array for three different specimens. The orthogonal array helps to determine the number of paths needed and the level of the factor for each parameter. The general orthogonal array of L9 consists of a combination of experiments with three factors at three levels.

Table 4.2: Levels and factors used in the Taguchi Method

Factors	**Layer height**	**Pattern**	**Nozzle temperature**
Level 1	0.1	Rectilinear	225
Level 2	0.2	Concentric	230
Level 3	0.3	Hilbert	235

4.3 Coefficient of friction analysis

4.3.1 Main effect plots

After performing the experiments as per Taguchi's experimental design, the main effects plots for three specimen types are plotted for three different parameters, i.e. layer height, pattern, and nozzle temperature. The main effect is a direct effect on the response parameters and the dependent variables. Typical main effect parameter plots for the specimens. It is plotted by considering the mean of response at each level of parameters. From the observation of the graph in Figure 4.1, Figure 4.2 and Figure 4.3, the rank of the parameter in the response Table 4.4, Table 4.8 and Table 4.12 shows that the column is the most influential factor as the mean deltas are calculated from rank 1 to rank 3 of the three factors considered to be the typical response of Minitab V19 in the experiment and the results obtained from the experiment.

4.3.1.1 Solid pin specimen

Table 4.3 below shows the response signal to noise ratios for solid pin specimens. The “smaller is better” option of Analysis Taguchi Design is selected to find the optimum values for the lowest coefficient of friction. As shown in the table the significant level of the factor to the response which is layer height (rank1) is more significant than nozzle temperature (rank 2) and pattern (rank 3).

Table 4.3: The Response Table for Signal to Noise Ratios of Solid pin specimen

Response Table for Signal to Noise Ratios

Smaller is better

Level	Layer height	Pattern	Nozzle temperature
1	10.92	10.79	10.74
2	11.15	10.49	10.41
3	10.09	10.88	11.02
Delta	1.06	0.38	0.61
Rank	1	3	2

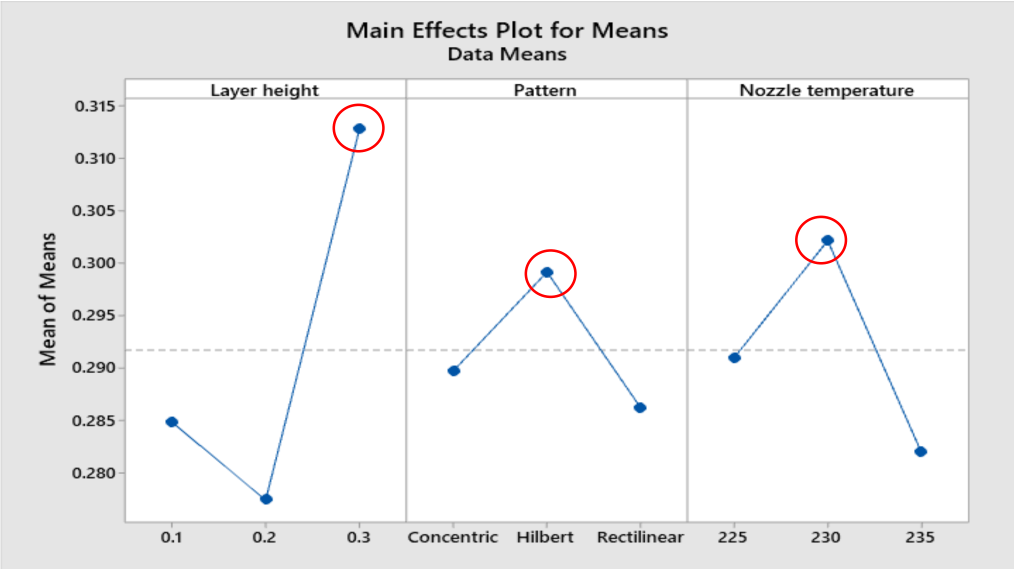


Figure 4.1: The graph of the Main Effects for Means for Solid pin specimen

The graph for the Main Effects Plot for Means is used to analyze the pattern or effect of the factors to the response which is the coefficient of friction (COF). According to the graph in Figure 4.1 the coefficient of friction (COF) increases with the layer height at 0.3 while decreases with Hilbert pattern and nozzle temperature at 230°C

Table 4.4: The Response Table for Means of Solid pin specimen

Response Table for Means

Level	Layer height	Pattern	Nozzle temperature
1	0.2849	0.2898	0.2910
2	0.2774	0.2992	0.3022
3	0.3129	0.2862	0.2820
Delta	0.0355	0.0129	0.0202

Table 4.5: The Prediction COF of Solid pin specimen

Prediction

S/N Ratio	Mean
11.6037	0.262215

Settings

Layer height	Pattern	Nozzle temperature
0.2	Rectilinear	235

4.3.1.2 Circle pin specimen

Table 4.6 below shown the response signal to noise ratios for the circle pin specimen. The “smaller is better” option of Analysis Taguchi Design is selected to find the optimum values for the lowest coefficient of friction. As shown in the table the significant level of the factor to the response which is layer height (rank 1) is more significant than nozzle temperature (rank 2) and pattern (rank 3).

Table 4.6: The Response Table for Signal to Noise Ratios of Circle pin specimen

Response Table for Signal to Noise Ratios

Smaller is better

Level	Layer height	Nozzle temperature	Pattern
1	9.651	9.666	9.938
2	10.579	10.408	10.295
3	10.019	10.174	10.016
Delta	0.929	0.743	0.357
Rank	1	2	3

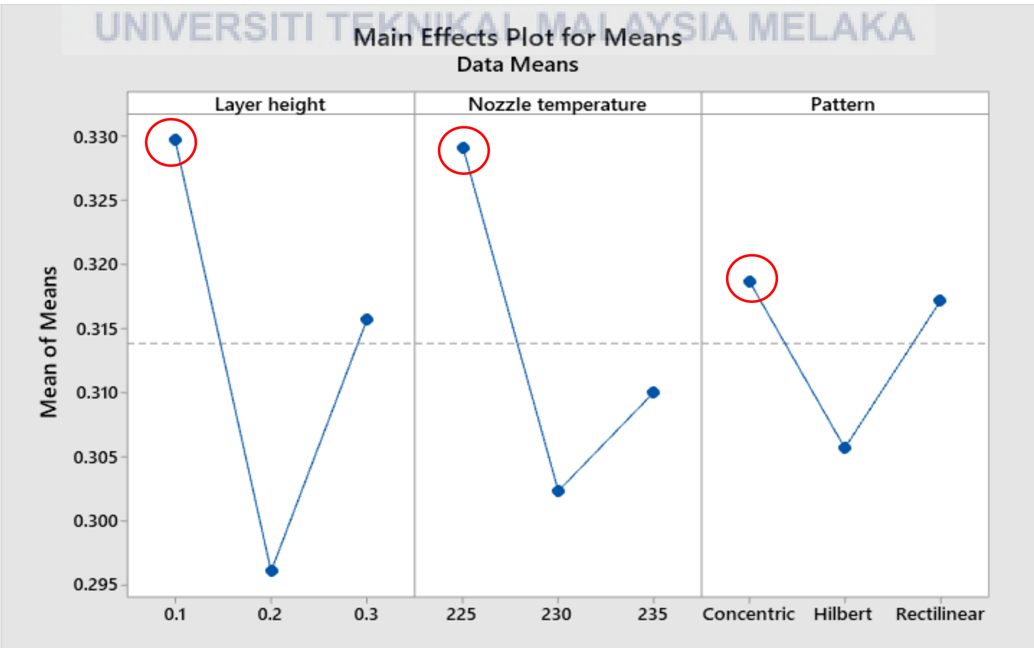


Figure 4.2: The graph of the Main Effects for Means for Circle pin specimen

The graph for the Main Effects Plot for Means is used to analyze the pattern or effect of the factors to the response which is the coefficient of friction (COF). According to the graph in Figure 4.2 the coefficient of friction (COF) increases with the layer height at 0.1 while decreases with concentric pattern and nozzle temperature at 225°C.

Table 4.7: The Response Table for Means of Circle pin specimen

Response Table for Means

Level	Layer height	Nozzle temperature	Pattern
1	0.3297	0.3292	0.3187
2	0.2961	0.3023	0.3057
3	0.3157	0.3100	0.3171
Delta	0.0336	0.0268	0.0130
Rank	1	2	3

Table 4.8: The Prediction COF of Circle pin specimen

Prediction

S/N Ratio	Mean
11.1169	0.276427

Settings

Layer height	Nozzle temperature	Pattern
0.2	230	Hilbert

4.3.1.3 Square pin specimen

Table 4.9 below shown the response signal to noise ratios for square pin specimens. The “smaller is better” option of Analysis Taguchi Design is selected to find the optimum values for the lowest coefficient of friction. As shown in the table the significant level of the factor to the response which is layer height (rank 1) is more significant than the pattern (rank 2) and nozzle temperature (rank 3).

Table 4.9: The Response Table for Signal to Noise Ratios of Square pin specimen

Response Table for Signal to Noise Ratios

Smaller is better

Level	Layer height	Pattern	Nozzle temperature
1	9.850	9.270	9.313
2	9.199	8.989	9.409
3	8.743	9.534	9.071
Delta	1.107	0.546	0.338
Rank	1	2	3

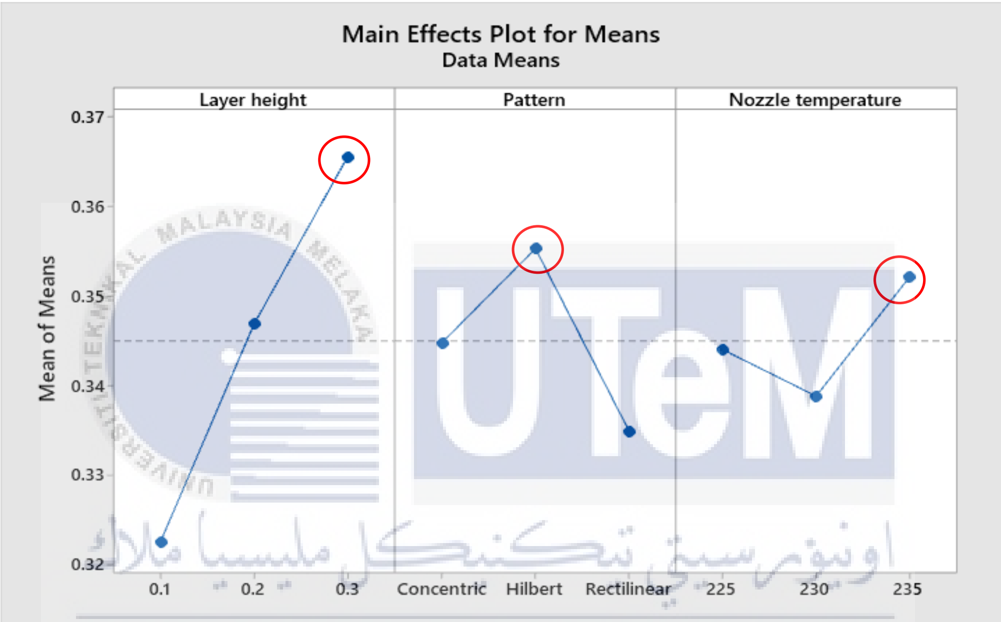


Figure 4.3: The graph of the Main Effects for Means for Square pin specimen

The graph for the Main Effects Plot for Means is used to analyze the pattern or effect of the factors to the response which is the coefficient of friction (COF). According to the graph in Figure 4.3 the coefficient of friction (COF) increases with the layer height (0.3) while decreases with Hilbert pattern and nozzle temperature at 235°C.

Table 4.10: The Response Table for Means of Square pin specimen

Response Table for Means

Level	Layer height	Pattern	Nozzle temperature
1	0.3225	0.3448	0.3440
2	0.3469	0.3553	0.3388
3	0.3656	0.3349	0.3521
Delta	0.0431	0.0204	0.0133
Rank	1	2	3

Table 4.11: The Prediction COF of Square pin specimen

Prediction

S/N Ratio	Mean
10.2645	0.306286

Settings

Layer height	Pattern	Nozzle temperature
0.1	Rectilinear	230

4.4 Signal/Noise Ratio

The S / N ratio is used as a measurable value instead of a standard deviation because, as the mean decreases, the standard deviation also dies and vice versa. In other words, the standard deviation cannot be minimized first, and the mean is brought to the target. In practice, the mean target value can change during the process development process. Two of the applications in which the concept of S/N ratio is useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio characteristics used in this analysis are small the best as shown below.

- smaller is the best characteristics: $\frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right)$

4.4.1 Signal/Noise Ratio for Solid pin specimen

The experiments have been conducted according to the design of the experiment which has 9 test runs that should be performed during the experiments. The optimum value solid pin specimen for each factor in which layer height, pattern, and nozzle temperature obtained from the experiment can be seen as shown in Figure 4.4. The highest SN ratios are chosen for the optimized value of each factor above. From the graph, the optimum value for the lowest coefficient of friction (COF) is layer height at 0.2, rectilinear pattern, and nozzle temperature at 235°C. The coefficient of friction (COF) for the optimized values can be found at Test Run 4 in Table 4.12.

Table 4.12: Testing parameter and COF of each Solid pin specimen

Test Run	Layer height	Pattern	Nozzle temperature	COF
1	0.1	Rectilinear	225	0.290575
2	0.1	Concentric	230	0.301122
3	0.1	Hilbert	235	0.283908
4	0.2	Rectilinear	235	0.283685
5	0.2	Concentric	235	0.29666
6	0.2	Hilbert	235	0.291915
7	0.3	Rectilinear	235	0.30544
8	0.3	Concentric	225	0.311483
9	0.3	Hilbert	230	0.3217117

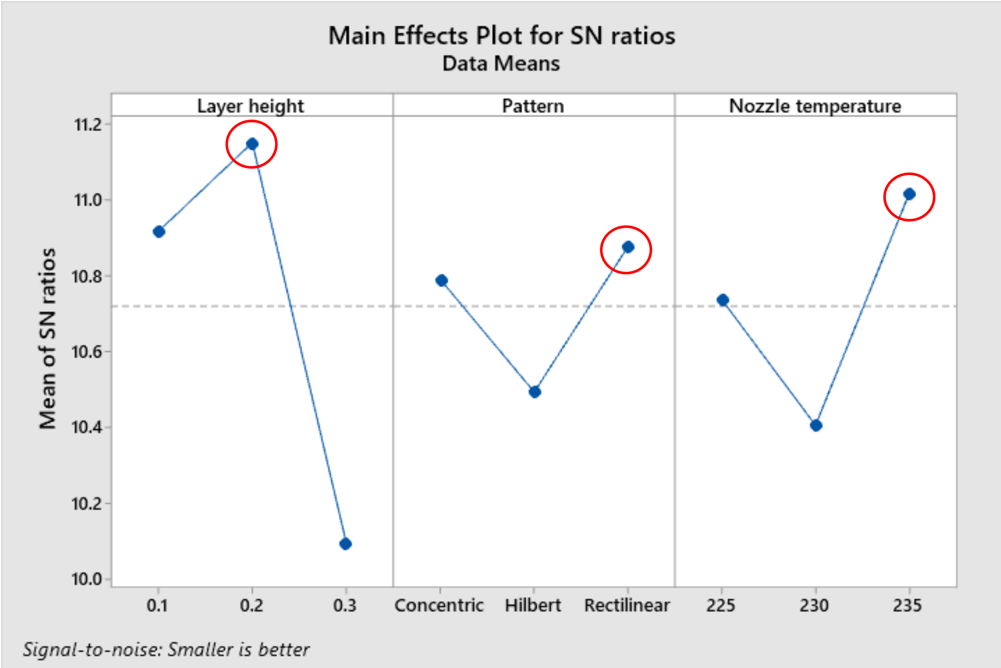


Figure 4.4: The graph of the Main Effects for SN ratios for Solid pin specimen

4.4.2 Signal/Noise Ratio for Circle pin specimen

The experiments have been conducted according to the design of the experiment which has 9 test runs that should be performed during the experiments. The optimum value for each factor in which layer height, pattern, and nozzle temperature obtained from the experiment can be seen as shown in Figure 4.5. The highest SN ratios are chosen for the optimized value of each factor above. From the graph, the optimum value for the lowest coefficient of friction (COF) is layer height at 0.2, Hilbert pattern and nozzle temperature at 230°C. The coefficient of friction (COF) for the optimized values can be found at Test Run 6 in Table 4.13.

Table 4.13: Testing parameter and COF of each Circle pin specimen

Test Run	Layer height	Pattern	Nozzle temperature	COF
1	0.1	Rectilinear	225	0.353445
2	0.1	Concentric	230	0.327007
3	0.1	Hilbert	235	0.308694
4	0.2	Rectilinear	230	0.328835
5	0.2	Concentric	235	0.32231
6	0.2	Hilbert	230	0.3072
7	0.3	Rectilinear	235	0.329158
8	0.3	Concentric	225	0.326866
9	0.3	Hilbert	230	0.311178

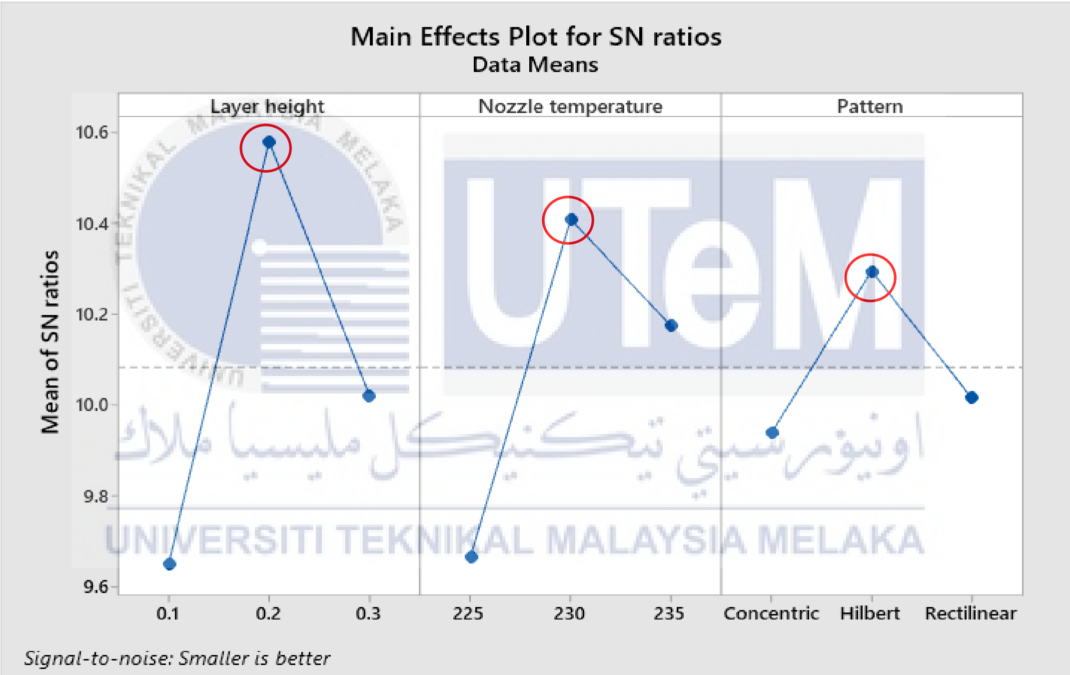


Figure 4.5: The graph of the Main Effects for SN ratios for Circle pin specimen

4.4.3 Signal/Noise Ratio for Square pin specimen

The experiments have been conducted according to the design of the experiment which has 9 test runs that should be performed during the experiments. The optimum value for each factor in which layer height, pattern, and nozzle temperature obtained from the experiment can be seen as shown in Figure 4.6. The highest SN ratios are chosen for the optimized value of each factor above. From the graph, the optimum value for the lowest coefficient of friction (COF) is layer height at 0.1, rectilinear pattern, and nozzle temperature at 230°C. The coefficient of friction (COF) for the optimized values can be found at Test Run 1 in Table 4.14.

Table 4.14: Testing parameter and COF of each Square pin specimen

Test Run	Layer height	Pattern	Nozzle temperature	COF
1	0.1	Rectilinear	230	0.296611
2	0.1	Concentric	230	0.319407
3	0.1	Hilbert	235	0.351524
4	0.2	Rectilinear	230	0.342233
5	0.2	Concentric	235	0.338908
6	0.2	Hilbert	225	0.35949
7	0.3	Rectilinear	235	0.3659
8	0.3	Concentric	225	0.37596
9	0.3	Hilbert	230	0.35486

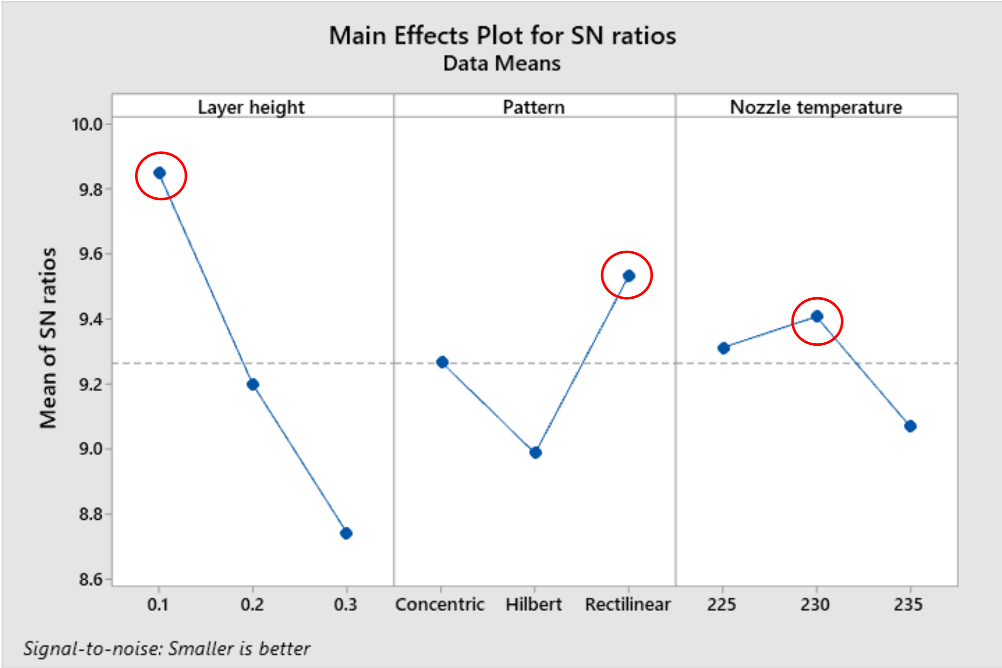


Figure 4.6: The graph of the Main Effects for SN ratios for Square pin specimen

4.5 Analysis of Variance (ANOVA)

ANOVA is a statistical tool that helps reduce error variance and quantifies the dominance of the control factor. This analysis helps to justify the effects of the change in inputs on the response to the experiment. Besides, ANOVA found that F-value and P-value could be obtained from the experiments.

4.5.1 ANOVA of Solid pin specimen

The data of Analysis of Variance (ANOVA) consists of a source, degree of freedoms, the sequential sum of squares, contribution, the adjusted sum of squares, adjusted means of squares, F-value and P-value. The P-value in the table of Analysis of Variance (ANOVA) is used to determine the degree of significance of the variables which is layer height, pattern, and nozzle temperature to the response coefficient of friction. The layer height and nozzle temperature are significant because the P-value is lower than 0.05 meanwhile the pattern is not significant due to the higher P-value which is 0.073. Besides, how much each factor contributed to the response can be calculated by dividing the Sum of Square (SS) into the total SS.

Table 4.15: The ANOVA for Transformed Response for Solid pin specimen

Analysis of Variance for Transformed Response

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer height	2	0.003325	72.03%	0.003325	0.001663	91.26	0.011
Pattern	2	0.000460	9.96%	0.000460	0.000230	12.62	0.073
Nozzle temperature	2	0.000795	17.22%	0.000795	0.000397	21.82	0.044
Error	2	0.000036	0.79%	0.000036	0.000018		
Total	8	0.004616	100.00%				

4.5.2 ANOVA of Circle pin specimen

The data of Analysis of Variance (ANOVA) consists of a source, degree of freedoms, the sequential sum of squares, contribution, the adjusted sum of squares, adjusted means of squares, F-value and P-value. The P-value in the table of Analysis of Variance (ANOVA) is used to determine the degree of significance of the variables which is layer height, pattern, and nozzle temperature to the response coefficient of friction. All the parameters which are the layer height and nozzle temperature and pattern are not significant because the P-value is higher than 0.05.

Table 4.16: The ANOVA for Transformed Response for Circle pin specimen

Analysis of Variance for Transformed Response

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer height	2	0.000680	47.91%	0.000680	0.000340	4.74	0.174
Pattern	2	0.000133	9.37%	0.000133	0.000066	0.93	0.519
Nozzle temperature	2	0.000463	32.61%	0.000463	0.000231	3.23	0.237
Error	2	0.000143	10.11%	0.000143	0.000072		
Total	8	0.001419	100.00%				

4.5.3 ANOVA of Square pin specimen

The data of Analysis of Variance (ANOVA) consists of a source, degree of freedoms, the sequential sum of squares, contribution, the adjusted sum of squares, adjusted means of squares, F-value and P-value. The P-value in the table of Analysis of Variance (ANOVA) is used to determine the degree of significance of the variables which is layer height, pattern, and nozzle temperature to the response coefficient of friction. The layer height with 0.264 P-value is significant and nozzle temperature and pattern are not significant because the P-value is higher than 0.05 which both have 0.736 P-value.

Table 4.17: The ANOVA for Transformed Response for Square pin specimen

Analysis of Variance for Transformed Response

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer height	2	0.002578	61.89%	0.002578	0.001289	2.79	0.264
Pattern	2	0.000331	7.95%	0.000331	0.000166	0.36	0.736
Nozzle temperature	2	0.000332	7.97%	0.000332	0.000166	0.36	0.736
Error	2	0.000924	22.19%	0.000924	0.000462		
Total	8	0.004166	100.00%				

4.6 Normal Probability Plot

4.6.1 Normal Probability Plot of Solid pin specimen

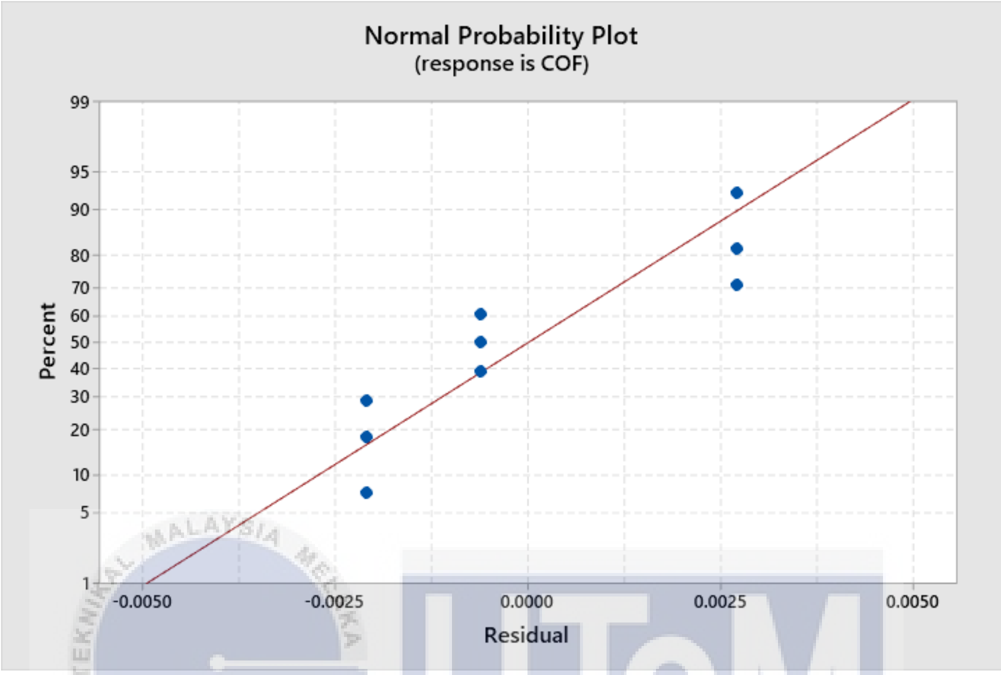


Figure 4.7: The graph of the Normal Probability for Solid pin specimen

The graph of the Normal Probability for solid pin specimens shown that the distribution of the data is well distributed and the data can be accepted. The balanced distribution of the blue circle around the red line becomes a good residuals plot.

4.6.2 Normal Probability Plot of Circle pin specimen

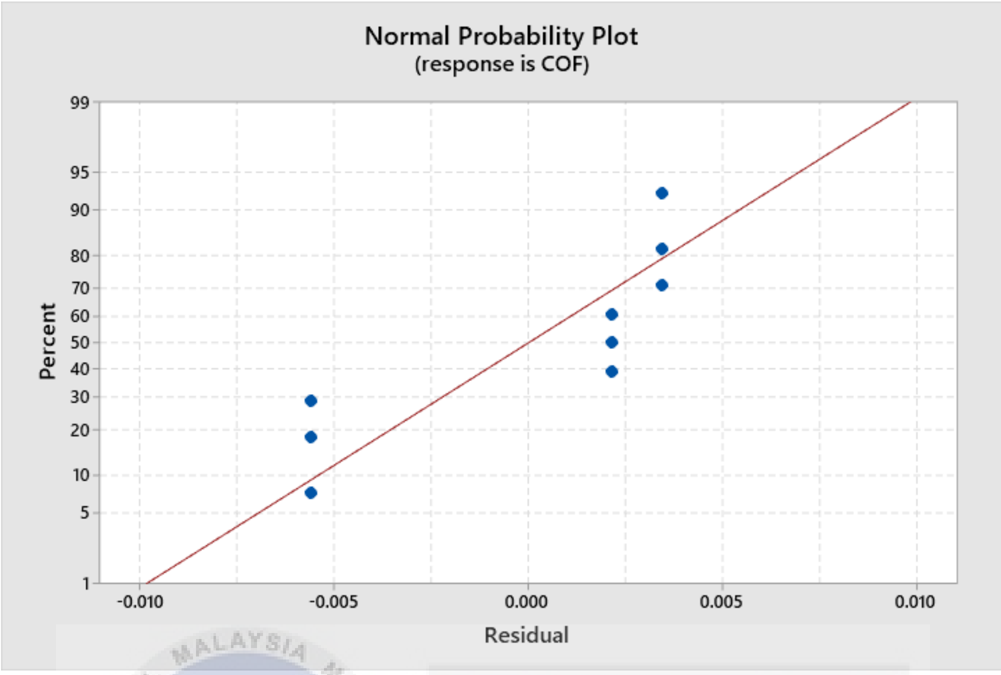


Figure 4.8: The graph of the Normal Probability for Circle pin specimen

The graph of the Normal Probability for circle pin specimen shown that the distribution of the data is well distributed and the data can be accepted. The balanced distribution of the blue circle around the red line becomes a good residuals plot.

4.6.3 Normal Probability Plot of Square pin specimen

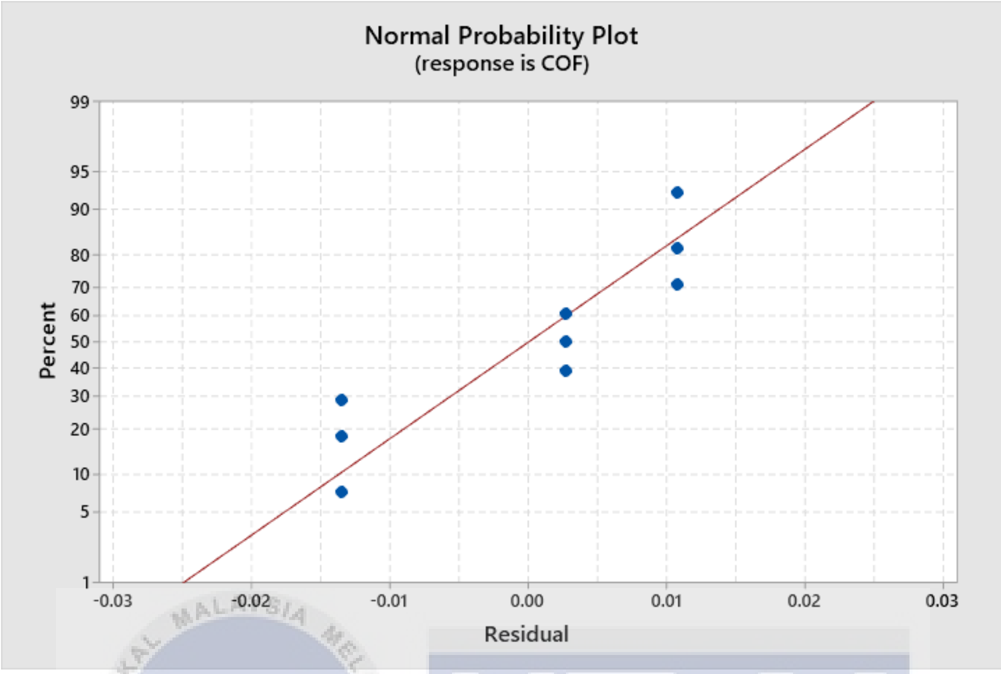


Figure 4.9: The graph of the Normal Probability for Square pin specimen

The graph of the Normal Probability for square pin specimen shown that the distribution of the data is well distributed and the data can be accepted. The balanced distribution of the blue circle around the red line becomes a good residuals plot.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Based on the results of this study, the tribological properties of 3D-printed acrylonitrile butadiene styrene (ABS) bearings can be optimized with the configuration of internal structure formation during the 3D-printing process. The mean S / N ratio for each level of 3D-printing parameters for solid and circle pin specimens shows that, when using 3D-printed ABS materials, the effect of 3D-printing parameters can be ranked as follows: layer height (0.1, 0.2 and 0.3), nozzle temperature (225°C, 230°C and 235°C), and pattern (rectilinear, concentric and hilbert), while the square pin specimen can be ranked as follows: layer height, pattern and nozzle temperature.

Among the parameters considered, the height of the layer has the most influence on the coefficient of friction of the ABS bearing. Taguchi S / N ratio analysis is useful to find the optimum combination of parameters to obtain a lower friction coefficient. The COF of the solid pin specimen is lower than the other two, which is a circle and a square pin specimen, and therefore the ABS bearing the solid pin specimen 3D-printing parameters will benefit the bearing life.

5.2 Recommendations for future studies

The coefficient of friction (COF) obtained from this study shows variations between the different specimens. However, this study only emphasizes certain testing parameters and the internal structure of materials in the 3D printing process. The 3D-printed ABS is the material used to produce a new automotive bearing. Acrylonitrile butadiene styrene is a commercially important amorphous polymer produced by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The presence of styrene gives a shiny appearance and good processability, while butadiene, a rubber substance, provides resilience even at low temperatures, good melting strength, and flexibility. It has good chemical resistance and a very polished surface. The most important mechanical properties of ABS are resistance to impact and durability.

To have a better performance of 3D-printed ABS automotive bearing, the author recommends for testing parameters which are layer height, pattern, nozzle temperature and the internal structure of materials in the 3D printing process such as solid, square and circle should be more different combinations of these both to produce a lower value of friction coefficient of the automotive bearing.

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APPENDICIES

Appendix A1: Project Gantt chart for PSM 1

No.	Topic	Weeks													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Working time for PSM 1														
2	Topic selection														
3	Topic confirmation														
4	Literature review of Tribology														
5	Literature review of ABS materials														
6	Literature review of Taguchi Method														
7	Methodology														

Appendix A2: Project Gantt chart for PSM 2

No.	Topic	Weeks													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Working time for PSM 2														
2	Fabrication of specimens														
3	Friction test														
4	Data analysis														
5	Report writing														
6	Submission of report														