MECHANICAL PROPERTIES INVESTIGATION OF 3D PRINTED PARTS UNDER THE EXCLUSION OF OXYGEN

MUHAMMAD IKRAMULLAH BIN AHMAD SALIM

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

MECHANICAL PROPERTIES INVESTIGATION OF 3D PRINTED PARTS UNDER THE EXCLUSION OF OXYGEN

MUHAMMAD IKRAMULLAH BIN AHMAD SALIM

A reported submitted
in fulfillment of the requirement for the degree of
Bachelor of Mechanical Engineering (BMCG)

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2020

DECLARATION

I declare that this project report entitled "Mechanical Properties Investigation of 3D Printed Parts Under the Exclusion of Oxygen" 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: ……………………………………….

ABSTRACT

In order to obtain the prototype in shorter times and in cost-effectiveness, 3D printing, also known as additive manufacturing (AM), have been introduced. AM is also capable of manufacturing complex part geometry without any additional tools and jigs. Fused deposition modeling (FDM) is one of the most popular techniques in AM. However, its design manufacturability and printed parts quality are the main limitations of FDM in terms of surface roughness, flexural strength and dimensional accuracy. In this research, the 3D printing process method using FDM were being discussed to examined the effect of pre-processing and in-processing techniques on mechanical properties which is specified on the surface roughness and the manufacturability of an open source 3D printing machine. As for the pre-processing, Taguchi analysis was conducted to determined the optimal printing parameter setting. Additionally, for in-processing technique, inert gas had been introduced to control thermal degradation as for the atmosphere condition to exclude the presence of the oxygen in the 3D printing chamber. Based on the comparison made, inert gas presence in the 3D printing chamber was selected at the best improvement techniques because of its capability to improve the whole printed parts quality including surfaced roughness, tensile strength and dimensional accuracy. In general, it was found that, the 3D printed parts surface roughness was improve by 48.29% for nitrogen ambient on 3D printer condition comparing to the oxygen ambient. For the Ra value of the optimum result for the surface roughness on the oxygen ambient which is 1.3667μm while the nitrogen ambient is reduce to 0.7067μm show the result for the in-processing method were significantly reduces. This study has proven that the improvement method during in-processing technique are better on the exclusion of the oxygen.

ABSTRAK

Untuk mendapatkan prototaip dalam masa yang lebih singkat dan mengurangkan kos secara efektif, percetakan 3D, juga dikenal sebagai pembuatan secara tambahan telah diperkenalkan. Percetakan 3D juga mampu menghasilkan geometri bahagian yang kompleks tanpa alat dan jig tambahan. "Fused deposition modelling" (FDM) adalah salah satu teknik yang paling sering digunakan dalam percetakan 3D. Walau bagaimanapun, kemampuan reka bentuk dan kualiti bahagian yang dicetak mempunyai had batasan dari segi kekasaran permukaan, kekuatan dan ketepatan dimensi. Dalam penyelidikan ini, kaedah proses pencetakan 3D menggunakan FDM, dibincangkan untuk mengkaji pengaruh teknik pra-pemprosesan dan pemprosesan pada sifat mekanikal yang diperolehi pada dapatan kajian dari aspek kekasaran permukaan dan pembuatan mesin cetak 3D sumber terbuka. Selain itu, untuk pra-pemrosesan, analisis Taguchi dilakukan untuk menentukan pengaturan parameter pencetakan yang optimum. Selain itu, untuk teknik pemrosesan, gas lengai telah diperkenalkan untuk mengendalikan degradasi termal dan kondisi atmosfera untuk mengecualikan kehadiran oksigen di ruang percetakan 3D. Berdasarkan perbandingan yang dibuat, kehadiran gas lengai di ruang percetakan 3D dipilih dengan teknik penambahbaikan terbaik kerana kemampuannya untuk meningkatkan keseluruhan kualiti bahagian yang dicetak dalam aspek kekasaran permukaan, kekuatan tegangan dan ketepatan dimensi. Secara amnya, kajian mendapati bahawa kekasaran permukaan bahagian bercetak 3D meningkat sebanyak 48.29% untuk percetakan 3D yang dibantu oleh gas lengai nitrogen berbanding dengan percetakan 3D yang mempunyai kehadiran oksigen. Nilai yang diperolehi bagi kekasaran permukaan (Ra) hasil yang optimal untuk percetakan 3D yang mempunyai kehadiran oksigen ialah 1.3667µm berbanding percetakan 3D yang dibantu oleh gas lengai nitrogen yang berkurang sebanyak 0.7067µm menunjukkan hasil untuk kaedah pemprosesan berkurang dengan ketara. Kajian ini telah membuktikan bahawa kaedah penambahbaikan semasa teknik pemprosesan adalah lebih baik dengan pengecualian oksigen.

ACKNOWLEDGEMENTS

In the name of Allah S.W.T , the Most Gracious and the Most Merciful, *Alhamdulillah,* praise to be Him. First and foremost, I would like to take this opportunity to express my deepest gratitude towards my supervisor, Dr Faiz Redza Bin Ramli from the Faculty of Mechanical Engineering Universiti Teknikal Malaysia Melaka (UTeM) for his constituent supervision, support and encouragement towards the completion of this studies.

I would like to extend my acknowledgement to my personal academic advisor Profesor Madya Dr Mohd Juzaila Bin Abd Latif from Faculty of Mechanical Engineering for his indirect involvement for this studies along my years in UTeM.

Last but not least, special thanks to my parents especially my mother, Puan Hjh Halimah Bte Zayadi, my siblings, my peers, and my fiance for their support in terms of emotional and financial in completing this Bachelor's degree. Lastly, thank you to every person that involve directly or indirectly throughout this studies.

TABLE OF CONTENT

LIST OF FIGURE(S)

LIST OF TABLE(S)

LIST OF ABBEREVATIONS

AM	Additive Manufacturing
3D	Three Dimensional
FDM	Fused Deposition Modelling
ABS	Acrylonitrile Butadiene Styrene
PLA	Polylactide Acid
CAD	Computer Aided Design
STL	Standard Tessellation Language
ASTM	American Society for Testing and Materials
DFM	Design for Manufacturability
S/N	Signal to noise ratio
N_2	Nitrogen gas
O_2	Oxygen gas

LIST OF SYMBOL

F	=	Force
σ	=	Stress (sigma)
A	=	Area
ε	=	Elongation
E	=	Elastic Modulus
T_m	=	Melting Temperature
T_g	=	Glass Transition Temperature

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The Additive Manufacturing (AM) is defined as the process of joining materials to make a product geometrical three-dimensional (3D) shape based on design data on computer aided design (CAD) that operate a layer upon layer additive fabrication which is also referred as 3D printing. Nowadays, the industry had been developed from the conventional machining such as casting and forging processes which is need more labour work into a single computer monitor controller. 3D printing has contributed to many industries such as automotive, aerospace and biomedical fields. Freedom of design and limited material selection are some of advantage and limitation in 3D printing.

The Fused Deposition Modelling (FDM) technique has proven up to be the best printing technology and FDM printers are broadly reachable in the industry at present. The product parts are generated by extruding small drop of material which harden immediately to form layers. A filament of thermoplastic, metal wire, or any different material is fed into an extrusion nozzle head, which heats the material and turn the flux on and off. FDM is really restricted in the variant of shapes that may additionally be fabricated.

Consequently, the use of polymers with a high mechanical load tolerance such as acrylonitrile butadiene styrene (ABS) is favoured and special polymers are available for the production of mechanically resistant parts, such as specialized nylon filaments. During the FDM process, the polymer filament is molten at a comparatively high temperature and layer by layer printed on a printing bed. Typically, the layer height is within the range of a few hundred micrometers, resulting in a large surface area of the hot polymer exposed to air during the printing process. This is in contrast to other manufacturing processes such as injection molding. As the expected result, each layers of polymers surface is suspected to degrade during the printing process which may influence the mechanical properties.

1.2 PROBLEM STATEMENT

Although AM has given many potential and advantages, the technology has a various relevant factor that could damage its formulation. The inadequate design guidance for AM is one of the limiting factors, especially in the FDM system (Adam et al. 2014). Furthermore, the manufacturing capability of the FDM system in terms of the mechanical properties of the printed parts is not achieved as high quality compared to the other AM technology. The performance of the FDM parts became of main consideration to the manufacturer and users, and the characteristics of the FDM part, such as tensile strength, flexural strength, compressive strength, dimensional accuracy, surface roughness, build time, yield strength and ductility, are often being discussed (Omar et al. 2015). Research studies suggested a technique aimed at finding optimal process parameters to improve the cultural value of the printed part elements in terms of surface finishing, quality in terms of mechanical properties, material usage and fabrication time of design (Nachariah et al. 2010). After all, there is still no best choice of process parameters for all kinds of materials. Typically, FDM process parts have lower mechanical properties by comparing conventional manufacturing processes such as injection molding.

There is a constrain in the AM system on the type and properties of the materials which could be manufactured. Several experiments have been carried with a view to systematically analyzing failures and the quality of designs, depending on each set of parameters that will identify the effect of part quality using the suitable approach (Nachariah et al. 2010). Part accuracy develops on AM techniques and has led to significant research problems. Optimization of the process parameter is a major challenge for accuracy, roughness and finishing and fabrication time for development (Galantuci et al. 2015). Further than that, as the ability to withstand deformation under load-printed components, flexural strength is an essential aspect of FDM technology that enables the components to work longer.

Several studies have been conducted over the last few years to improve the mechanical properties and aesthetic value of the FDM printed part by acceptable alteration of process parameters, however the findings didnt focus on the set of in-process techniques designed to improve the quality of the 3D printed part. Of starters, owing to specific factors, specific oxidation processes occurring in polymers contribute to substance degradation at higher temperatures in the presence of oxygen. In most situations, the polybutadiene stage (which affects the active two-fold bonding) is affected by oxidation reactions, which result in a high significant reduction in mechanical properties (Lederle et al. 2016).

Here, the investigations will introduce a short examination of FDM printed parts at typical activity conditions contrasted with the printing procedure performed under the severe avoidance of oxygen. The report on a serious improvement of the mechanical properties, for example, yield quality if the print is performed inside an enclosure overflowed with nitrogen. The upgraded properties of parts printed under inert gas conditions were found as the print of response vessels for most oxygen will performed under the inert gaseous. The strategy exhibited here may prompt a fairly straightforward improvement of FDM printers.

1.3 OBJECTIVE

The main objective of this research is to get the comparison on mechanical properties of 3D printed parts between the manipulated variable of chamber condition to study the effect on the presence of oxygen which is between the normal process and inert gas assisted 3D printed parts. Hence, the specific aim are:

I. To design and fabricate an enclosure box in addition to flooding the inert gas into 3D printer machine and develop a suitable guideline for 3D printer for FDM technique.

II. To study the effect of improvement method during in-process technique on mechanical properties of 3D printed parts using two different conditions.

III. To compare between mechanical properties of 3D printed parts and determined which technique get better quality.

1.4 SCOPE OF PROJECT

This project is carried out experimentally. A simple model has been developed using cheap available materials to assist the nitrogen flooding the 3D printing machine. The project is mainly focused on the study of mechanical properties and some mechanical testing is conducted to determine the printed parts quality. The evaluation of the testing is from standard testing method according to ISO standard which is ASTM D638 for universal testing procedure. Process parameter that being choosen are the most crucial parts which are, layer thickness, infill density, and raster angle. The machines involve for the mechanical testing are as below:

I. Surface roughness : Using TR200 Surface Roughness Tester Profilometer

II. Surface image : Using 3D Non Contact Profilometer, to get the data profile of surface arrangement of printed parts.

The studies are using an open source 3D printer. 3D printer model used in this experiment is A8 3D Printer. The material used through the experimental study is thermoplastic material, Polylactic acid (PLA).

CHAPTER 2

LITERATURE REVIEW

2.1 Additive Manufacturing

Additive Manufacturing (AM) is a concept used to define techniques that create 3D structures by incorporating layer-by-layer material created from plastic, metal or concrete products. The usage of machines, 3D CAD design tools, process machinery and layering materials is essential to these developments. AM developments started in the 1980s to produce components in specific design by implementing CAD and Computer Aided Manufacturing (CAM) (Luzanin et al. 2014). Figure 2.1 shows the 3D printing full process from the model design to the finished parts which is considered as the additive manufacturing (AM) known as 3D printing.

AM technology considering a three process flow:

1. The pre-processing which is a computer aided design (CAD) in 3D solid model is developed and converted into a standard AM file format such as the traditional standard tessellation language format or the recent additive manufacturing file format.
2. The printing process which is a file is sent to an AM machine where it is manipulated by the machine and the part is built layer by layer on the AM machine.
3. The post processing which is cleaning or deburring debris on the surface of the finished part.

Figure 2. 1: Flowchart of 3D Printing Process

AM is known as 3D printing but in actuality, this designation is a subset of the AM concept. In all, there are seven types of AM established by ASTM under the Standard Terminology for Additive Manufacturing Technologies. The seven types of AM and their use are shown in Table 2.1 and Figure 2.2 show the schematics diagram of the types of additive manufacturing process.

Table 2.1: Types of Additive Manufacturing and it definitions

(Source: Piazza & Alexander, 2015)

1) Binder jetting	AM process where a liquid bonding agent is deposited to join powdered materials together.
2) Direct energy deposition	AM process where thermal energy fuses or melts materials together as they are added
3) Material extrusion (fused deposition modeling)	AM process that allows for depositing material via a nozzle
4) Material jetting	AM process where droplets of material are deposited
5) Powder bed fusion (laser sintering)	AM process where thermal energy fuses or melts material from a powder bed
6) Sheet welding	AM process where sheets of materials are bonded together
7) Vat photo-polymerization	AM process where liquid photopolymer in vat is cured by light.

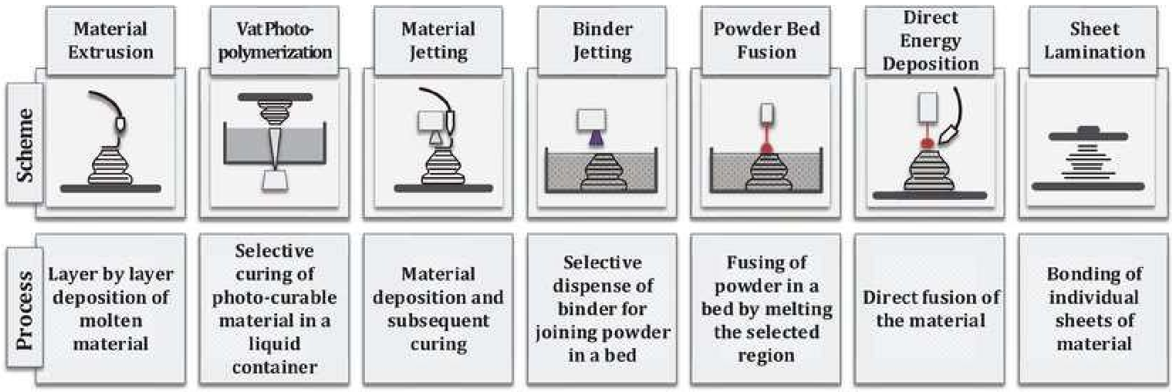
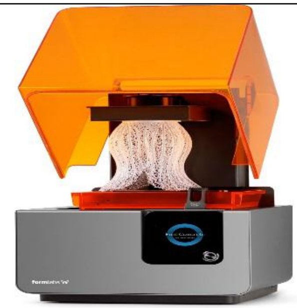
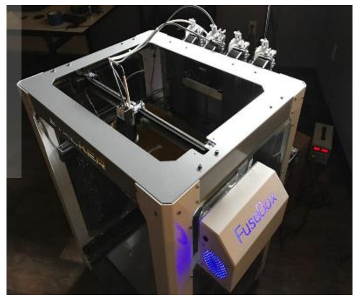


Figure 2.2 : Method of 3D printing

(Source: Perrot & Amziane, 2019)

Table 2.2 listed the comparison that have been made between different techniques of additive manufacturing technology. The technologies that were describes such as stereolithography (SLA), laminated object manufacturing (LOM), selective laser sintering (SLS), and fused deposition modelling (FDM). In the meantime, the comparison had been made between the method of 3D printing as shown in Table 2.3 which is covered the material description, product quality and design complexity.

Table 2.2:Comparison of additive manufacturing technology

AM System	Description	3D Printer Machine	References
Streolithography (SLA)	• The first technique in AM • The process converted liquid plastic into solid 3D objects. • Once all layers are printed the object was rinsed with a solvent chemical and place in an oven to post-process treatment.		William et al.1998
Laminated Object Manufacturing (LOM)	• Layers of adhesive coated paper, plastic or metal laminated are combine together and by using heat and pressure to laser or knife.		Spancer et al.1993
Selective Laser Sintering (SLS)	• Uses laser as power source to form solid 3D objects • SLS doesn't need to use any support structure as because the printed part was placed on un-sintered powder.		Gornet et al. 2014

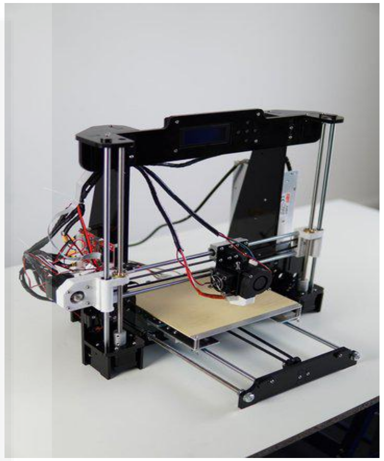
Fused Deposition Modelling (FDM)	• Usually, mid end technology always refers the FDM technique in which the parts are built through layer by layer concept, However, the differences between low cost FDM printer and Mid-end printer is its designated with the casing. By providing the casing, the temperature and ambient temperature can be controlled		Gornet et al. 2014
	• FDM having the poor quality in mechanical properties which is included surface roughness, mechanical strength and less dimension accurate compare to high end technology.		Wohler et al. 2013

Table 2.3: Comparison between method of 3D printing

AM Type	Material Description	Surface Finishing	Geometric complexity	Description	Structured of printed part	Reference
SLA	Liquid photo-polymer	Have a very good surface finish	Easily obtain for complex geometry	It is used as major for the production of silicone mold for vacuum or injection molding.		Penga et al. 2007
SLS	Sintering powder	Good surface finish and high durability	The powder is completely embedded in un-sintered powder such that the production of a complicated element has no question	If overhanging features are produced, powder does not require assistance because powder is highly formable.		Johnson et al. 2014

LOM	Paper Rolls, Recently used plastic filaments	Mild surface finishes	Can fabricate complex design, but also need a self-supporting for overhanging	The basis commercial of LOM systems, Helisys, in 2000. The technology did not challenge well with other RP methods that were advanced		Klahn et al. 2014
SLM	Metallic powder, also can use metal like stainless steel, titanium, cobalt chrome and aluminum	Produce very fine metal powder surfaces	Complex geometries and structures with thin walls and hidden voids or channels.	Many innovative SLM projects have been dedicated to various lightweight components in the aerospace industry. The product is not commonly used among domestic consumers, but rather by air and surgical orthopedics manufacturers.		Yasa et al. 2011

2.2 Fused Deposition Modelling (FDM)

Fused Deposition Modeling (FDM) is an AM technology developed by Stratasys in Eden Prairie, Minnesota, United States, 1996. It is a technology commonly used for modeling, experimentation and production applications. These are among the methods used from 3D printing. The 3D method applies its first 3D printer which utilizes a technology that uses an inkjet printing procedure to place wax material layer-upon-layer (Haul et al. 2014). FDM is a new technology that allows design and production engineers to give precise, multi-material models in an engineering setting right at the CAD work area. Material solidifies soon after coming out of the nozzle and adhesion to the surface under it. The material available involves acrylonitrile butadiene syterene (ABS), polyamide polycarbonate, polyethylene , polypropylene and investment casting wax. FDM does not contain any dangerous substances that create a high degree of contamination, minimize time upon its market to reduce product development costs and enable testing of manufacturing equipment (Stratasys, 1992). Figure 2.3 show a schematic diagram for a FDM 3D printer machine.

In FDM technique, a plastic material is heated from a nozzle that points to the cross-geometric layer-by-layer part. The most widely accepted non-wax substance of high value in FDM is thermoplastic, ABS and PLA. The material has been checked to be adequate for melted out of a ceramic structure with limited conversion to a normal foundry procedure. For FDM, the nozzle provides resistive heaters that hold plastic at a temperature slightly above the melting point, such that it discharges effectively through the nozzle and structures the layers according to G-code guidance. Is therefore deposited through nozzle as a semi-molded filament (Gornet et al. 2014). In addition to produce a fine surface finishing and several others mechanical properties, numerous studies have performed a number of experiments to render FDM components appropriate for final usage. In order to increase the quality of the 3D printed component, numerous changes have been introduced to 3D printing. By theory, the enhancements should be categorized into the following:

a) Pre-processing method: By adjusting and optimization of the FDM process parameter.

b) In-processing method : Improving the pan while printing process occurs.

c) Post-processing method: Applying treatment after the printed part is ready.

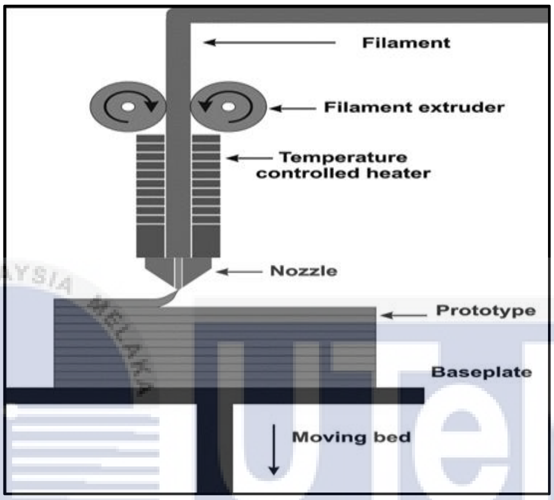


Figure 2.3 : Schematic Diagram for FDM printer

(Source: Olivera, 2016)

2.2.1 New Technology Development in FDM 3D Printer

The current study focused majorly on the development of the FDM process to improve surface finishing, mechanical strength, and dimension accuracy. The key goal of the analyst previously was to optimize mechanical strength and surface finishing by advanced in-processing techniques. In FDM, this phase consists of the layer-on-layer through which the line section is formed as can be seen from printed parts' surfaces. Therefore, the tensile power, porosity rate, surface roughness, and dimensional accuracy have been extended to a small sample for reduced section (Majid et al. 2016). The study showed that the tensile strength was improved, and better surface roughness achieved. However, the dimensional accuracy reduced by a reduction of 0.0647 mm compared to the actual CAD drawing.

It is also necessary to increase the strength of the pieces by utilizing the fill compositing process by inserting the voids in the printed sections by filling them with high strength resins. The power total rose by 45 percent to 25 percent (Belter et al. 2015). The existence of layer grooves is a major problem in the FDM printed system, which has enabled the removal of layer grooves by using a 3D-Chemical Melting Finishing (3D-CMF). In this operation the material used for the 3D printed structure was filled with a pen-like device for the dissolution of the material. The method may also be used to complex shapes, and by eliminating the sheet grooves, it increases the surface finish of the component (Takagishi et al. 2017). Using barrel finishing will also enhance the surface quality (Alberto et al. 2015).

Jun et al. (2016) applied a laser-assisted upgrade to the FDM method to improve the structure accuracy, shape precision and even mechanical properties. It also analyse the effect of shaping velocity, laser strength, and laser heating. Based on this process, when the lateral laser-assisted heating was used, tensile strength was dramatically improved by 195 per cent. Also increased was the form quality of the components, and the efficient bonding distance between the layers was 24 percent greater than before the upgrade. However, the laser input parameters like laser speed and laser temperature must be monitored as it may damage the consumer while operating the machine.

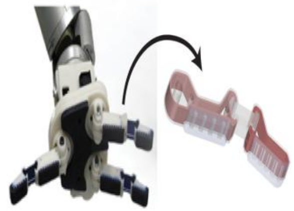
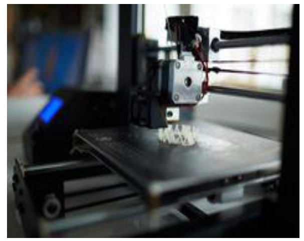
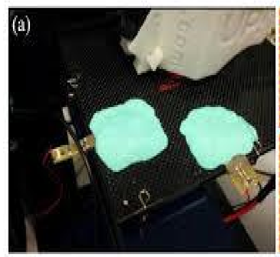
High strength is needed for producing a functioning component to avoid stress and strain loss. In FDM, due to the incomplete bonding between the layers at the z-axis it generates low value intensity as the layers did not fuse correctly when the deposition phase did cost 3D printer to utilizing a roller and the mechanical action of the quick. Thus, it will support the cycle by combining the vacuum device with the FDM 3D printer to reinforce bonding between the layers such that the tensile strength can be increased as well. The results of microstructure observations showed that the specimens produced in a vacuum environment were tightly bonded between the layers and increased the tensile strength to be better (Maidin et al. 2017).

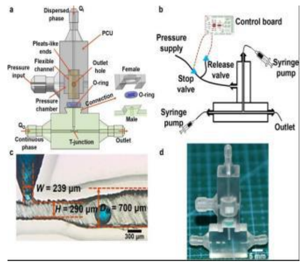
Mohamed et al. (2017) examined the results of a vacuum process that was supported with 1 ultrasonic to achieve smooth surface finish for the FDM samples and proved to be superior in the component coating. In other experiments, the FDM 3D printer was mounted with an ultrasonic system to enhance surface quality. The research was conducted since ultrasonic application has been used in traditional machining and the final product created a better surface finish. According to the results it produced the best surface finish by using 21 kHz frequency (Maidin et al. 2015).

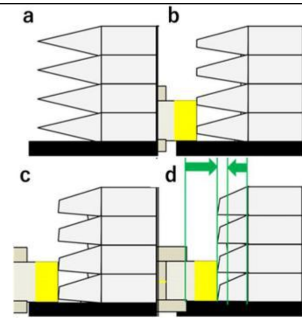
The polymer filament (ABS) is melted in the FDM process at high temperatures ranging from 200-280°C and layer-upon-layer printed on a printing bed, causing the heated filament to be controlled by temperature during the printing process and affecting the plastic resin's mechanical properties. Because of the degradation process the mechanical properties can be reduced. Thus, nitrogen gas was used in the experiment performed by Felix et al. (2016) to remove oxygen when the printing cycle was taking place. The tensile strength was improved by 10.19 per cent by applying this method.

Building on the changes made by previous studies, the analysis concentrated on enhancing surface finishing and mechanical properties but did not mentioned the structure accuracy in terms of the complicated geometries dimensional differences and manufacturability. With this in mind, the present study investigates the extended research conducted by Felix et al. (2016) focusing on the improvement made for FDM by excluding oxygen with inert gas conditions. The study focuses on the effects of the atmospheric inert gas condition using nitrogen (N_2), evaluating in terms of surface finishing, tensile strength, dimensional accuracy and manufacturing design. The summary on new technology development for improving pan's quality in FDM was listed in Table 2.4 for better understanding and comparison

Table 2.4: Summary of FDM Technology 3D Printer

Author / Year	Method	Respond	Results	Disadvantage	Experiment diagram
Belter et al. 2015	Fill compositing technique using high strength	Tensile strength	The tensile strength is improve by 45-25%	Post Processing technique cannot applied for in-situ technique	
Jun et al. 2015	Laser Assisted Technique	Forming quality, shape accuracy and mechanical properties	The dimensional accuracy and tensile strength is improved	Precaution needed when handling the machine	
Maidin et al. 2015	Ultrasonic application in FDM	Surface Finishing	The surface finishing is improved	Not stated	

Felix et al. 2016	Exclusion of Oxygen Technique	Tensile strength	The tensile strength is improved	Not stated -The study was not included surface finishing and dimensional accuracy investigation	
Majid et al. 2016	Applied pressure	Tensile strength and surface roughness	The tensile strength and surface roughness is improved	Reduce part's accuracy by 0.0647 compared to the actual CAD drawing	
Mohamed et al. 2017	Integrated Vacuum system and Ultrasonic with 3D printer	Surface finishing	The surface finishing is improved	Not stated	

Maidin et al. 2017	Integrated Vacuum System with 3D printer	Tensile strength	The tensile strength is improved	Not stated	
Takagishi et al. 2017	3D -Chemical Melting Finishing Technique	Surface finishing	The surface finishing is improved	Post processing technique to enhance the surface finishing using chemical	

2.3 Thermoplastic

Thermoplastics are characterized as polymers which can be melted and recast almost indefinitely. When heated, they are molten and hardened when cooled. But, when a thermoplastic is frozen, it becomes like a glass and is subject to break. Such characteristics, which give the material its name, are reversible, so that the material can be repeatedly warmed, reshaped, and frozen. Thermoplastics are therefore mechanically recyclable. Some of the most common types of thermoplastics are polypropylene, polyethylene, polyvinyl chloride, polystyrene, polyethylene and polycarbonate. Figure 2.4 show a resin structure of thermoplastics with a basic molecular structure, consisting of chemically distinct macro-molecules. When heated, they are softened or melted, then shaped, formed, welded and solidified when cooled. Several heating and cooling cycles can be replicated, allowing for reprocessing and reuse.

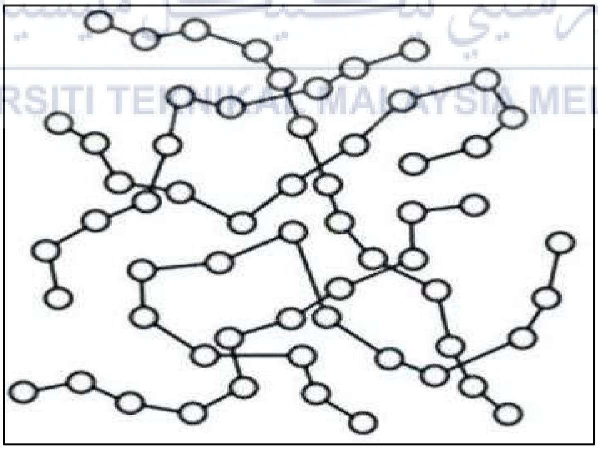


Figure 2.4: Thermoplastic resin structure

(Source: Anand, 2012)

Properties of thermoplastic materials are:

- It may melt before passing to a gaseous state.
- Allow plastic deformation when it is heated.
- They are soluble in certain solvents.
- Swell in the presence of certain solvents.
- Good resistance to creep.

2.3.1 Thermoplastic of PLA

Polylactic acid (PLA) is a thermoplastic aliphatic polyester that derived from renewable resources. This thermoplastic does harmless towards its application and immunologically inert that make its suitable in the field of medicine. According to Cuiffo et al. 2017, PLA has a low glass transition temperature, T_g which is range between 60°C to 65°C while melting temperature, T_m which is range between 173°C to 178°C that make it suitable for the 3D printing machine parameter of hot bed and nozzle temperature.

A study by Cuiffo et al. 2017 examined the effect of the FDM printing process on the structure and chemistry of the thermoplastic PLA where it found the printing process which is heating, melting and restructure of the PLA has definitely change its characteristic which is making it more strong and more chemically reactive.

Besides that, a research by Drummer et al. (2012) investigated the behavior of PLA during FDM printing process. The test specimens were printed at three different nozzle temperature to acquire the relationship between the temperature parameter and the resulting elastic modulus. Table 2.5 show the nozzle temperature and the resulting elastic modulus.

Table 2.5: Nozzle Temperature used and resulting elastic modulus

(Source: Drummer, 2018)

Nozzle Temperature	Elastic Modulus of PLA
215°C	2.691 GPa
225°C	3.122 GPa
235°C	2.730 GPa

The printing parts have a higher strength when the nozzle temperature increased. This is because of the deliberate recrystallization when previous layers are being heated again by the next layer of filaments (Drummer et al. 2017).

2.4 Variable of 3D Printing Process Parameter

The impact of process parameters has appeared to significantly affect the mechanical properties of the 3D printed part (Torres et al. 2016). There are seven variable process parameters on a 3D printer utilizing polymer materials. Table 2.6 show the clarification of each variable processes.

Table 2.6: The variable process parameters on 3D printing machine and its clarification

(Source: Btech, 2017)

Process Parameter	Process definition
1. Layer thickness	Indicates the height of each filament in printed parts
2. Infill density	Refers to the density of the space inside the outer shell of an object. If an object is printed with 100% infill, it will be completely solid on the inside. The higher the percentage of infill, the stronger and heavier the object will be, and the more time and filament it will take to print.
3. Speed	Speed of the extruder travel when the filament lay down
4. Perimeters	The number of times the outer walls of the design are traced by the 3D printer before starting the hollow inner sections of the design.
5. Temperature	The temperature of the filament when its extruded at.
6. Build orientation	Build orientation is the angle at which the infill is extruded at. It can range between 0° to 180°.
7. Infill pattern	Refers to the structure or pattern that is printed inside an object. There are several different infill pattern options, each with advantages and trade-offs between print time, strength, and material usage.

2.4.1 Pre-processing Technique Process Parameter Selection

Although FDM is the most common additive manufacturing technologies for different engineering applications, the performance of the manufactured parts relies on the process parameter selection. Identifying the parameters of the FDM method can cause significant effects on product quality therefore is of critical importance. Using different approaches of experimental modeling techniques and definition, researchers have recently investigated many ways to enhance the mechanical properties and quality of FDM printed parts. Several statistical models of the studies and optimization have been used to analyze the optimal process parameters for the manufacture of FDM components in order to verify the quality of printed parts is at optimum results.

Horvath et al. (2007) examined surface roughness optimization of sample temperature using 2^3 and 3^2 full factorial designs, layer thickness and component till form, while Kumar et al. (2012), Ahn et al. (2002) and Ang et al. (2006) have researched method parameter optimization using 25 full factor calculation of tensile strength results, time constructed compressive power, and material support. Thrimurthulu et al. (2004) studied various methods of optimization with a mathematical model for optimization of build-in time. They disclosed that the build orientation was the most significant process that could affect the build time (Thrimurthulu et al. 2004). Zhang et al. (2008) developed a finite element model to evaluate the distribution of stress at different build deposition and orientation. The central composite design (CCD) and ANOVA were used to observe the relationship between process parameters and residual stress in the FDM process (Zhang et al. 2008).

2.4.2 Process Parameter Optimization

Since the FDM technique generates layer-on-layer, the staircases effect on the finished part could not be completely eliminated. Previous researchers (Patel et al. 2012) (Ibrahim et al. 2014) (Gaul et al. 2004) have therefore suggested the idea of implementing the process parameter optimization and modifying the slicing technique. The study shows that perhaps the optimization of the process parameter provides better surface roughness and mechanical properties. The following sections discuss the different process parameters in FDM as pre-processing techniques.

2.4.2.1 Layer Thickness

The layer thickness is described as the height of the layer deposited from the extruder of the printer and is the main factor that influences the process parameter affecting the surface finish, strength and accuracy of the printed part. The filament is extruded layer-upon-layer in the phase-step process (Vasudevarao et al. 2000). Reducing the value of the layer thickness helps increase the built time. A few researchers investigated the effects of layer thickness and claimed that surface finish and dimensional accuracy had a significant effect on the layer thickness. Is its, however has a minimum limit of layer thickness. It can not be lowered further than limit stated for this parameter. Layer thickness varies between different FDM 3D printer machines. Within few machines, there is no possibility of controlling the layer thickness that leading to optimization studies and effective experimental analysis in order to find the optimum value (Marcincin et al. 2012).

2.4.2.3 Build Orientation

Build orientation is the angle of orientation or angle of deposition to build an array. This is perhaps the most adjustable pre-processing parameter studied by researchers to achieve the best surface finish. Reeves et al. (1997) studied the optimization of the built orientation and stated that the ideal range is between 90° and 130°, to obtain the optimal surface roughness of the SLA parts. The most significant degree of orientation of the building is in the range of 0 and 90°, as the effective build orientation generates a better surface finish. It reduces surface finish for a built angle between 40 and 60° but at the same time increases production costs due to better production support materials (Vijay et al. 2011) (Sreedhar et al. 2012).

2.4.2.4 Raster Angle

Raster angle is the angle where the filament deposited into the first layer to form the part as seen in Figure 2.5 in the schematic diagram of process parameter setup. The raster angles can be usually between 0 and 90 degrees and the raster angles between -45 and +45 degrees. Several researcher compare the 30 and 60 ° raster angle to maximize the output parameter. The structure plays a critical part in connecting the inner and top layers with strength. At the raster angle of 0 degrees the best surface finish was obtained and at 60 degrees the worst was attained. The +45/-45° raster angle is shown to reduced both the build time and surface roughness, but the raster angle of 0 degree is the better option for dimensional accuracy, although it increases the time required to produce the product. (Sood et al. 2011) (Ahn et al. 2009) (Nacharaiah et al. 2010).

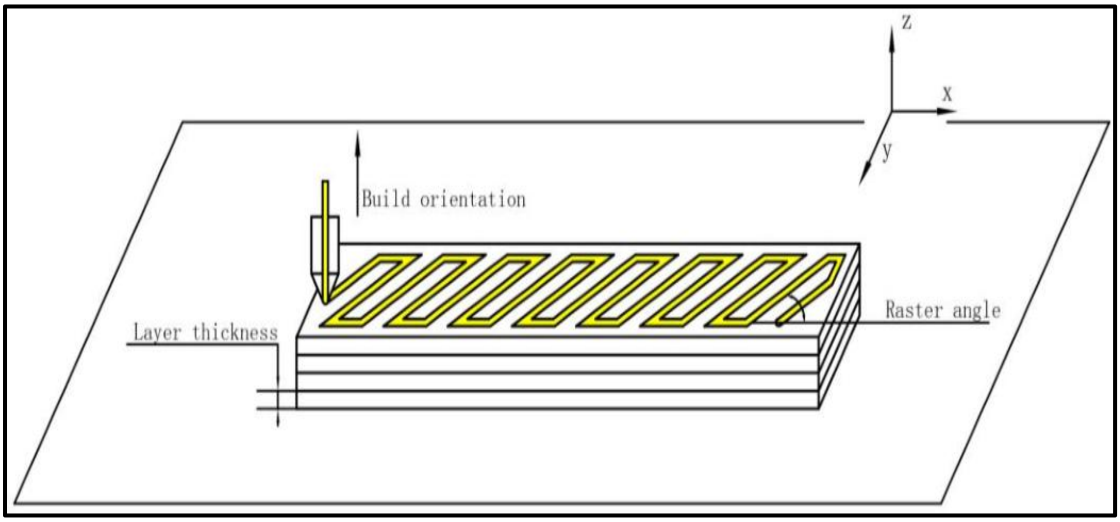


Figure 2.5: FDM Process Parameter setting

(Source: Wu, 2015)

2.4.2.5 Temperature

Temperature is a very important aspect to consider for FDM, as the material used to make the model is thermoplastic. As heaters are allocated to melt the ABS wires before extrusion phase for the building of the model temperature, they are heated to any temperature level. Due to the time of solidification process, the higher temperature provides a smooth surface finish. If higher temperatures are used, the stair step effect is minimized as the viscosity of the ABS-molten plastic decreases the effect of rounding, which contributes to improved surface qualities thus increasing the bond between the filament layers (Luzanin et al. 2013). Temperature has been recorded as the third most significant factor in improving the surface finish after layer thickness and orientation angle of printed parts. This decreases the surface finish by using lower temperature, but prevents the adhesion of part material, so that the component can easily detach from the surface printer bed because the adhesion factor is lower. Higher temperature results in good surface finish but due to the higher flowability of plastic content certain dimensional changes occur.

2.5 Taguchi Analysis

Taguchi analysis is a statistical analysis of the quality of the produced products. More recently it has been extended to the marketing and ads of biotechnology engineering. The study is used to refine selected parameters for different types of responses, including checking the impact of flexural and intensity, as described in Table 2.7 The central composite design (CCD) and variance analysis (ANOVA) are used in the analysis to check the relationship between the method parameter selected and the responses under review (Sood et.al., 2010). The various parameters selected that include layer thickness, built orientation, raster angle, raster width and air gap (Darbar et al. 2013). Also, Taguchi method can be combined with inductive inference to improve the dimensional accuracy of the printed FDM component. By using the Taguchi orthogonal array method, significant parameters can be determined that affect the flexural strength, where the layer thickness is said to be one of the most significant parameters affecting the strength of the printed part (Luzanin et al. 2014), (Sood et al. 2010).

The layer thickness is also a significant parameter based on the Taguchi study that affects the elastic efficiency of a compliant ABS prototype (Lee et al. 2005). Mendoza et al. (2015) examined the effect of FDM process parameter on the time built using Taguchi and ANOVA method to obtain FDM component in less time built. By this method, the density of infills is the most important parameter to reduce the time built on the FDM framework for processing. Percoco et al. (2012) examined the effect of chemical treatment on the compressive strength and mechanical actions of the FDM components by using a chemical reaction from ABS and selected chemical finishing agents to do treatment.

Table 2.7: Overview of the Optimize Process Parameter using Taguchi Analysis

References	Methods	Materials	Inputs	Response/Output	Significant output
Anitha et al. 2001	Taguchi, S/N and ANOVA procedure	ABS	Layer thickness, road width, speed of deposition	Surface roughness	Layer thickness
Nancharaiah et al. 2010	Taguchi, ANOVA procedure	ABS	Layer thickness, road width, raster angle and air gap	Surface finish and dimensional accuracy	All input parameter settings
Wang et al. 2007	Taguchi method, ANOVA along with Grey analysis	ABS	Layer thickness, deposition style, support style, deposition orientation	Tensile strength, dimensional accuracy, surface roughness	Layer thickness and deposition orientation
Sood et al. 2009	Gray Taguchi method, ANN	ABS	Part orientation, road width, layer thickness, air gap, raster angle	Dimensional accuracy	Build orientation
Zhang et al. 2012	Taguchi method	ABS	Wire-width compensation, extrusion velocity, layer thickness	Dimensional error and warpage deformation	All input parameter
Sahu et al. 2013	Taguchi method, Fuzzy logic	ABS	Air gap, raster angle, raster width, layer thickness	Dimensional accuracy	All input parameters
Lee et al. 2005	Taguchi method, ANOVA	ABS	Air gap, raster angle, raster width, layer thickness	Elastic performance	Air gap, raster angle and layer thickness

2.6 Surface Roughness

Nacharaiah et al. (2010) examined parameter effects such as layer thickness, road width, raster angle and air gap on the surface finish of the FDM processed ABS part using the Taguchi and ANOVA approaches. It has been stated that the best surface roughness of the ABS part was created at lower layer thickness values (Nacharaiah et al. 2010). Anitha et al. (2001) explored the process parameter influencing the surface roughness of the printed pieces of ABS and using Taguchi's noise ratio (S/N) and variance analysis (ANOVA) matrix. The process parameter affected in the research studies is layer thickness, track width and speed of deposition. In the analysis, layer thickness as opposed to deposition speed and road width was the most important parameter that can affect surface roughness (Anitha et.al., 2001). Additionally, Wang et al. (2007) was using a DOE optimization method to investigate the roughness of the surface using the control parameters of layer thickness, deposition angle, support style and orientation of depositions using Taguchi analysis tool. It was concluded that 62.27 percent improved the optimal factor settings to maximize the roughness and analysis. Taguchi seems to have been the best statistical approach to evaluate the right optimization, since it reduced the number of experiments rather than complete factorial analysis (Wang et al. 2007).

2.7 Mechanical Strength in FDM

In their research Lee et al. (2005) studied the optimization of AM parameters by creating the flexible object for exerting pressure from ABS content. For optimization, they use Taguchi method and the selected process parameter is the raster angle of the layer thickness and the air distance. The key factors in this experiment have been an air gap, because it can have a greater effect on the parts elasticity. From the ANOVA review the final results indicate that the crucial element which is an air gap contributes just 0.18 percent of errors (Lee et al. 2005). Laeng et al. (2006) The process parameter of air gap, raster angle, raster width and layer thickness was examined using Taguchi method for elasticity of the ABS material. Based on the results, the optimum can be acquired from the combination of parameter settings. The study also recommended the use of response surface methodology (RSM) as Taguchi, as the findings would be more accurate and acceptable (Laeng et al. 2006).

Ognjan et al. examine the process parameter effects of the layer thickness, deposition angle, and infill density towards the maximum bending force for the specimen created by FDM. The research was about the behavior of mechanical properties on flexural strength for PLA. The experiments performed were based on unreplicated factorial experiments and three center bending check points. The layer thickness has been statistically shown to have a significant influence and dominant when assessing flexural strength (Luzanin et al. 2014). Two manufacturing processes, which is injection molding as in traditional method and FDM method (additive manufacturing technology), carried out the experiment to compare the effect strength percentages. The findings show that the impact strength of ABS made by FDM is 47 percent compared to the impact strength of ABS made by injection molding (Gorski et al. 2014).

2.8 Dimensional Accuracy

Sood et al. (2010) investigated the influence of five various process parameters which affect the accuracy of pans manufactured by FDM. The results show that the orientation shaped and the thickness of the layer have a significant effect. Nacharaiah et al. (2010) studied the consistency of the surface and dimensional accuracy of the FDM components. They selected various process parameters including layer thickness, infill density, raster angle, surface finish and dimensional accuracy. The constraint in this project is the type of material used and the fabrication properties of the parts. The results showed that layer thickness and road width significantly influenced surface roughness and accuracy and greatly contributed to better quality (Nacharaiah et al. 2010). Using smaller layer thickness scale increased both quality aspects and negative air gap that degraded the dimensional tolerance (Raju et al. 2010). Galantucci et al. (2015) examined the dimensional accuracy of the 3D open source printer to enhance the dimensional accuracy of the rectangular test specimens based on the FDM technique. This was achieved by using factorial analysis (DOE) to minimize the difference in length, width , and height. The parameter selected for the process is layer thickness, raster width and printer speed as well. The test specimens were also produced using high-end technology printer and low-cost 3D printer to research the performance of open source 3D printer. The results give the thickness of the layer the greater impact on dimensional precision (Galantucci et al. 2015).

Meanwhile, Gorski et al. (2014) studied the effect of process parameter on the dimensional accuracy of parts produced using FDM technology to define the relationship between the basic parameter and the built-orientation FDM process during the manufacturing phase. In this research, FDM 's accuracy is poor compared to other plastic forming technologies such as FDM's. (Gorski et al. 2013). Bakar et al. (2010) evaluated the output of FDM by measuring the quality of the generated FDM part in terms of dimensional accuracy and roughness of surfaces. The specimen is used in the design of benchmarking composed of slots, cylinder and ring. Taguchi process was used in the experiment. Different selected parameters were tested and proposed optimum condition. From the test, deviation in height was within 0.3 mm of tolerance range (Bakar et al. 2010).

2.9 In-process Technique Using Nitrogen Gas

One of the techniques for enhancing the 3D printed component in FDM is the in-situ treatment process. Researchers usually do not perform the in-process treatment since it required modifications to the 3D printer itself. When the printing process occurs, the procedure works together with the pre-processing technique. Prior to this, researchers did have mentioned the in-processing technique for improving the FDM 3D printer. Other researchers did few work as discussed below.

2.9.1 Nitrogen Gas Application in AM

Nitrogen gas is shown in a wide variety of industrial applications, from food product packaging with adjusted ambient to prevent from fire and explosion in chemical plants. In some applications the gas is often used as heat treatment. A persistent issue has always been the oxidation of materials undergoing heat treatment. With the presence of oxygen in heat treatment, it not only produces an undesirable colouring oxide layer on the component's surface, but may also influence the molecular properties of the material but affects and change its strength and durability. Nitrogen gas is usually used to remove oxygen from furnaces and ovens for heat treatment (Tiganis et al. 2002) (Tymrak et al. 2014).

In AM, the occurrence of nitrogen gas in the 3D printing atmosphere will enhance both the mechanical properties of the printed part and the precision of the part. Argon and nitrogen gas are widely used to provide the inert atmospheres to meet the high-tolerance requirements required in AM. An inert atmosphere offers many advantages on a printed component, especially in metal printing. The benefit includes:

a) Reduce the oxidation of sintered pieces by reducing the oxygen content during printing.

b) Improve protection by inerting combustible dust during handling and sieving of powder.

c) Build a stable printing atmosphere by keeping the pressure on the chamber constant.

d) Minimizing the clumping of powder in feed tube.

e) Preventing deformation of component by controlling thermal stress by incremental cooling.

In AM industry, the selective laser sintering machine's development process has to be realized in an inert setting in which the technique of using a laser as the source of power to sinter powdered metal. Nitrogen gas is pumped into the processing process to raise the oxygen levels. Even the purge process is called the blanketing process. Due to dust projection it reduces the probability of combustion by raising the oxygen concentration in the process. The term inert atmosphere typically refers to a gaseous mixture containing little to no oxygen and consisting mainly of non-reactive gases to gasses with a high threshold before they react. Nitrogen, argon helium and carbon dioxide are common components of inert gas mixtures. In SLS, the entire process is performed in a nitrogen gas atmosphere to avoid nylon oxidization during laser beam heating. The temperature within the building chamber is held at 170°C, just below the melting point of the polymer material, so that as soon as the laser reaches the surface particles, they are immediately fused by a temperature rise of 12°C (Malaika et al. 2003).

Under the practical conditions of the world, Tymrak et al. (2014) studied the impact of mechanical properties of components produced with open source 3D printer. In this analysis, the mechanical properties of ABS and PLA components were produced using different types of open source 3D printers and the standard tensile test was used to assess the tensile strength , tensile strength and elastic element. (Tymak et al. 2014).Result shows that when proper temperature, environmental conditions will create functionally strong parts within the limits of their mechanical properties, the tensile strength is increased. The use of polymers with a high mechanical load tolerance such as ABS is therefore favored and special polymers are required for the manufacture of mechanically resistant parts such as modified nylon filaments (Tiganis et al. 2002).

2.9.2. Degradation of ABS Polymer

During the FDM process, the polymer filament is molten at a comparatively high temperature between 200 and 280°C and layer-by-layer stitched on a printing bed. The layer height is typically within a range of a few hundred micrometers, resulting in a wide surface area of the warm polymer that is exposed to air during the printing process. Additionally the polymer surface of each layer is expected to degrade during the FDM process which may affect the mechanical properties of the printed component. The degradation of various polymers at higher temperatures was studied in more detail. In the ABS case, the oxidation processes lead to material degradation in the oxidation at a higher temperature. Polybutadiene phase (PB) in possession of unstable from two bonding particles is affected by gas present reactions, which lead to a significant reduction in mechanical properties (Blom et al. 2006).

In the case of ABS, hydrogen absorption by oxygen is thermal dynamic favor by the presence of tertiary substituted carbon atoms in the PB phase. The existence of sufficient thermal energy activates the absorption of hydrogen to initiate oxidation and accelerates the overall process of degradation. During heat and oxygen exposure, the mechanical properties of ABS, such as impact strength and elongation to break, deteriorate as a result of this polymer degradation, including premature failure. Micro-indentation measurements also show that degradation cams and incrimination in Young's modulus at the specimen surface, which in turn upgrade brittle failure (Tiganis et al. 2002).

Several studies examined ABS coloration to thermal process, during which it is assumed that radical scavengers cowl with radical proxy produced during degradation reactions (Faucitano et al. 1996). Degradation of ABS and loss of mechanical properties are highly temperature dependent. Time and temperature of aging affect the rate of formation and thickness of the degraded surface layer and therefore the extent to which degradation may occur in the bulk polymer. At ambient temperature, the degradation mechanism may differ from that at elevated temperatures, including both surface and bulk polymer degradation effects. In the 3D printer method, due to the element of ABS degradation, an inert gas was used to slow down the ABS degradation cycle so that the mechanical properties in ABS material remain stable. By conducting the experiment, the strength of the printed component particularly for nylon material can be improved (Felix et al. 2016).

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology used in this project to obtain data for the mechanical properties of the 3D printed parts under the inert gas assist. The flowchart of the project is shown in Figure 3.1. This projects starts with planning the test for the mechanical properties of the printed parts. The planning was carried out according to the ASTM standard for the guideline.

3.2 Flowchart

A good planning is very crucial to make sure that the project can run smoothly and also to estimate the time needed for the project to complete is enough according to the requirement. Flowchart in Figure 3.1 shows the beginning of the project in determining the objective until analyzing the result from the tests.

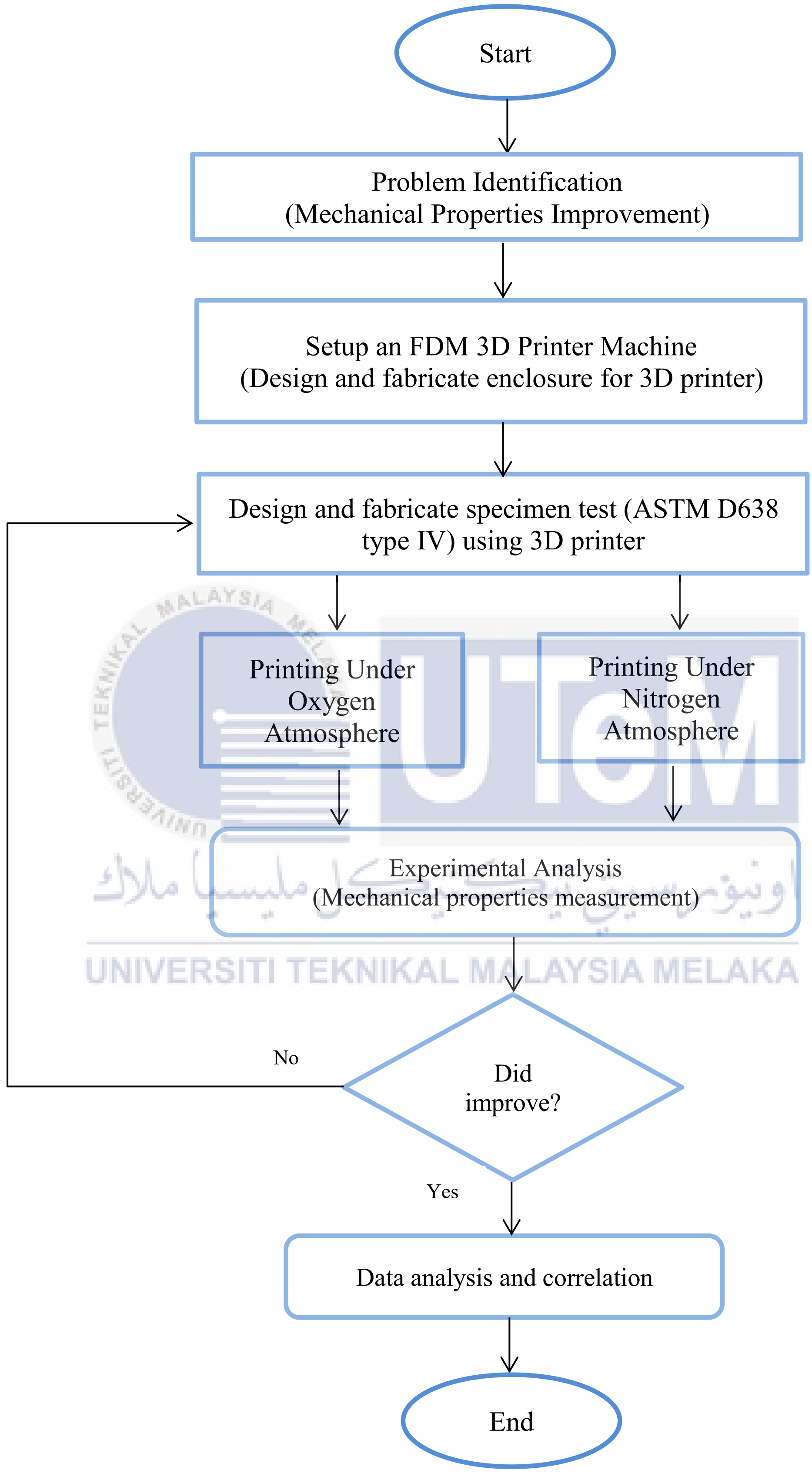


Figure 3.1: Flowchart of the experiment

From Figure 3.1, the flow chart shows the overall process from the start of the project until the end. The project was started by gathering information by doing literature review on the behavior and parameter of FDM printer machine and the mechanical test that needs to be carry out which is surface roughness measurement, hardness test and the tensile test.

3.3 Design of Experiment

3.3.1 Enclosure Chamber

A design of experiment using an enclosure chamber to assist the inert gaseous flooding the printing area is done with the initial design in Catia V5 as a model and later need to be produced. Figure 3.2 show the initial design of the enclosure box.

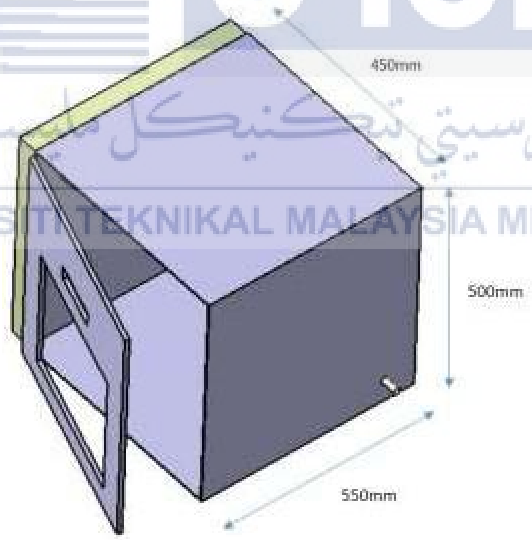


Figure 3.2: Enclosure Chamber for The FDM Printer

3.3.2 FDM 3D Printer

The A8 3D Printer was built as FDM printer that will print the test specimen under the exclusion of oxygen. Figure 3.3 show the schematic diagram for the 3D printer machine.

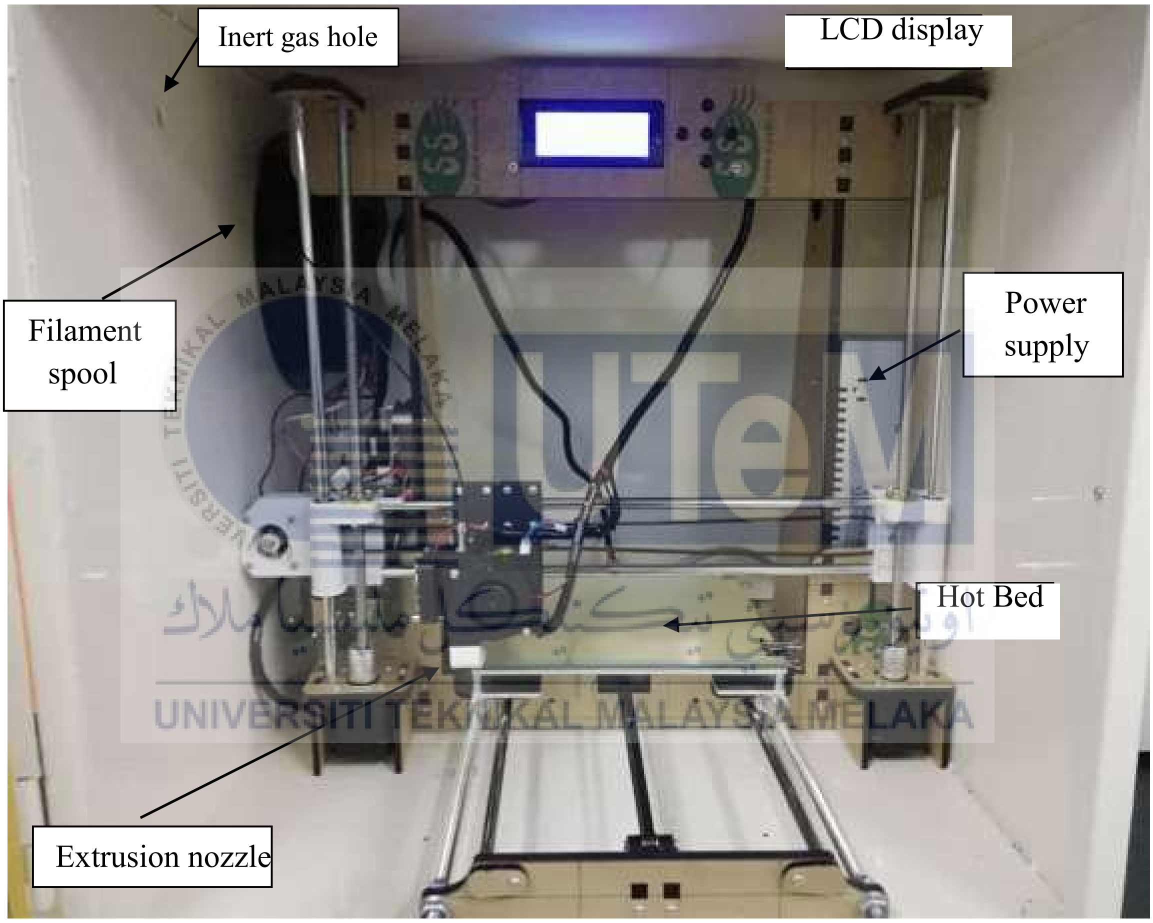


Figure 3.3: Schematic Diagram for 3D Printer Machine

3.3.3 The Rig of Experiment

An experiment to investigated the mechanical properties of the printed parts under the exclusion of oxygen must need the chamber that will let the printing process undergoes the inert gaseous atmosphere to minimize the oxidation while printing process occur. The enclosure box design was produced to assist the inert gaseous flooding the printing area. Figure 3.4 and table 3.1 show the schematic diagram for the rig of the experiment and its specification respectively.

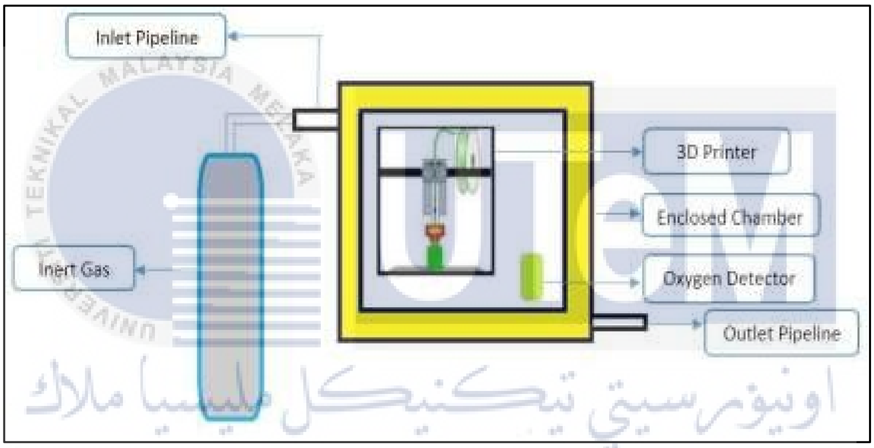


Figure 3.4: Schematic diagram for the rig of the experiment

Table 3. 1: Description of the rig experiment

Item	Description
Nitrogen gas tank	Size: Height: 800mm, Weight: 20Kg, Volume: 2.256 m^3
Enclosure Chamber	Height: 500mm, Width: 550mm, Length: 450mm
Oxygen Detector	Measuring range: 0-25%, Resolution: 0.1% Temperature: -10-50°C

3.4 Preparation of The Specimens Test

Dogbone type specimens seen in Figure 3.5 were prepared according to the geometry and dimensions specified in D638 – IV Standard Test Method for Tensile Properties of Plastics (ASTM Norma, 2004). The dog-bone specimen was designed using Catia V5 and thus it was exported in an STL format. This is the file format that can be imported to slicer, the program used by the 3D printer machine to allocate each dimensional location of the model.

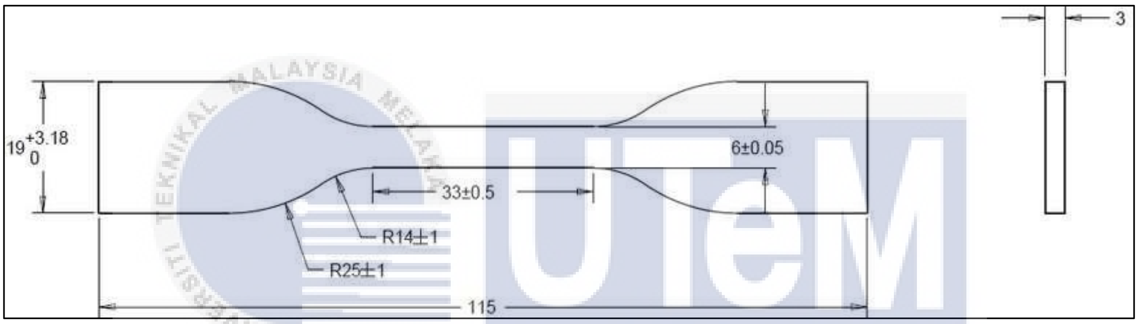


Figure 3.5: Dogbone ASTM D638 type IV specimen test

3.5 Selection of Machine Parameter

A slicer software which is Repetier Host will process the CAD data save in STL file into the geometrical code to deliver the printing process as shown in Figure 3.6. The software provides the configuration setting for process parameters that have to choose to print the specimens test. A set of 4 specimens test pieces printed under the nitrogen atmosphere and other 4 specimens test pieces printed under the argon atmosphere will be printed with the parameters shown in Table 6. The samples will be tested to determine the sample data for each mechanical test.

Table 3.2: Controlled Printing Parameters

Processing Parameter	Value Used
Temperature (°C)	180
Infill pattern	Linear, Rectilinear
Speed (mm/s)	30
Infill direction (°) (raster angle)	45, 60, 90
Relative density/infill (%)	30, 50, 70
Layer thickness (mm)	0.18, 0.25, 0.35

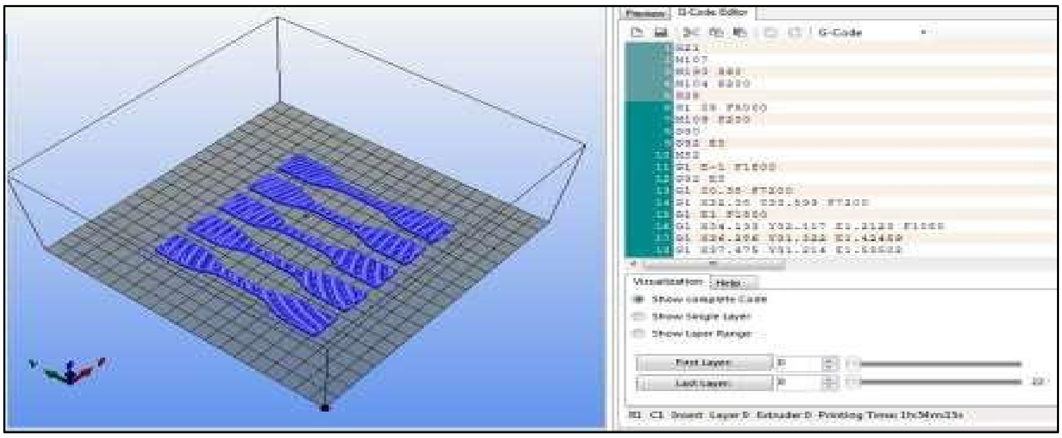


Figure 3.6: Orientation of the specimens

3.6 Surface Roughness

All the specimens of dogbone will be analyzed between two inert gaseous to get the comparison under the avoidance of oxygen. The surface layout of the printed part under nitrogen treatment and the printed part under normal process will be measure using precision measuring instrument which TR200 Surface Roughness Tester Profilometer as shown in Figure 3.7.

Figure 3.7: TR200 Surface Roughness Tester Profilometer

3.7 3D Non-Contact Profilometer (Surface Profile)

Figure 3.8 show a 3D non-contact Profilometer which is used to study the surface profile of printed part in micro view as well as the top surfaces. By using this method, the arrangement of the particles in the surface area of the printed parts can be inspected and evaluated. Images of the micro measurement can also help to determine the properties of outer layer in terms of height, width, area, surface length and roughness in the outer layer structure by using a software to calculate. Sample capture from the machine is shown in Figure 3.9.

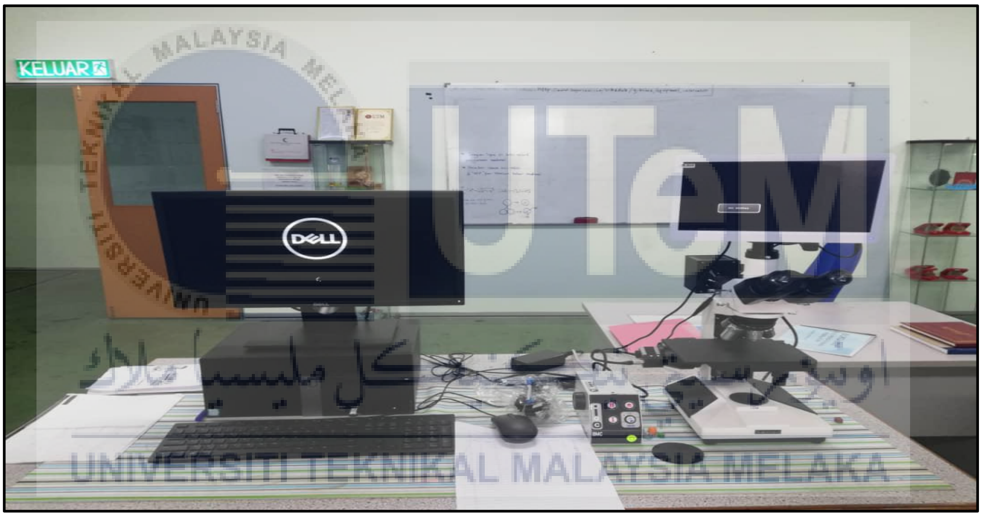


Figure 3.8: 3D Non Contact Profilometer

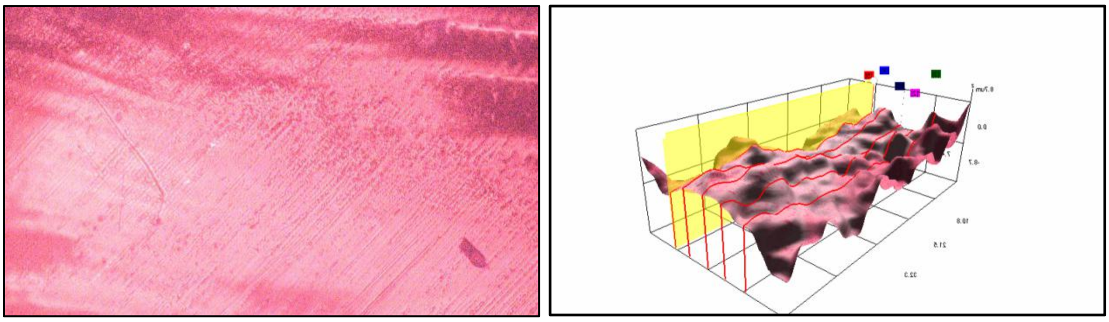


Figure 3.9: Surface sample images for 2D view (left) and 3D view (right)

CHAPTER 4

RESULT AND DISCUSSION

4.1 3D Printing Data Analysis

This chapter explain on the data acquired from the experiment carried out to determine which process of printing gives the better quality on the printed parts. As mentioned in the literature review, fused deposition modelling (FDM) is a 3D additive manufacturing (AM) technology that produced a part layer-by-layer. Although, the printed parts have a poor quality compared to other printing techniques in term of surface roughness and tensile strength. In corresponding way, a new approach was introduced to enhance the accuracy of the 3D part model. This technique includes the manufacturing of 3D printed parts, and serves as a control variable to increase the consistency of manufactured 3D objects, where the printing process is flood with the inert gas which is nitrogen to reduce the percentage of oxygen in the printing chamber. As known, the oxidation process will affect the printed parts and produced a poor quality printed parts. A comparison was made between the parts printed in the chamber flooding with nitrogen and the parts printed with normal condition. It was found that the proposed method was able to improve the part quality. Meanwhile, Table 4.2 show the S/N ratio and deviation value respectively for overall printed parts quality.

Table 4.1: Optimize process parameter to printing the parts

Parameter	Unit	Specifications
Layer Thickness	mm	0.25
Infill Density	%	70
Raster Angle	°	45
Infill Pattern	-	rectilinear

Table 4.1 show the optimize process parameter configuration that being selected for the FDM 3D printer based on the Taguchi analysis performed for 3-level design with 3 number of factors. The Taguchi array is L9(3^3). Figure 4.1 and Figure 4.2 show the corresponding effect between the process parameter with the ambient condition. The layer thickness selection of 0.25 mm is different than the optimal thickness from previous research study which is 0.18 mm Meanwhile, the parameter setup for an infill density was choose to use 70 percent, as one of the important factors to be considered in 3D printing, it can radically influence the build time (Luzanin et al. 2014). The longer the production build time, as the part will be used with better quality surface. The raster angle is the angle provided for filament deposited, so the 45° angle was selected to observe the deposited filament arrangement when using the 3D non-contact Profilometer. Generally, the process parameter selection depends on the use of a 3D printer because it is necessary to determine the characterization of the mechanical properties desired for the functional end-used prototype.

Table 4.2: Tabulated data of the surface roughness (S/N ratio and deviation)

Specimen Numbers	Surface Roughness (Oxygen)	S/N Ratio	Surface Roughness (Nitrogen)	S/N Ratio	Deviation	STD Deviation
1	1.0867	-0.7219	1.7700	-4.9594	0.2334	0.4831
2	1.5300	-3.6938	1.2567	-1.9844	0.0373	0.1932
3	1.0133	-0.1150	1.0667	-0.5605	0.0014	0.0377
4	1.6667	-4.4370	0.9733	0.2347	0.2403	0.4902
5	0.8600	1.3100	0.8933	0.9797	0.0005	0.0235
6	4.8600	-13.7327	1.4417	-3.1773	5.8424	2.4171
7	0.6000	4.43700	0.8267	1.6533	0.0256	0.1602
8	0.9000	0.9151	0.8689	1.2207	0.0004	0.0220
9	2.9800	-9.4843	1.1667	-1.3389	1.6440	1.2822

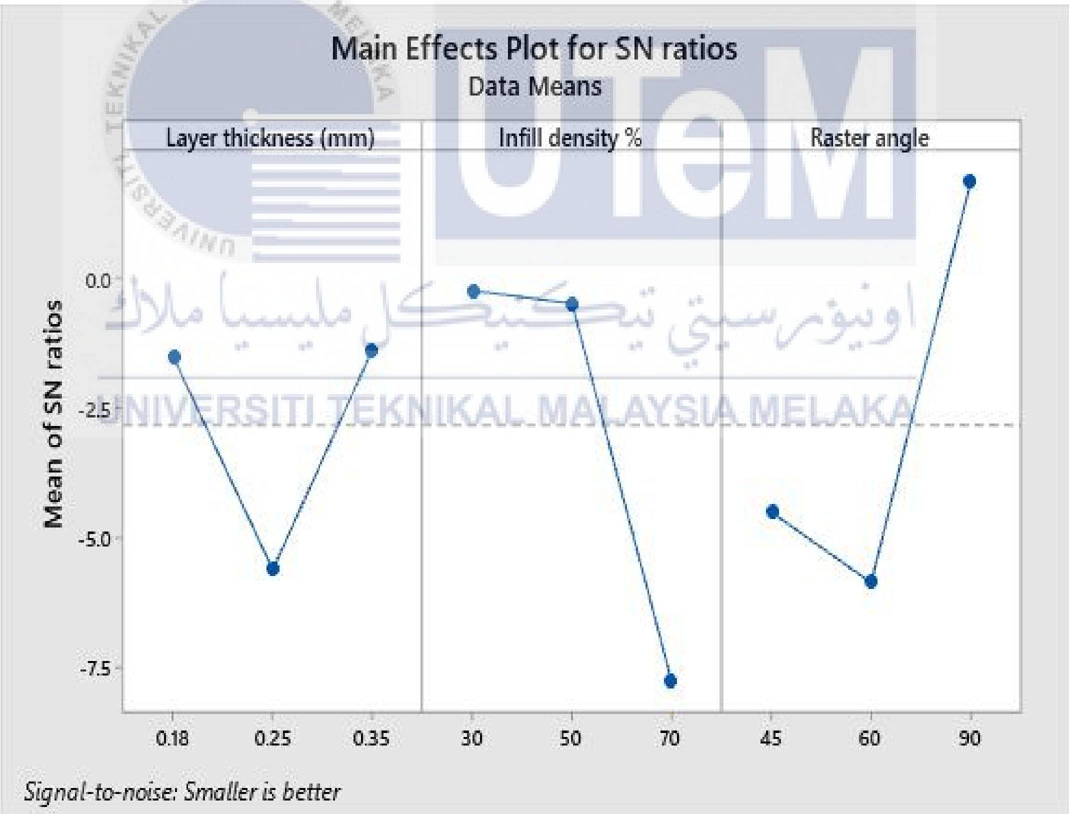


Figure 4.1: S/N ratio graph for surface roughness under Oxygen ambient

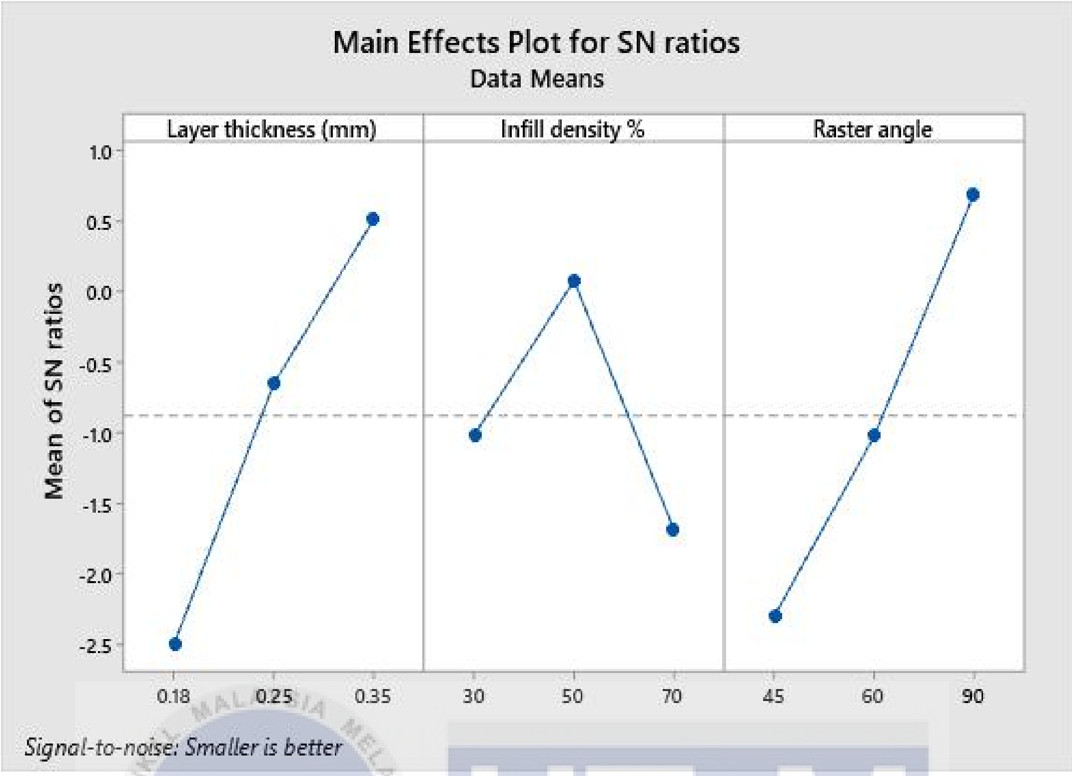


Figure 4.2: S/N ratio for surface roughness under Nitrogen ambient

4.3 Inert Gas Assisted 3D Printing

As experimental parameter using DOE was set up to investigate the effects of gas flow in in-processing technique using nitrogen gas. The mechanical properties and surface roughness were measured for each test parameter before and after the experiment. The sample component was fabricated based on the test criterion tabled in Table 4.3. Accordingly, the parameter check series was taken from the control log of experiment fabrication and Taguchi analysis performed for the deviation between the oxygen ambient and nitrogen ambient as shown in the Figure 4.3.

Table 4.3: Experimental parameter for inert gas assisted 3D printer

Specimen Number	Layer thickness (mm)	Infill density (%)	Raster angle (°)
1	0.18	30	45
2	0.18	50	60
3	0.18	70	90
4	0.25	30	60
5	0.25	50	90
6	0.25	70	45
7	0.35	30	90
8	0.35	50	45
9	0.35	70	60

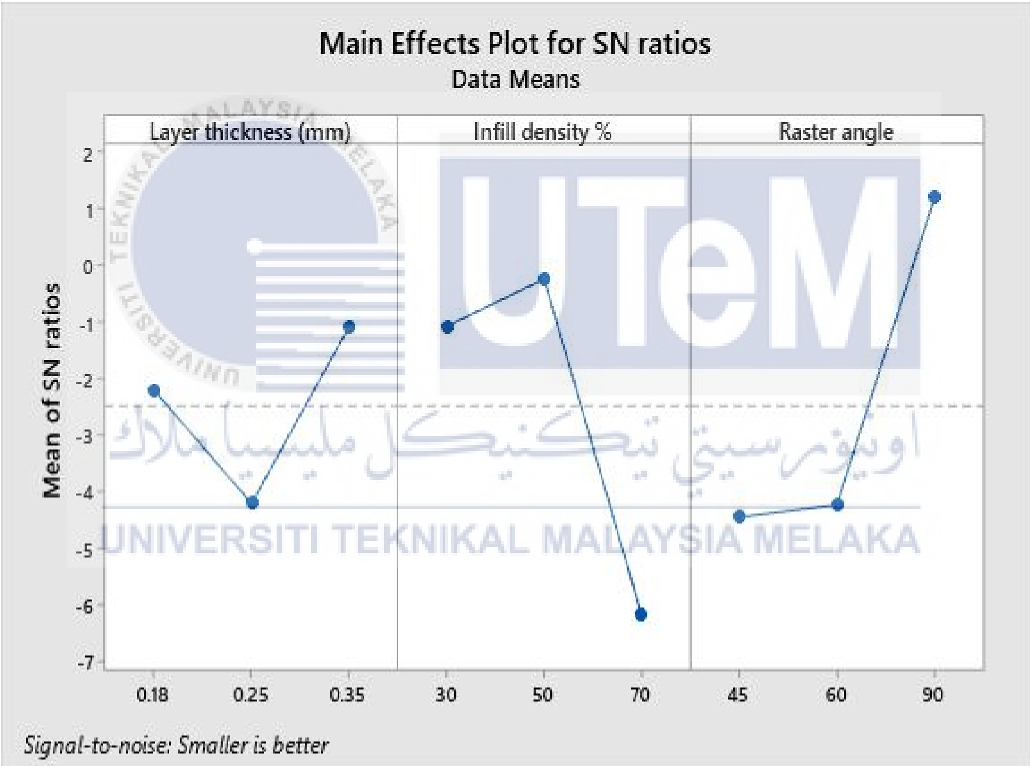


Figure 4.3: S/N ratio for deviation

4.3 Surface Roughness Analysis

High temperature is needed to extrude the filament when manufacturing the parts using FDM method, since the PLA melting temperature is 130 to 180°C as used in this experiment. One of the limiting factors of high-temperature plastic use is their propensity not only to become thinner but also to thermal degradation. Thermal degradation can lead to loss of mechanical properties. As a result, the tensile strength of the 3D printed part was affected, and the surface roughness of the specimen was also affected.

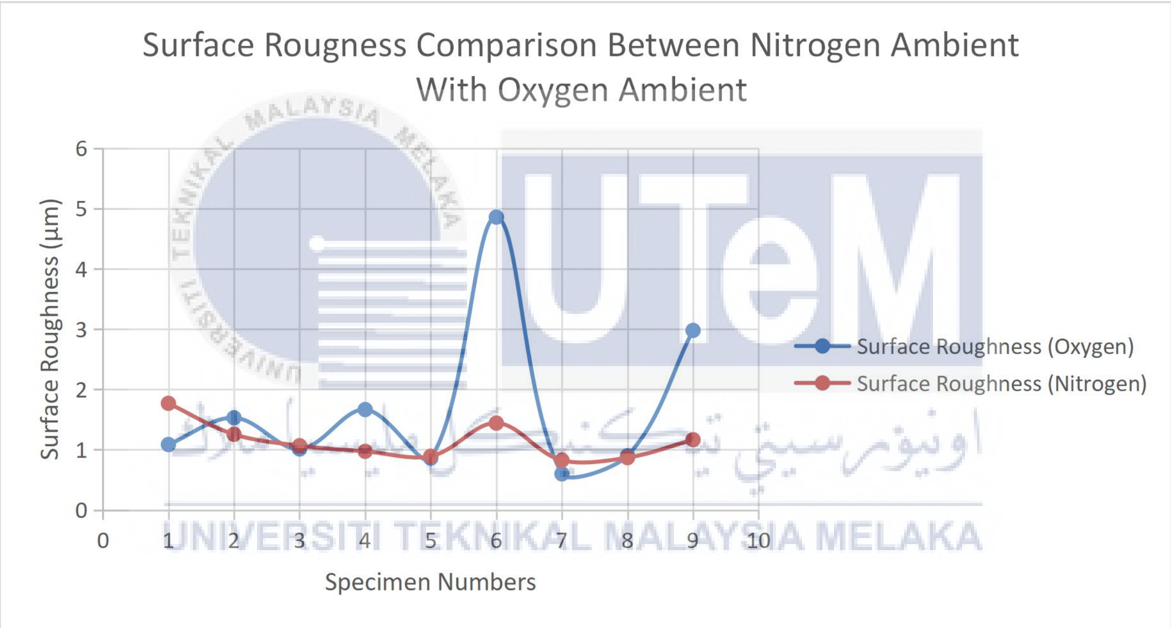


Figure 4.4: Surface roughness comparison between Oxygen ambient printing process and Nitrogen ambient printing process

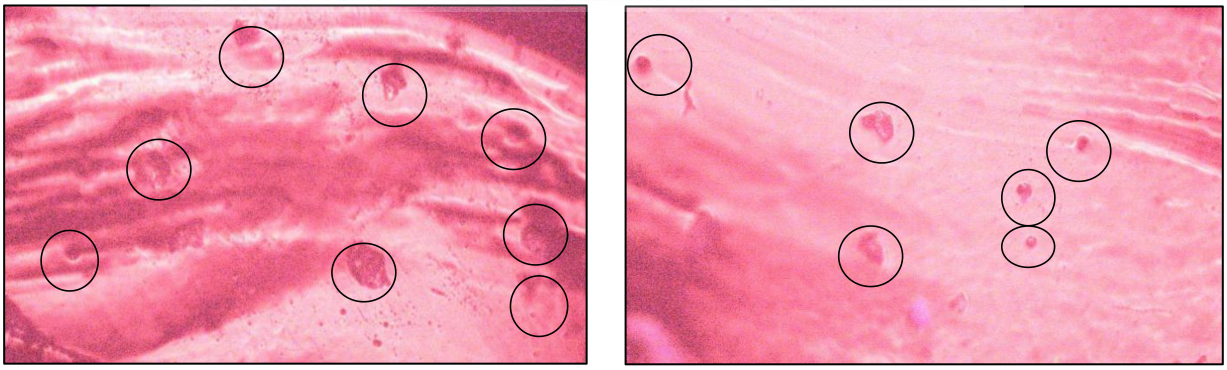
Figure 4.1 shows the comparison of surface roughness when the printing conditions are in present of oxygen and nitrogen atmosphere respectively. Literally, the roughness of the surface was slightly better which is more stable and relevant when no oxygen was in the chamber. The roughness of the surface show the decreasing value of Ra for each test specimen. At high temperature, the components of the polymer's long chain backbones started to detach and reacted to alter the polymer's properties with one another. Polymer degradation occurs in the presence of oxygen from various causes such as heat, thermal degradation and thermal oxidative degradation, and light (photo-degradation). The type of degradation involved in this experiment was from heat which resulted in thermal degradation and thermal oxidative degradation.

The complexity of this oxidation reaction was due to two factors, the concentration of heat and oxygen, because the low-cost 3D printer was installed outdoors. The cracking effect was not apparent from the current experiment but due to the bubble forming on the top surface the surface of the component was rough. This was supposed to occur as the filament absorbed ambient humidity and became oxidized. The experimental setup is shown in Figure 4.5.

Figure 4.5: Experimental setup for inert gas assisted in low cost 3D printer

In the case of PLA, oxidation phase in the presence of oxygen resulted in polymer deterioration at a higher temperature. The oxidation process affected the chemical reaction in polymer which resulted in a major decrease in the mechanical properties. The polymer filament was melted during the FDM process at a comparatively high temperature between

130-180°C and layering on the printing bed and the molten polymer that was exposed to the air during the printing process. Consequently, the polymer surface of each layer is weakened as the layer-by-layer cycle happens which may affect the mechanical properties. As stated in the preceding section, the surface roughness improved due to a better layer of adhesion and influenced the surface profile data as the melted filament had a strong bond and well melted within the presence of the inert gas to controlled the temperature of the melted filament between the particles. The surface profile measurement of the part with the oxygen ambient printing process and the nitrogen ambient printing process is shown in Figure 4.4 to visualize the arrangement of outer layer of the printed part surface. Overall, this can lead to better layer adhesion by suppressing the oxidation process in 3D printing if the thermal degradation can be controlled, in particular by using PLA polymer. This is because at air-printing conditions PLA is most same with the ABS thermoplastic which is less of moisture and other contaminants and in addition PLA is biodegradable material. In addition to this, better quality 3D printed part could be achieved by providing better atmosphere for 3D printing.



(a) (b)

Figure 4.6: (a) Outer surface of the Oxygen ambient (b) Outer surface of the Nitrogen ambient

Figure 4.6 (a) and (b) demonstrates the optimize surface profile comparison between the oxygen ambient and nitrogen ambient after improvement of the 3D printed parts specimen have been made from the observation, experimentation analysis and Taguchi analysis from 27 experimental run. The marked circle demonstrates deviation in layer adherence between oxygen ambient and nitrogen ambient 3D printing process. Adhesion means the process of adhering to a surface, and in this case, it addresses the close bond between the layers and well melted to create a good bonding within the layer which resulted in the fine surface quality. According to Figure 4.6 (a), the outer layer did had 8 bubble form from the fabrication process which is show the layer adhesion is more porous compare with Figure 4.6 (b) where there was greater adhesion between the layers which resulted the less porous. Because of superior adhesion, tensile strength was also improved by strong bond between the layers of the parts.

4.4 Surface Roughness Comparison Between Different Techniques

Figure 4.7 displays surface roughness values between the original portion of the current 3D printer and the enhanced portion from the enhanced 3D printer process. For the measurement of surface roughness, the lower the value of Ra, the better finishing quality of the component. The part of the surface from the existing 3D printer shows rougher value, while the surface of the part had improved slightly better from the original for in-process technique using inert gas.

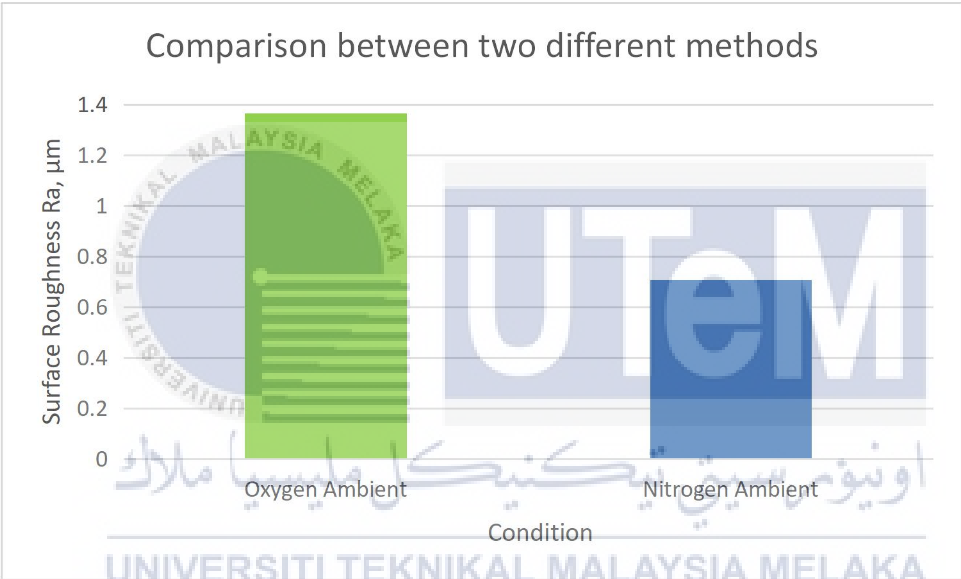


Figure 4.7: Comparisons of surface roughness using different methods

In-processing technique using inert gas assisted 3D printing which is flooding the chamber with nitrogen ambient is performed up to 48.29% better than the initial surfaces of the oxygen ambient process 3D printing, rendered the most important change in finishing. The better quality will be achieved by adding the post-processing techniques using blow cold acetone vapor and eliminating the effects of staircase developed from 3D printing, layer-by-layer manufacturing process (Mazlan et al. 2018) will improve the surface roughness of the printed parts.

4.5 Summary

After the specimens was produced the visual inspection was made using the portable Profilometer and 3D Non-Contact Profilometer. Generally, experiments were all produced successfully using a 3D printer but have reduced manufacturing efficiency at some dimensions. Compared to nominal structure measurements, the successfully built structures were compared and the results are recommended. The improvement in the quality of the printed parts in 3D was discussed. A few methods were suggested to improve the quality in 3D printing process for the best end- use products or prototype. The discussion focused more on aesthetic surface roughness and its profile for high impact prototype. In further studies the dimensional accuracy is highly recommended. The proposed new method included both pre-processing and in-processing techniques. For in-process technique, the enhancement was done when the process of printing proceeded using an inert gas aided to remove the presence of oxygen from the chamber surrounding. The surface roughness show a different result in terms of better quality. However, the proposed new method for post-processing will be in recommendation for the further studies. These methods were successfully enhanced the quality of the printed part. The comparison in part quality between the new methods was conducted using the same parameter settings.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This experimental studies based on the development of the FDM printed parts quality and manufacturability using an open source 3D printer. There are three major factor of design for manufacture (DFM) that have been take into consideration to focus on the utilizing the open source 3D printer. FDM process fabricates parts layer-by-layer and it resulted a poor quality of printed parts compare to others technique of AM. In order to enhance the good surface quality, some method and improvement were introduce to this studies. The improvement are divided into two section which is, from pre-processing and in-processing method while conducted the experiment. The optimization choosing process is conducted with the Taguchi analysis method to choose the optimal process parameter setup. Meanwhile, the inert gas (Nitrogen) assisted the printing process, flooding the ambient of the printing chamber with the Nitrogen (N_2) to reduce and remove Oxygen (O_2) from the chamber surrounding. The in-processing method with inert gas assist is conducted to controlled the temperature variable so the bonding of the layer is well melted and placed. Additionally, the thermal degradation can be reduce to get better mechanical properties of the printed parts. In conclusion 3D printing is still new in the Manufacturing Industry and has a constrain in the quality of the product in term of mechanical properties. So, the continuous development has to be in the priority of the mechanical engineer in order to ensure the quality surface, tensile strength and the dimensional accuracy of the printed parts product design. This studies prove that the presence of the Nitrogen (N_2) is a good alternative for the printing process.

5.2 Recommendations

Lately, AM is being used to manufacture product in aircraft, dental restorations, medical implants, automobile and even fashion products for end consumer and retailers. Therefore, more research and studies is needed to focus on the material used in AM to enhance its quality and mechanical properties especially for high-strength and fine surface quality product. The future works and some recommendation suggested as follows:

1. More detail design guideline for FDM: The study was focused on some of the design attributes only. Future researchers can add more design structure to discuss on the design manufacturability and design limitations
2. New 3D printer material: Currently, for open source 3D printer, thermoplastic is widely used in a roll of filament. The thermoplastic material that widely used for the applications is ABS and PLA.

However, the other material can also be tested especially for metal, resins, and others. New filament can also be proposed in order to improve the part's quality.

Other mechanical properties: The study concentrate on common discuss such as roughness and strength. Future works may integrate other properties such as fatigue test, porosity, impact and etc.

REFERENCES

Alafaghani, A., Qattawi, A., Alrawi, B., & Guzman, A. (2017). Experimental Optimization of Fused Deposition Modelling Processing Parameters: A Design-for-Manufacturing Approach. *Procedia Manufacturing*, *10*, 791–803.

Mazlan, S. N. H., Alkahari, M. R., Maidin, N. A., Ramli, F. R., Sudin. M. N., Lim, G. D., & Mohamad. I. S., (2018). Influence of inert gas assisted 3D printing machine on the surface roughness and strength of printed component, *Proceeding of Mechanical Engineering Research Day,* 2018, 154-155.

Arnold, C., Monsees, D., Hey, J., & Schweyen, R. (2019). Surface quality of 3D-printed models as a function of various printing parameters. *Materials*, *12*(12), 1–15.

Alafaghani, A., Qattawi, A., Alrawi, B., & Guzman, A. (2017). Experimental Optimization of Fused Deposition Modelling Processing Parameters: A Design-for-Manufacturing Approach. *Procedia Manufacturing*, *10*, 791–803.

Btech, E. O. C. (2018). *Determine the Mechanical Properties of 3D Printed Polymer Parts for School of Engineering MSc . Biomedical Device Materials Determine the Mechanical Properties of 3D Printed Polymer Parts for Computer Modelling Applications* (August).

Cuiffo, M. A., Snyder, J., Elliott, A. M., Romero, N., Kannan, S., & Halada, G. P. (2017).

Impact of the fused deposition (FDM) printing process on polylactic acid (PLA) chemistry and structure. *Applied Sciences (Switzerland)*, *7*(6), 1–14.

Duda, T., & Raghavan, L. V. (2016). 3D Metal Printing Technology. *IFAC-PapersOnLine*, *49*(29), 103–110.

Farbman, D., & McCoy, C. (2016). Materials testing of 3D printed ABS and PLA samples to guide mechanical design. ASME 2016 11th International Manufacturing Science and Engineering Conference, MSEC 2016, 2(June).

García Plaza, E., Núñez López, P. J., Caminero Torija, M. Á., & Chacón Plaza, J. M. (2019). Analysis of PLA geometric properties processed by FFF additive manufacturing:

Effects of process parameters and plate-extruder precision motion. *Polymers*, *11*(10).

Huang, S. H., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive manufacturing and its societal impact: A literature review. International Journal of Advanced Manufacturing Technology, 67(5–8), 1191–1203.

Karuppiah, A., & Engineering, G. (2016). Predicting the Influence of Weave Architecture on the Stress Relaxation Behavior of Woven Composite Using Finite Element. (December 2016), 4–5. https://doi.org/10.13140/RG.2.2.17881.16482

Lederle, F., Meyer, F., Brunotte, G.-P., Kaldun, C., & Hübner, E. G. (2016). Improved mechanical properties of 3D-printed parts by fused deposition modeling processed under the exclusion of oxygen. Progress in Additive *Manufacturing*, *1*(1–2), 3–7.

Melenka, G. W., Cheung, B. K. O., Schofield, J. S., Dawson, M. R., & Carey, J. P. (2016). Evaluation and prediction of the tensile properties of continuous fiber-reinforced 3D printed structures. *Composite Structures*, *153*, 866–875.

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, *143*(December 2017), 172–196.

Perrot, A., & Amziane, S. (2019). 3D Printing in Concrete: General Considerations and Technologies. *3D Printing of Concrete*, 1–40.

Piazza, M. C., & Alexander, S. E. (2015). *Additive Manufacturing: a Summary of the Literature Center for Economic Development*. Retrieved from http://urban.csuohio.edu

Tanikella, N. G., Wittbrodt, B., & Pearce, J. M. (2017). Tensile strength of commercial polymer materials for fused filament fabrication 3D printing. *Additive Manufacturing*, *15*(2010), 40–47.

Wohlers, T., & Caffrey, T. (2016). Additive manufacturing: The state of the industry.

Manufacturing Engineering, *156*(5), 45–52.

Wu, W., Geng, P., Li, G., Zhao, D., Zhang, H., & Zhao, J. (2015). Influence of layer thickness and raster angle on the mechanical properties of 3D-printed PEEK and a comparative mechanical study between PEEK and ABS. *Materials*, *8*(9), 5834–5846.

Yap, Y. L., Wang, C., Sing, S. L., Dikshit, V., Yeong, W. Y., & Wei, J. (2017). Material jetting additive manufacturing: An experimental study using designed metrological benchmarks. *Precision Engineering*, *50*, 275–285.

D. Drummer, S. Cifuentes- Cuellar, and D. Rietzel, (2012). *Suitability of PLA/TCP for Fused Deposition Modelling. Rapid Prototype.* J., vol. 18, no. 6, pp. 500-507

A. R. Torrado and D. A. Roberson, "Failure Analysis and Anisotropy Evaluation of 3D-Printed Tensile Test Specimens of Different Geometries and Print Raster Patterns," J. Fail. Anal. Prev., vol. 16, no. 1, pp. 154–164, 2016.

J. Torres, M. Cole, A. Owji, Z. DeMastry, and A. P. Gordon, "An approach for mechanical property optimization of fused deposition modeling with polylactic acid via design of experiments," Rapid Prototype. J., vol. 22, no. 2, pp. 387–404, 2016.

Ahn, S.H., Montero, M. and Odell, D., 2002. Anistropic Material Properties of Fused Deposition Modelling ABS. *Rapid Prototyping Journa*l, 8(4), pp. 248-257.

Ang, K.C., Leong K.F. and Chua, C.K., 2006. Investigation on the Mechanical Properties and Porosity Relationship in Fused Deposition Modelling-Fabricated Porous Structure. *Rapid Prototyping Journa*l, 12(2), pp. 100-105.

Adam, G. A. O. and Zimmer, D., 2014. Design for Additive Manufacturing Element Transitions and Aggregated Structure. *Journal of Manufacturing Science and Technology,* 7(1) pp 20-18.

Blair, B.M., 1998. *Post Build Processing of Streolithography Molds,* 1st ed., School of Mechanical Engineering: Georgia Institute of Technology.

Blom, H., Yeh, R., Wojnarowski, R and Ling, M ., 2006. Detection of Degradation of ABS Materials via DSC, Journal of Thermal Analysis and Calorimetry, 83(1), pp. 113-115.

Byun, H.S. and Lee, K.S., 2006. Determination of the Optimal Build Direction for Different Rapid Prototyping Processes Using Multi-Criterion Decision Making Robotics and Computer-Integrated Manufacturing, 22(1), pp. 69-68.

Bakar, N.S.A., Alkahari, M.R. and Boejang, H., 2010. Analysis On Fused Deposition Modelling Performance, *Journal of Zheijiang University-Science A*, 11(12), pp, 972-977

Belter, J.T and Dollar, A.M., 2015. Strengthening Of 3D Printed Fused Deposition Manufacturing Parts Using the Fill Compositing Technique, *Plos One*, 1-12, pp. 1-19

Darbar, R., and Patel, D.M., 2013. Process Parameters Optimization of FDM Process And Application of Taguchi Approach And ANN-The Review. *International Journal of Engineering Research and Applications,* 3(1), pp. 743-746.

Felix, L., Frederick, M., Gabriella, P.B., Christian, K. and Eike, G.H., 2016. Improved Mechanical Properties of 3D-Printed Part by Fused Deposition Model Parts. *Manufacturing Technology*, 58(1), pp. 189-192.

Stratatys., 1992. Rapid Prototyping Using FDM : A Fast, Precise, Safe Technology, Solid Freeform Fabrication Symposium, Washington, 35 August 1992. Stratasys, Inc.

Ibrahim, D., Ding, S. and Sun, S., 2014. Roughness Prediction for FDM Produced Surfaces. *Proceedings of International Conference Recent Trends in Engineering & Technology (ICERT'2014),* bATAM, Indonesia, 13-14 Februari 2014.

Nancharaiah, T., Raju D.R., and Raju V.R., 2010. An Experimental Investigation on Surfaced Quality and Dimensional Accuracy of FDM Components, *International Journal on Emerging Technologies*

Maidin, S., Wong J. H. U., Mohamed, A. S. and Mohamed, S. B., 2017. Effect on Vacuum Assisted Fused Deposition Modelling on 3D Printed ABS Microstructure, *International Journal of Applied Engineering Research,* 12(15), pp, 4877-4881.

Omar, A.M., 2015. Optimization of Fused Deposition Modelling Process Parameters: A Review of Current Research and Future Prospect. Advance in Manufacturing, 3(1), pp. 42-53.

Marcincin, J.N., Marcincinova, L.N., Barma, J. and Janak, M., 2012.Application of FDM Rapid Prototyping Technology in Experimental Gearbox Development Process Technical Gazette. *Journals of Croatio,* 19(3), pp. 689-694.

Majid, S.N.A, Alkahari, M.R., Maidin, S. and Fai, T.C., 2017. Influenced of Integrated Pressing During Fused Filament Fabrication on Tensile Strength and Porosity. *Journal of Mechanical Engineering,* 3, pp. 185-197.

Malaika, A.S., 2003. Oxidative Degradation and Stabilisation of Polymers. *Journal of International Material and Reviews*, 48(3), pp. 165-185.

Luzanin, O., Movrin, D. and Plancak, M., 2013. Experimental Investigation of Extrusion Speed and Temperature Effects on Arithmetic Mean Surface Roughness in FDM Built Specimens, *Journal for Technology of Plasticity, 38(2),* pp. 179-190.

Lee, B. H., Abdullah, J. and Khan, Z., 2005. Optimization of Rapiid Prototyping Parameters for Production of Flexible ABS Object. *Journal of Materials Processing Technology,* 169(1), pp. 54-61.

Jun, D., Zhengying, W., Xin W., Jijie, W. and Zhen, C., 2016. an Improved Fused Deposition Modelling Process for Forming Large-Size Thin-Walled Parts. *Journal of Material and Processing Technology, 234,* pp. 332-341.

Johnson, W.M., Rowell, M., Deason, B. and Eubanks, M., 2014. Comparative Evaluation of An Open Source FDM system. *Rapid Prototping Journal,* 20(3), pp. 205-214

Mohamed, A. S., Maidin, S., Wong, J. H. U., Arif, N,M., and Mohamed, S.B., 2017. Effect of Ultrasonic of Vacuum System Assisted Mild-End Fused Deposition Modelling to Improve Printed Parts Surface Finish . *Proceeding of Innovative Research and Industrial Dialoque'16,* Melaka, Malaysia, May 2017. Advance Manufacturing Centre.

APPENDICES

APPENDIX A

WORKSHEET 1

Taguchi Analysis: Surface Roughness (Oxygen) versus Layer thickness (mm), Infill density %, Raster angle

Response Table for Signal to Noise Ratios

Smaller is better

Level	Layer thickness (mm)	Infill density %	Raster angle
1	-1.5103	-0.2406	-4.5132
2	-5.6199	-0.4895	-5.8717
3	-1.3774	-7.7774	1.8773
Delta	4.2425	7.5367	7.7490
Rank	3	2	1

Response Table for Means

Level	Layer thickness (mm)	Infill density %	Raster angle
1	1.2100	1.1178	2.2822
2	2.4622	1.0967	2.0589
3	1.4933	2.9511	0.8244
Delta	1.2522	1.8544	1.4578
Rank	3	1	2

APPENDIX B

WORKSHEET 1

Taguchi Analysis: Surface Roughness (Nitrogen) versus Layer thickness (mm), Infill density %, Raster angle

Response Table for Signal to Noise Ratios

Smaller is better

Level	Layer thickness (mm)	Infill density %	Raster angle
1	-2.50148	-1.02377	-2.30535
2	-0.65427	0.07201	-1.02952
3	0.51172	-1.69227	0.69085
Delta	3.01320	1.76428	2.99620
Rank	1	3	2

Response Table for Means

Level	Layer thickness (mm)	Infill density %	Raster angle
1	1.3644	1.1900	1.3602
2	1.1028	1.0063	1.1322
3	0.9541	1.2250	0.9289
Delta	0.4104	0.2187	0.4313
Rank	2	3	1

Response Table for Standard Deviations

Level	Layer thickness (mm)	Infill density %	Raster angle
1	*	*	*
2	*	*	*
3	*	*	*
Delta	*	*	*
Rank	2	2	2

APPENDIX C

WORKSHEET 1

Taguchi Analysis: Surface Roughness (oxygen), Surface Roughness (Nitrogen) versus Layer thickness (mm), Infill density %, Raster angle

Linear Model Analysis: SN ratios versus Layer thickness (mm), Infill density %, Raster angle

Estimated Model Coefficients for SN ratios

Term	Coef	SE Coef	T	P
Constant	-2.4950	0.9355	-2.667	0.117
Layer th 0.18	0.2935	1.3231	0.222	0.845
Layer th 0.25	-1.7211	1.3231	-1.301	0.323
Infill d 30	1.4238	1.3231	1.076	0.394
Infill d 50	2.2564	1.3231	1.705	0.230
Raster a 45	-1.9589	1.3231	-1.481	0.277
Raster a 60	-1.7441	1.3231	-1.318	0.318

Model Summary

S	R-Sq	R-Sq(adj)
2.8066	89.82%	59.28%

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Layer thickness (mm)	2	15.26	15.26	7.629	0.97	0.508
Infill density %	2	61.99	61.99	30.994	3.93	0.203
Raster angle	2	61.77	61.77	30.887	3.92	0.203
Residual Error	2	15.75	15.75	7.877		
Total	8	154.77				

Response Table for Signal to Noise Ratios

Smaller is better

Level	Layer thickness (mm)	Infill density %	Raster angle
1	-2.2015	-1.0712	-4.4539
2	-4.2160	-0.2386	-4.2391
3	-1.0674	-6.1752	1.2080
Delta	3.1486	5.9366	5.6619
Rank	3	1	2

Response Table for Standard Deviations

Level	Layer thickness (mm)	Infill density %	Raster angle
1	0.23806	0.37791	0.97411
2	0.97699	0.07961	0.65525
3	0.48817	1.24569	0.07385
Delta	0.73893	1.16607	0.90025
Rank	3	1	2

APPENDIX C

Table Appendix 1: Optimize Data from Sample Specimen

Point Taken	Point 1	Point 2	Point 3	
Optimize Oxygen Ambient	1.7	0.9	1.6	Profile 1
	1.9	1.1	1.7	Profile 2
	1.7	0.8	1.5	Profile 3
	1.1	0.9	1.7	Profle 4
	1.5	0.8	1.6	Profle 5
Average	1.58	0.9	1.62	1.366666667

Table Appendix 2: Optimize Data from Sample Specimen

Point Taken	Point 1	Point 2	Point 3	
Optimise Nitrogen Ambient	0.5	0.5	0.8	Profile 1
	1	0.5	0.8	Profile 2
	0.6	0.8	0.9	Profile 3
	0.3	0.5	0.8	Profile 4
	0.9	0.5	1.2	Profile 5
Average	0.66	0.56	0.9	0.706666667

APPENDIX D

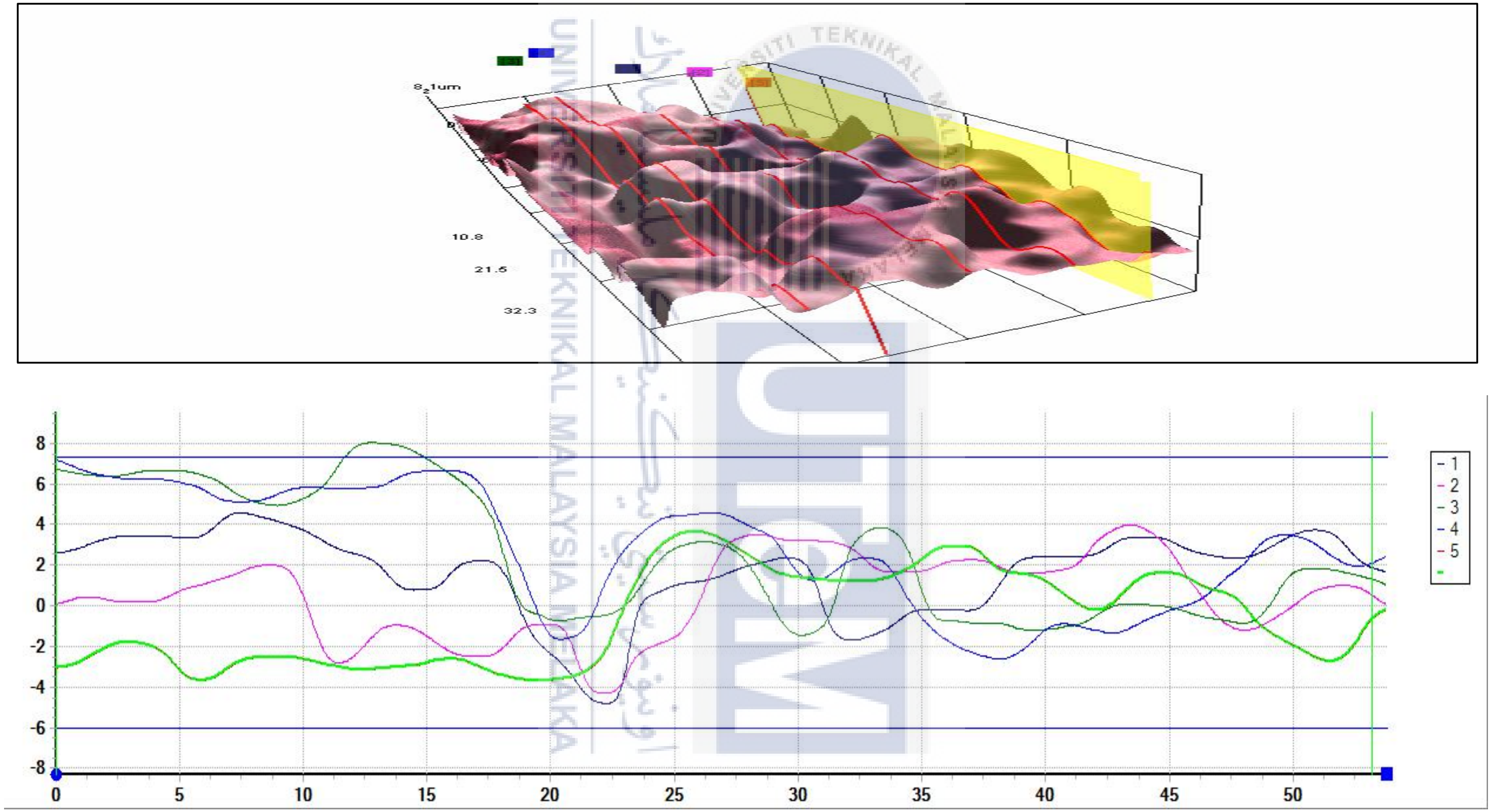


Figure Appendix 1: Point 3 Oxygen Ambient Result Surface Profile Analysis

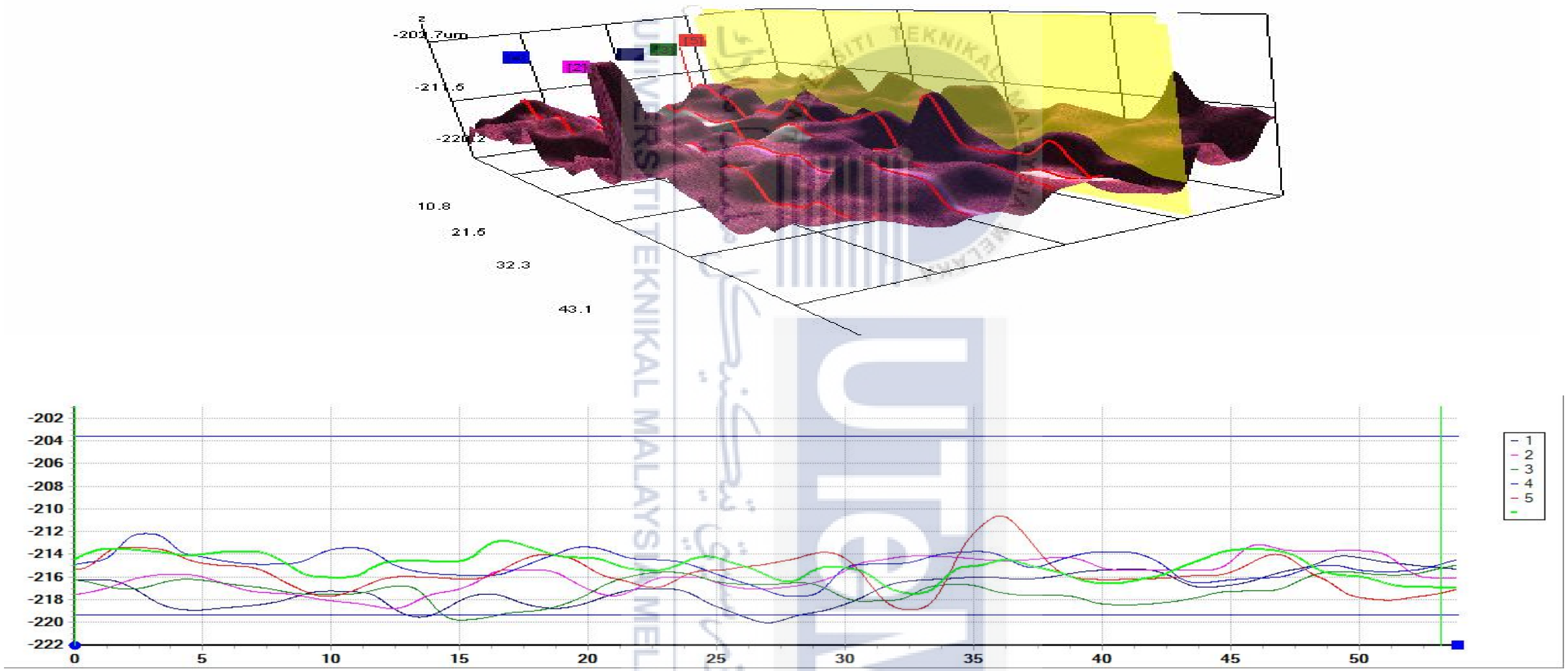


Figure Appendix 2: Point 3 Nitrogen Ambient Result Surface Profile Analysis