QUALITY ASSESSMENT OF 3D-PRINTED PLASTIC PARTS USING IMAGE ANALYSIS TECHNIQUE

CHIM JIA WEN

UNIVERSITI SAINS MALAYSIA

2018

SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

UNIVERSITI SAINS MALAYSIA

QUALITY ASSESSMENT OF 3D-PRINTED PLASTIC PARTS USING IMAGE ANALYSIS TECHNIQUE

By

CHIM JIA WEN

Supervisor: Professor Dr. Zulkifli Bin Mohamad Ariff

Dissertation submitted in partial fulfillment
of the requirements for the degree of Bachelor of Engineering with Honours
(Polymer Engineering)

Universiti Sains Malaysia

JUNE 2018

DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled: **“Quality Assessment of 3D-Printed Plastic Parts Using Image Analysis Technique ”**. I also declare that it has not been previously submitted for the award for any degree or diploma or other similar title of this for any other examining body or university.

Name of Student : Chim Jia Wen Signature:

Date : 11th June 2018

Witness by,

Supervisor :Professor Dr. Zulkifli Bin Mohamad Ariff Signature:

Date : 11th June 2018

ACKNOWLEDGEMENTS

Firstly, I wish to thank God for giving me the opportunity to embark on my degree and for completing this challenging journey successfully. Thank you USM especially all staffs in School of Materials & Mineral Resources Engineering for providing me a good platform to learn and reach a new height in my life. My utmost appreciation goes to my respectful supervisor, Professor Dr. Zulkifli Bin Mohamad Ariff, who offered a lot of helpful advise and guidance. Not forgetting to mention all helpful technicians that assisted me in my lab works and are generous to share their knowledge with me. Special thanks to my colleagues and friends for helping thorough the journey.

Finally, this thesis is dedicated to the loving father and mother for the vision and determination to educate me. This piece of victory is dedicated to both of you.

TABLE OF CONTENTS

CONTENTS **PAGE**

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF ABBREVIATIONS

3D	Three-dimensional
ABS	Acrylonitrile-Butadiene-Styrene
ANOVA	Analysis of Variance
ANN	Artificial Neural Network
CAD	Computer-Aided Design
CCD	Concrete Capacity Design
DOE	Design of Experiment
DSC	Differential Scanning Calorimetry
EVA	Ethylene-Vinyl-Acetate
FDA	Food and Drugs Administration
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
GA	Genetic Algorithm
HDPE	High-Density Polyethylene
HIPS	High Impact Polystyrene
LDPE	Low-Density Polyethylene
MI	Melt Index
PC	Polycarbonate
PLA	Polylactic Acid

PVC	Polyvinyl Chloride
SLA	Stereolithography
STL	Standard Tessellation Language
TPC	The Polyolefin Company
VA	Vinyl Acetate

LIST OF SYMBOLS

R_a	Average surface roughness value
R_q	Root-mean-square surface roughness value
R_{sk}	Skewness
R_{ku}	Kurtosis
Tg	Glass transition temperature
X_c	Crystallinity
F	Euler’s critical load
E	Modulus of elasticity of column material
I	Minimum area moment of inertia of the cross section of the column
L	Unsupported length of column
ΔH_f	Enthalpy of fusion of EVA sample
ΔH_{f°	Enthalpy of fusion of perfect polyethylene crystal

PENILAIAN KUALITI KOMPONEN CETAKAN 3D MENGGUNAKAN TEKNIK ANALISIS IMEJ

ABSTRAK

Percetakan tiga dimensi (3D) atau pembuatan tambahan telah muncul untuk menjadi teknologi yang penting dalam perubahan industri pembuatan. Percetakan 3D mempunyai beberapa ciri yang menarik berbanding pembuatan konvensional (contohnya pengacuanan suntikan), seperti fleksibiliti pengeluaran dan produk. Walau bagaimanapun, percetakan 3D mempunyai kekangan dari segi saiz produk, masa pembinaan dan ketersediaan bahan. Namun begitu, impak percetakan 3D pada masyarakat telah ditemui di dalam bidang sains hayat, di mana kesesuaian produk tersuai untuk individu masih diperlukan. Pecetakan 3D juga boleh memendekkan masa yang diperlukan oleh sesuatu produk untuk mencapai pengguna akhir dan ia mampu mengubah sistem perniagaan. “Ethylene Vinyl Acetate” adalah salah satu bahan yang dilaporkan selamat untuk penggunaan bidang perubatan dan oleh itu ia dijadikan sebagai bahan pilihan untuk dikaji dalam percetakan 3D. Untuk projek ini, pencubaan untuk mencetak EVA dengan menggunakan pencetak 3D UP Plus 2 telah dilakukan. Walau bagaimanapun, percubaan ini tidak berjaya kerana perubahan kelikatan gred EVA yang dipilih semasa proses percetakan. Oleh yang demikian, kajian selanjutnya mengenai penilaian kualiti bagi produk yang dicetak secara 3D dilakukan dengan menggunakan filamen Akrilonitril Butadiena Stirena (ABS). Eksperimen ini direkabentuk dengan menggunakan kaedah faktorial 2^k. Kesan ketebalan lapisan, sudut “raster” dan suhu pelantar terhadap kekasaran permukaan produk yang dicetak telah dikaji. Penilaian kekasaran permukaan dilakukan menggunakan perisian analisis imej, ImageJ yang menggunakan perisian SurfCharJ.

Kesan ketebalan lapisan pada kekasaran permukaan dilaporkan sebagai yang faktor yang paling penting dan merupakan satu-satunya faktor penting dari segi statistik. Interaksi antara suhu pelantar dan ketebalan lapisan berada di tempat kedua penting. Parameter-parameter optimum di mana nilai kekasaran permukaan yang paling rendah didapati apabila ketebalan lapisan = 0.2 mm, sudut “raster” = 45° dan suhu pelantar = 80℃.

QUALITY ASSESSMENT OF 3D-PRINTED PLASTIC PARTS USING IMAGE ANALYSIS TECHNIQUE

ABSTRACT

Three dimensional (3D) printing or additive manufacturing has arisen to become an important technology that change the manufacturing industry. 3D printing has several attractive points compared to conventional manufacturing (eg. injection moulding), such as production flexibility and part flexibility. However, 3D printing has limitation in terms of product size, build time and materials availability. Nonetheless, the impact of 3D printing on society has been found especially in life sciences field, where customized product for individual is needed. Ethylene Vinyl Acetate (EVA) is one of the material that is reported safe for medical application and hence make it a good choice of material to be studied for 3D printing. In this project, attempt to 3D print EVA using UP Plus 2 3D printer was done. However, this attempt was not successful due to variation in viscosity of the chosen EVA grade during the printing process. Hence, further studies on the quality assessment of 3D printed part was done using Acrylonitrile Butadiene Styrene (ABS) filament. The experiment was designed using 2^k factorial method. The effect of layer thickness, raster angle and platform temperature on the surface roughness of printed parts were studied. The evaluation of surface roughness was done using an image analysis software, ImageJ using a plugin called SurfCharJ. The effect of layer thickness on the surface roughness was reported to be the most significant and is the only one that is statistically significant. The interaction between platform temperature and layer thickness has the second place of significance. The optimum parameter settings where lowest surface

roughness value is observed is when layer thickness = 0.2 mm, raster angle = 45° and platform temperature = 80℃.

CHAPTER 1
INTRODUCTION

1.1 3D PRINTING

3D printing is sometimes called additive manufacturing, rapid prototyping, solid freeform fabrication and digital fabrication. 3D printing is a process of building products from a computer-aided design by transferring the data of image into a certain type of 3D printer. Unlike traditional manufacturing process, in 3D printing process, software is one of the important aspect to handle. Charles W. Hull was the first person to patent 3D printer. He also created a file format that is suitable for 3D printing: the SLA file format, abbreviated as STL. STL sometimes is considered an abbreviation for *standard tessellation language*. STL works by taking a 3D model from CAD software, converting it into surface mesh consisting of many triangles, which determines the detail of the resulting surface mesh, making it scalable. The SLA or STL file format remains the standard file format for today’s 3D printing (Coward, 2015).

There are many types of 3D printers and their working based on different principles. The major types of 3D printer are summarized as follows:

Table 1.1: Major types of 3D printing processes (Wong and Hernandez, 2012)

3D Printing Method	System	How It Works	Material
Fused Deposition Modelling (FDM)	Hot-melt extrusion system	The raw materials in filament form is heated up to the material's melting temperature, and extruded as semi-molten layers on a platform which stacks up to build a product.	Usually thermoplastics
Stereolithography	Photopolymerization system	UV laser is applied on liquid-resin on a platform. The UV light solidifies or cures the resin according to the CAD as it comes into contact with the resin.	Mainly polymers
Selective Laser Sintering	Sintering system	The powder of raw material is sintered or fuses when it is applied with a carbon dioxide laser beam. The laser beam can fuse the powder at specific location of layers according to the design.	Polymers, metals, as well as combination of metals with other materials such as ceramics

1.1.1 Societal Impact of 3D Printing

The use of 3D printing in pharmaceutical and medical field had been gaining more recognition in recent years, ever since the first 3D-printed drug being approved by US Food and Drugs Administration (FDA) in August 2015 (Norman *et al.*, 2017). 3D printing had reformed the medical and pharmaceutical field in such a way that accurate control on spatial distribution of active pharmaceutical ingredients (API) can be made possible, with more control on producing complex geometry and drug release rate. The production of drug delivery system can be made highly personalized according to patient's dosage requirements (Prasad *et al*, 2016).

Huang *et al* (2013) reported the impact of additive manufacturing on population health and well being. He claimed that one of the key societal challenges in 21st-century is to deliver high quality and cost-efficient healthcare to the entire population, as there are increased number of elderly. Additive manufacturing technology is believed to play an important role in healthcare and wellbeing of people as it can produce customized products that meet every individual needs. Examples of personalized healthcare products include customized surgical implants and assistive devices. By using additive manufacturing to produce medical implants, Singare *et al* (2004) reported that very accurate implants with functionality and good aesthetic property can be produced. This approach will greatly reduce the design cycle and delivery lead time of customized surgical implants.

The use of additive manufacturing to produce customized personal protective equipment, such as helmets and protective garmets, is another exciting opportunity for the application of additive manufacturing. By customizing safety equipment of professionals that are constantly exposed to danger during their work, such as policemen, firefighters, athletes and construction workers, it can provide great protection to these people without sacrificing comfort of the user. This is because additive manufacturing made it possible to consider variations in shape and size of every individual.

Additive manufacturing is believed to be able to transform the supply chain by shortening the steps require to deliver a product to end user starting from an idea or design (Özceylan *et al*, 2017). Stratasys, one of the leader in additive manufacturing industry today, had informed their reader about the impact of 3D Printing on supply chain as follows:

Traditional supply chain involves sourcing of raw materials that will go into multiple suppliers that produce different parts required for a product. Then, these different parts will be supplied by different suppliers to manufacturer. The production of manufacturer usually situated offshore in low-cost location. After combining these multiple parts and make a product, manufactured goods will go through multi-stage distribution, where the goods and spare parts shipped in from large inventory. These goods will be sent to retailers before reaching to consumer. Figure 1.1 shows the traditional manufacturing chain flow stated by Stratasys.

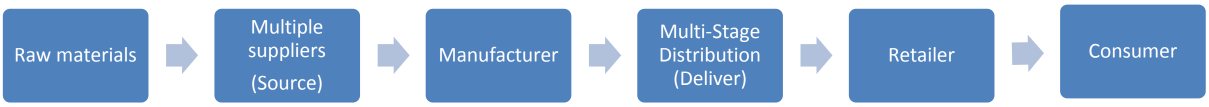

Figure 1.1: Traditional Manufacturing Chain Supply Flow (Stratasys)

On the other hand, manufacturing that incorporates 3D Printing require far less steps. The source of raw materials and the making or manufacturing process of goods can be done in one place. After the goods are manufactured, it can be directly distributed to end user. This supply chain flow was shown in Figure 1.2.

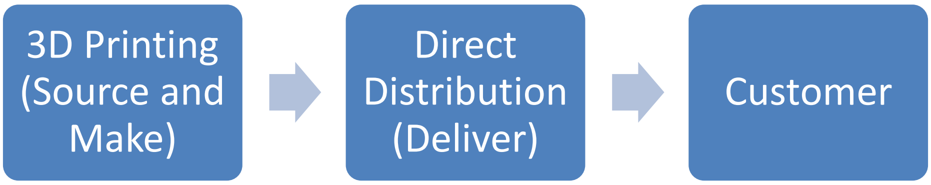

Figure 1.2: 3D Printing Manufacturing Supply Chain

Özceylan *et al* (2017) had reported similar informations on how 3D printing can eliminate few steps in manufacturing industry that shorten the lead time for a product to be delivered to customers as shown in the Figure 1.3.

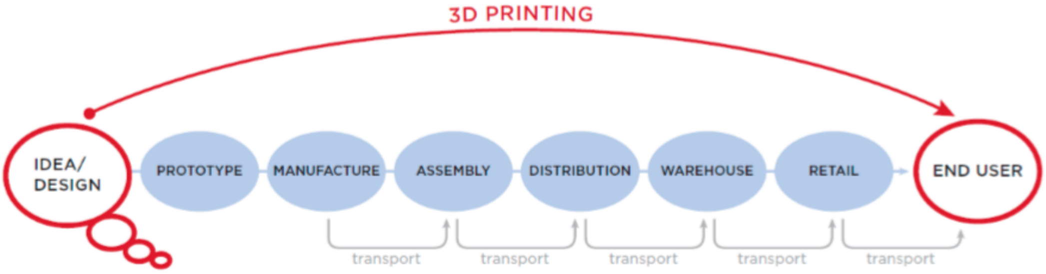

Figure 1.3: Traditional vs 3D printing supply chain (Özceylan *et al*, 2017)

3D printing has change the way some company operates. In automobile industry, Bugatti Veyron dashboards are customized according to purchaser. By doing this, purchaser can customize their low volume production car, at the same time reducing assembly time. Other companies, such as BMW, also offers 3D printed components to their customers (Özceylan *et al*, 2017). Amazon has created and filed patent for a new system that use a truck-based 3D printer to print customers' order quickly. They will produce the products upon customers' order and this eliminates the needs to stock in inventory in warehouse. Amazon believes this system could help to speed up delivery process and reduce the warehouse space needed by company, as shown in Figure 1.4.

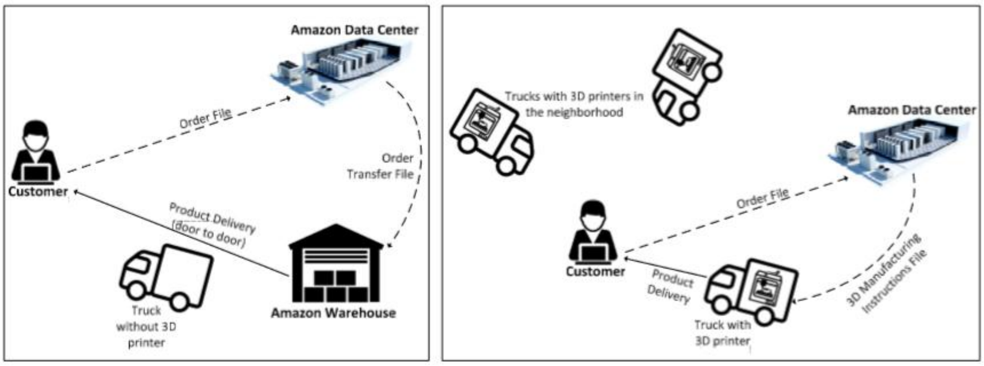

Figure 1.4: Traditional (left side) vs 3D printing (right side) truck delivery system (Özceylan *et al*, 2017)

1.1.2 Advantages of 3D Printing

Since last decade, 3D printer had arisen to become the most sought-after rapid prototyping tool. Its application does not only limit to rapid prototyping. The rise of 3D printer has provided an exciting option for makers and hobbyists (Coward, 2015). With this additive manufacturing technology becomes more popular, it is expected to transform the lifestyle of people and how businesses work. Consumer's 3D printer may allow people to print their own product and replace a broken part of their belongings.

It is possible to use additive manufacturing for small scale production that replace traditional manufacturing due to the following reasons:

- Production flexibility: The setup of additive manufacturing is relatively cheaper than the conventional one, as it does not require auxiliary resources as needed in conventional manufacturing processes, such as jigs, fixtures, cutting tools, main machine tools and so forth (Huang *et al*, 2013). This is attractive in small batch manufacturing as it is more economical. Additive manufacturing requires less resources than it is needed in conventional manufacturing. Due to this flexibility, the additive manufacturing is potential for simpler supply chain flow (Özceylan *et al*, 2017), in which the lead time required for a product to be marketed is significantly decreased. The "just-in-time" (JIT) production or lean production is easier to be done as the production can be easily synchronized with customer demands.

- Part flexibility: FDM provides the design freedom to produce complex shapes and features of products without consideration or investments in dies and molds (Alafaghani *et al*, 2017). FDM is more capable of producing complicated internal features compared to traditional manufacturing. This is because there is no tooling constraint that needs to be considered in order to ease the manufacturing process (Huang *et al*, 2013). In addition, a part of which consists of more than one type of materials can be produced shortly.

Bhasin *et al* (2014) had compared the total manufacturing cost for traditional manufacturing which is injection molding and 3D printing. The comparison has been made on machine cost, setup cost, product design cost, tooling cost and raw material cost. The result is presented in the graph in Figure 1.5. Their findings show that 3D printing is a more favourable choice in small scale manufacturing in the context of manufacturing cost.

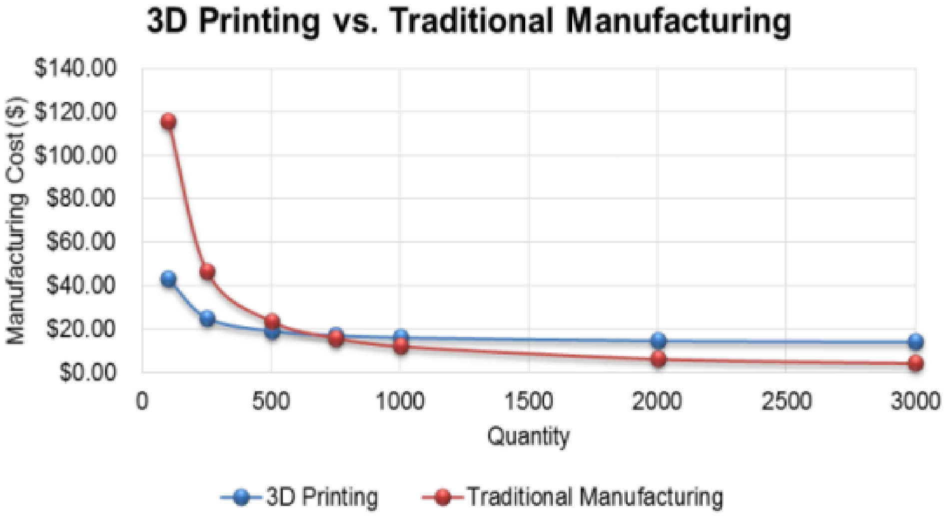

Figure 1.5: Comparison of Manufacturing Cost of 3D Printing and Traditional Manufacturing vs Quantities (Bhasin *et al*, 2014)

1.1.3 Disadvantages of 3D Printing

Although 3D printer has opened new possibilities for prototyping and small scale manufacturing, there are still some drawbacks for 3D printing technology, which are:

(i) Limited material for consumer's 3D printer. For printing plastics, the filaments that are commonly used for 3D printing available in the market are limited, and mostly dominated by ABS and PLA (Coward, 2015).

(ii) The time needed to print a product. Since 3D printer that primarily used in the market functions by extruding the filament and depositing it layer-by-layer according to the cross-sectional area of the product, it could take more time than traditional manufacturing method such as injection moulding. When a 3D printer may take hours to produce a product, injection moulding only takes several seconds for a cycle. This makes 3D printing not suitable for mass production (Coward, 2015).

(iii) Size limitations. Usually, large-sized objects can be impractical to be produced using additive manufacturing method due to lack of material strength, as well as the extended amount of time needed for the build process (Huang *et al*, 2013).

(iv) The surface finishing of the printed part. As the 3D printer works by stacking the filaments layer-by-layer, thus the product's surface will inevitably have a series of layer ridges. This is due to the plastic beads or powder particles that are stacked on top of each other (Huang *et al*, 2013). However, post-surface treatment can be done to minimize the surface finish issue (Coward, 2015).

Despite its drawbacks, 3D printing technology still makes progressive changes in many industries, such as biomedical field, construction field, industrial field, research, and so forth (Noorani, 2006). Nowadays, 3D printing can even be done by directly feeding plastic pellets into 3D printer itself (talesofa3dprinter.blogspot.com, 2014).

1.2 PROBLEM STATEMENT

There are quite many studies have been done on the optimization of fused deposition process based on ABS. Omar *et al* (2014) had reviewed studies related to fused deposition process optimization. They concluded the studies related to fused deposition process optimization have lots of development area yet to be focused on, such as expanding the materials used for this study area, the environmental parameters that affect the print quality (such as humidity) and so forth. They reported that the studies made are mainly based on ABS. As the study material was dominated by ABS, it remains a gap that only very little work done to study the process optimization of other thermoplastic materials. The liquefier head are designed to be able to print different materials, such as PC, PC-ABS, etc. However only very little work made to study the process optimization of other 3D-printed material. (Mohamed *et al,* 2015)

In this work, 3D printing of EVA using consumer's 3D printer was studied. The ability to print a new plastic material in 3D printing will open more possibilities to 3D printing technology. EVA is flexible, non-toxic and has very good low-temperature flexibility due to its low glass transition temperature. These characteristics make EVA to behave rubber-like, but remain processible like a thermoplastic. The use of EVA in 3D-printed medical and pharmaceutical field can be promising due to its safety. The gap of study area in process optimization of Fused Deposition Modeling (FDM) is expected to compensated in this project by using a less studied but highly potential material, which is the thermoplastic EVA. The other potential application of 3D printed EVA includes customized athletic shoe soles, toys, and etc. However, the 3D printing of EVA which is a type of flexible filament was not an easy task, The problems encountered while 3D printing EVA will be discussed in this work.

1.3 SCOPE OF PROJECT

This work focuses on evaluating the surface roughness of FDM printed part. Surface roughness is one of the properties that can play an important role in ensuring functionality of printed part, especially those application that require intimate contact between moving parts, as well as to ensure high aesthetic property of printed part. The surface roughness characterization and quantification was done using an image analysis software, ImageJ, together with a portable microscope. ImageJ is an open-source image analysis software used for image analysis procedure. This paper also aims to expose the use of this useful software as a tool for research and analysis purposes.

Like any other conventional processing methods, FDM printed parts are dependent on the process parameters. These process parameters or input parameters can have significant effect on the quality of printed parts. The input parameters that are commonly manipulated during FDM are: layer thickness, nozzle temperature, platform temperature, nozzle height, printing speed, raster angle, and so forth. In this work, three FDM parameters were selected to study their effect on the surface roughness value of printed part, namely layer thickness, raster angle and platform temperature. The experiment was done with the use of 2^k factorial method in designation of experiment and interpretation of the results.

1.4 OBJECTIVE

1. To determine significant factor(s) that affect surface roughness of 3D printed plastic component.
2. To evaluate surface roughness of printed plastic component using ImageJ and analyse the obtained data using 2^k Factorial method.

1.5 THESIS OUTLINE

In this thesis, the brief introduction and overview of the study will be discussed in Chapter 1, which include problem statements, significance of project and project objectives. Chapter 2 will be the literature review in which related researches and studies that has been done are discussed. In Chapter 3, methodology of the experimental works are discussed. The results and analysis from the experimental work will then be discussed in Chapter 4. Next, conclusion and recommendations are highlighted in Chapter 5 while references will be covered at the last of the thesis.

CHAPTER 2
LITERATURE REVIEW

2.1 FUSED DEPOSITION MODELLING

2.1.1 Working Principle of FDM

The method of today's most common 3D printing technology is known as Fused Deposition Modelling (FDM), or the Fused Filament Fabrication (FFF). Both are the same process. However, FFF was named differently to avoid legal problems with Stratasys who patented the FDM process (Coward, 2015). The process of FDM requires handling of three aspects, which are the materials, software and hardware (Comb *et al*, 1994). The materials used in current consumers' 3D printer are based on thermoplastic, mainly ABS, PC and PLA. Other materials such as HDPE, HIPS, PVC and Nylon are available too (Hausman, 2014). FDM works based on extrusion process, where the thermoplastic is subjected to heat inside the nozzle and extruded as semi-liquid plastic, which is then deposited into build platform. This extrusion-based process makes the rheology of materials becomes a crucial parameter. As the material is deposited layer by layer, the adhesion between layers required sufficient liquidity of the extruded filaments, but not too high liquidity that cause it to be extruded as droplets.

FDM works by first slicing and creating layers for the 3D model (generally in STL format) to be printed. A slicing software is required for this process. The layer thickness can be controlled while slicing has significant role on the print quality. The thinner is the layer, the smoother surface finish can be obtained, but it takes longer time for the slicing and printing process to be completed. After slicing, the filament is extruded. The filament is fed into an extruder which has a motor and drive system to push the filament into hot end. The filament then melts and extruded out of the nozzle in thin thread of soft molten plastic state (Coward, 2015).

The FDM hardware utilizes a system which is also known as melt extrusion additive manufacturing system. It generally involves these four key elements (N. Turner *et al*, 2014), which are:

1. The material feed mechanism
2. Liquefier, print head and gantry
3. Build surface and environment
4. Part finishing

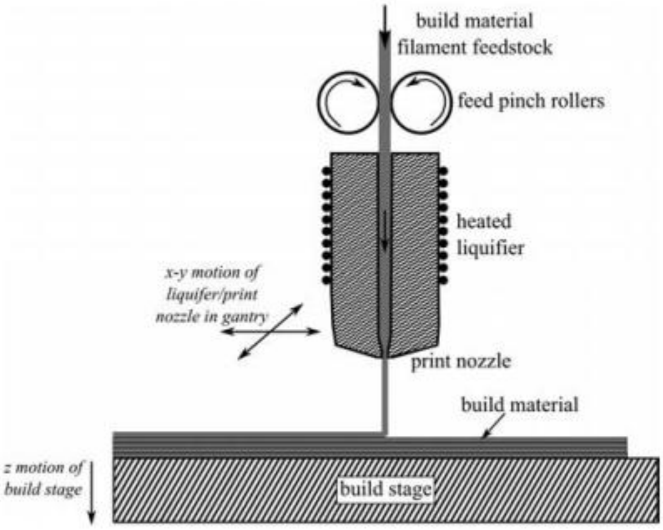

Figure 2.1: Illustration of a typical extrusion based additive manufacturing process (N. Turner *et al*, 2014)

- **Material feed mechanism** is the zone where the filament is fed into. In traditional manufacturing process such as extrusion and injection molding, the feedstocks are usually in granular or pellet form. In additive manufacturing, the working mechanism works on the feeding of filament. In the common filament feeding mechanism, the feedstocks of diameter about 1.5-3 mm, are fed from a cartridge and pushed through the system using a pinch roller mechanism as illustrated in Figure 2.1. The rollers are connected to a stepper motor to provide energy to move the filament. To create adequate friction for the roller to grab the filament, one or both the rollers are usually grooved or toothed. This can also ensure the materials is fed into liquefier without slippage. The presence of moisture in this feed mechanism is undesired as it can cause morphological changes in the material, blockages of print nozzle, and bubble formation on printed part’s surface (N. Turner *et al*, 2014).

- **Liquefier, print head and gantry:** Liquefier zone consists of heat flux that supply heat to the polymer feedstock and melt it. As the polymer is melted, the viscosity drop allows the polymer melt to flow through the print nozzle easily. The higher the temperature, the faster the polymer flow and there will be higher pressure drop as the polymer will become more liquefied. This will make the adhesion between layers become better in the printed parts. However, too high temperature could lead to degradation of polymer chain, leaving the residue in the nozzle.

  The gantry is attached to the print head and liquefier assembly and functions to enable motion in the x and y directions. The size of printed parts is limited by the gantry’s dimensions (N. Turner *et al*, 2014).

- **Build surface and environment**

The build surface (or platform) move in the z direction in conjunction with the gantry’s motion to allow 3D structure to be manufactured. The surface which the melt is printed on is a critical element of the system. The surface material should allow the melt to adhere to the surface, but not adhered too well that it cause difficulty while removing parts when the print process is complete. The temperature gradient between the build surface and the printed part should be optimized. Large temperature gradient might lead to warping and distortion of the printed parts (N. Turner *et al,* 2014).

- **Part finishing**

In additive manufacturing of FDM, ridged surface is inevitable. The ridges size is affected by the dimensions of polymer filaments extruded from the print nozzle. To achieve a smooth surface, chemical smoothing, mechanical smoothing and/or surface coating can be implemented. (N. Turner *et al*, 2014).

2.1.2 Important Parameters and Quality Characteristics in FDM Process

The parameters that affect the print quality of FDM process include: build orientation, deposition speed, layer thickness, raster angle, raster width, air gap, contour width, etc. These parameters are defined as follows:

- *Build orientation* is the direction of orientation of the part on the print platform.

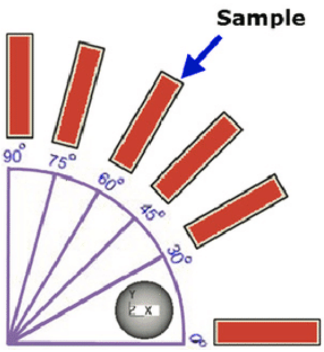

Figure 2.2: Build orientation (Mohamed *et al*, 2016)

- *Layer thickness* is the height of layer being deposited by nozzle tip in the direction of z-axis. It is affected by type of material and tip size.

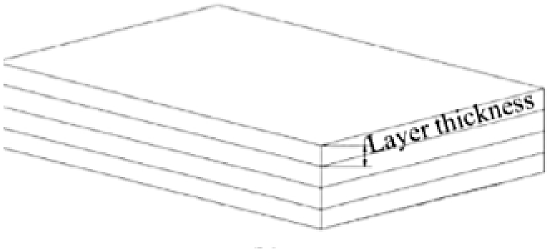

Figure 2.3: Layer thickness (Mohamed *et al*, 2015)

- *Deposition speed* also refers to the printing speed, which is how fast the filament is pushed through feed gear into the nozzle and being deposited on the platform.
- *Raster angle* is the angle of raster with respect to the x-axis.

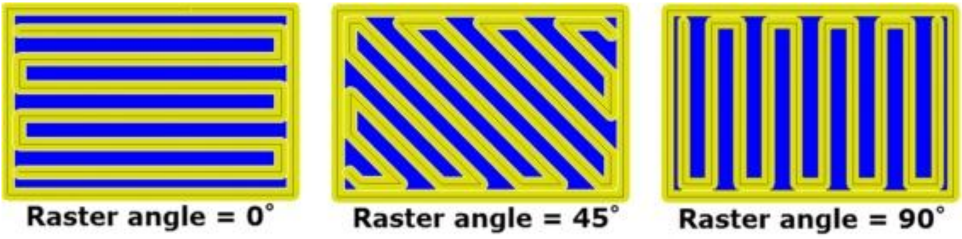

Figure 2.4: Raster angle (Mohamed, 2017)

- *Contour* is the outer part that surrounds the raster. Other tool path parameters are shown in Figure 2.5.

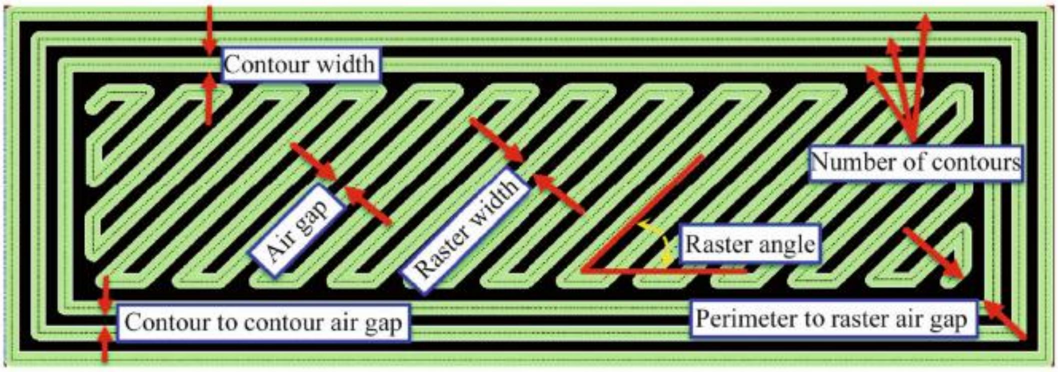

Figure 2.5: FDM tool path parameters (Mohamed *et al*, 2016)

The quality characteristics that were studied can be mainly categorized into five categories, which are the surface roughness, dimensional accuracy, material behaviour, build time, and mechanical properties (Mohamed *et al*, 2015).

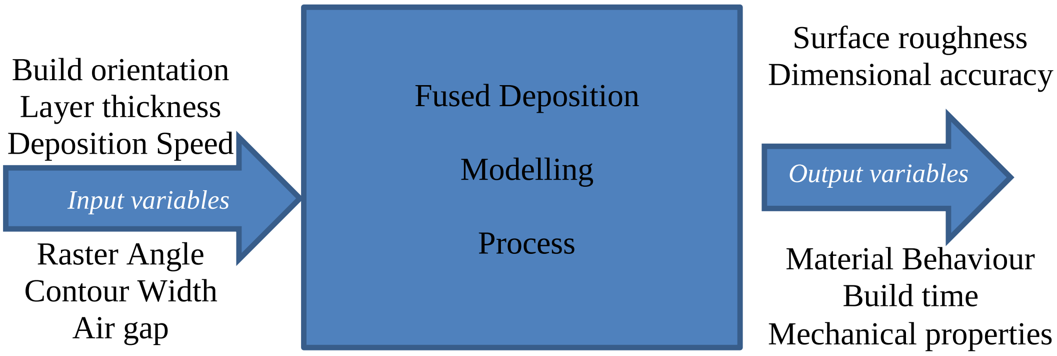

Figure 2.6: Input variables that affect the output responses in FDM

2.1.3 Studies Related to Process Optimization of FDM

The optimization of FDM process is not a novel research and there are several studies done based on more commonly 3D-printed materials (e.g. ABS, PC). These studies are based on investigation of parameters to optimize the print quality of printable materials. For example, there are studies that revealed that layer thickness is the most significant factor when compared with deposition speed and road/printing width, which contributes most to the surface roughness of printed ABS part. In general, higher layer thickness leads to higher surface roughness. This is in line with the findings in one study done by Nidagundi *et al* (2015).

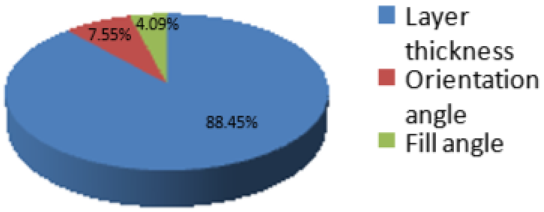

Figure 2.7: Percentage contribution of process parameter on surface roughness (Nidagundi *et al*, 2015)

Mohamed *et al* (2015) had published a review paper the optimization of FDM process. The published work for FDM process optimization are tabulated in Table 2.1.

Table 2.1: Summary of published work on FDM process optimization (Mohamed *et al*, 2015)

References	**Methods**	**Materials**	**Inputs**	**Outputs**	**Significant inputs**
Anitha *et al*, 2001	Taguchi Method	ABS	Layer thickness, road width, speed of deposition	Surface roughness	Layer thickness
Thrimurthulu *et al*, 2004	GA	ABS	Slice thickness, build deposition orientation	Surface finish and build time	All input parameters
Nancharaiah *et al, 2010*	Taguchi method, ANOVA procedure	ABS	Layer thickness, road width, raster angle, air gap	Surface quality and dimensional accuracy	All input parameters
Horvath et al, 2007	2^3 and 3^3 full factorial designs	ABS	Model temperature, layer thickness, part fill style	Surface roughness	Layer thickness
Wang *et al,* 2007	Taguchi method, ANOVA along with grey relational analysis	ABS	Layer thickness, deposition style, support style, deposition orientation	Tensile strength, dimension accuracy and 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, filling velocity, layer thickness	Dimensional error and warpage deformation	All input parameters
Sahu *et al*, 2013	Taguchi method, fuzzy logic	ABS	Layer thickness, orientation, raster angle, raster width, air gap	Dimensional accuracy	All input parameters
Lee *et al,* 2005	Taguchi method, ANOVA procedure	ABS	Air gap, raster angle, raster width, layer thickness	Elastic performance	Air gap, raster angle and layer thickness
Laeng *et al,* 2006	Taguchi method, ANOVA procedure	ABS	Air gap, raster angle, raster width, slice height	Elastic performance	Air gap, raster angle and slice height
Zhang *et al*, 2008	Finite element analysis, CCD & ANOVA	ABS	Scan speed, layer thickness, road width	Residual stresses and part distortion	Scan speed, layer thickness
Nancharaiah, 2011	Taguchi's design, ANOVA procedure	ABS	Layer thickness, air gap, raster angle	Production time	Layer thickness, air gap
Kumar *et al* 2011	2^5 full factorial design, ANOVA procedure	ABS	Layer thickness, raster angle, orientation, contour width, part raster width	Support material volume, build time	All iinput parameters
Ahn *et al,* 2002	2^5 full factorial design	ABS	Air gap, raster orientation, bead width, raster width, model temperature, colour	Tensile strength, compressive strength	Air gap, raster orientation

2.2 ETHLENE-VINYL-ACETATE (EVA)

2.2.1 Properties of EVA

In this project, a new material, which is EVA was tested as the feed filament material for FDM process. EVA is a type of copolymer made up of ethylene and vinyl acetate (VA). The properties of EVA are affected by its VA content. As polyethylene is made of simple structure non-polar molecule, the increase in VA content mainly affect its crystallinity and polarity. Incorporation of VA in polyethylene backbone will reduce the crystallinity, as VA comprised of bulkier side group. The presence of oxygen atom in VA causes it to be more polar, thus increasing the polarity and solubility of EVA (Salyer and Kenyon, 1971).

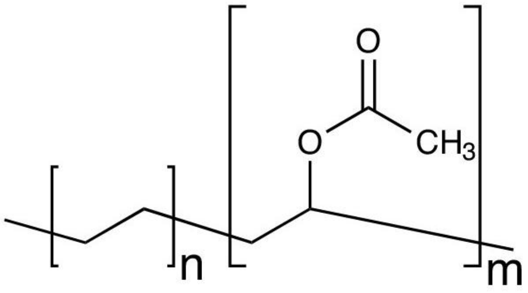

Figure 2.8: Structure of ethylene vinyl acetate (EVA)

EVA are theoretically random copolymer (Arsac *et al*, 2000). It is a type of thermoplastic that possess rubberlike behaviour, like an elastomer, with the increase in VA content. It has relatively low melt temperature and heat softening temperature. According to Arsac *et al* (2000), the melting temperature of EVA usually falls between its corresponding homopolymer: LDPE’s melting point (110–120°C), and softening temperature of poly(vinyl-acetate), 35–50°C. Similarly, glass transition temperature

(Tg) of EVA should have a value in between its own homopolymer, which is LDPE (Tg: –110°C) and poly(vinyl-acetate) (Tg: 28–31°C). Usually, it has relatively low glass transition temperature (Tg), between −35 to −25 °C, depending on the VA content (Schneider *et al.*, 2017).

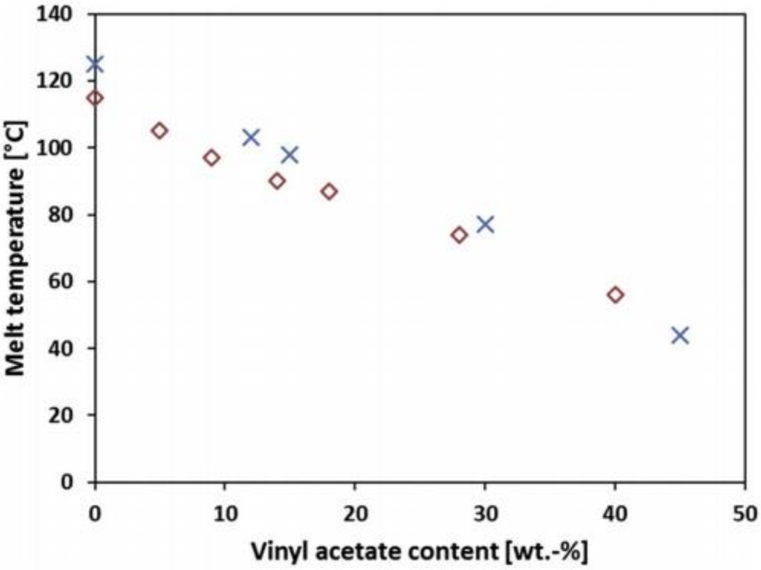

Figure 2.9: Melt temperature of EVA as a function of the vinyl acetate content (Schneider *et al*., 2017)

Other than the ethylene and VA composition, there are two other attributes that will affect the properties of EVA, which are the molecular weight and distribution, and the degree of chain-branching (Salyer *et al*, 1971). The rheological behaviour of EVA, like other polymeric materials, is mainly dependent on the molecular weight and molecular weight distribution. Schneider (2017) reported that increase in VA content tends to reduce the shear sensitivity of EVA, in which the viscosity reduces less when shear stress increases.

In summary:

- **Increase of VA content** decreases the crystallinity of EVA, lower the melting point and glass transition temperature, and increases the polarity and solubility.
- **Increase in molecular weight** leads to increase of viscosity, softening point, impact strength, chemical resistance, and environmental stress crack resistance. However, in contrast to the increase of viscosity, the processability decreases with increase of molecular weight (Henderson, 1993).

The use of EVA in medical and pharmaceutical field had been gaining more attentions and being reported in several studies, due to its biocompatibility and non-toxicity, in addition its usage has been approved by US Food and Drugs Administration (FDA). As FDA first approved a 3D-printed drug in recent years (Prasad *et al*, 2016), the application of 3D printing in medical and pharmaceutical field had gained increased attention. Many studies about the applications of 3D-printing in medical and pharmaceutical had been reported. 3D printing is believed to be revolutionary to medical and pharmaceutical field as it enables the production of personalized drug content with controlled release rate, with almost no harm to human body.

The use of EVA in drug delivery system have been studied and found having good performance in term of drug release rate and safety, as EVA have good low temperature flexibility and eliminate the need for migratory plasticizer in its application. This greatly reduced the risk profile of EVA (Schneider *et al.*, 2017). The absence of plasticizer also makes EVA comparable to PVC (Henderson, 1993). EVA is also biocompatible, and its usage is approved by FDA. These characteristics make EVA