SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

UNIVERSITI SAINS MALAYSIA

COMPARISON OF MECHANICAL, PHYSICAL AND THERMAPROPERTIES OF CONVENTIONAL PLASTICS FABRICATED USING 3D PRINTING AND INJECTION MOULDING

By

NUUR LAILA NAJWA BINTI THAJUDIN

Supervisor: Dr Raa Khimi Shuib

Dissertation submitted in partial fulfillment

of the requirement 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 "Comparison of Mechanical, Physical and Thermal Properties of Conventional Plastics Fabricated using 3D Printing and Injection Moulding". I also declare that it has not been previously submitted for the award or any degree or diploma or other similar title of this for any examining body or University.

Name of Student:	Nuur Laila Najwa binti Thajudin	Signature:
Date:		

Witness by:

Supervisor:	Dr Raa Khimi Shuib	Signature:
Date:		

ACKNOWLEDGEMENTS

First and foremost, I would like to express my heartfelt to Engineering School of Material and Mineral Universiti Sains Malaysia for providing me with the machine and equipment to carry out this research successfully as well as prepared me a suitable and convenient place to proceed my experimental work.

My deepest appreciation and sincere thanks is dedicated to my supervisor Dr Raa Khimi bin Shuib who has helped me improves my thesis provides constructive advice during completing my final year project. This project would not have been possible without his knowledge and moral support.

I owe my sincere gratitude to polymer technician, Encik Norshahrizol bin Nordin and Encik Mohammad bin Hassan for their valuable advice and helped me along my research. I also wish to thanks all the other technician of Polymer Engineering Laboratory at Universiti Sains Malaysia for providing the necessary technical support.

Moreover, my warm thanks to all Polymer Engineering lecturers for providing valuable knowledge during my degree in Universiti Sains Malaysia. My special gratitude to my family and friends for their loving support and to those directly or indirectly helped me to complete my final year project.

My ultimate thanks to the Almighty ALLAH for his endless pleasure bestowed upon me. Thank you

Nuur Laila Najwa Thajudin

May 2018

TABLE OF CONTENTS

CONTENTS PAGES

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATION

$$Impact\ strength = \frac{Fracture\ energy\ (kJ)}{Cross\ sectional\ area\ of\ a\ specimen\ (m)(m)} \text{...(1)}$$

$$Percent\ weight\ loss = \frac{Wet\ weight - Dry\ weight}{Dry\ weight}\ X\ 100\% \text{...(2)}$$

$$\%\ of\ crsytallinity = \frac{sum\ of\ crystalline\ area}{sum\ of\ crystalline\ area + sum\ of\ amorphous\ area}\ x\ 100\% \text{......................(3)}$$

$$v = Kc.t \text{...(4)}$$

LIST OF ABBREVIATION

3D	Three Dimensional
SLA	Stereolithography
SLS	Selective Laser Sintering
DLP	Digital Light Processing
LOM	Laminating Object Manufacturing
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
SDL	Selective Deposition Lamination
UV	Ultraviolet
ABS	Acrylonitrile Butadiene Styrene
PLA	Polylactic Acid
PA6	Polyamide 6 (Nylon 6)
HDPE	High-Density Polyethylene
HIPS	High Impact Polystyrene
PC	Polycarbonate
PET	Polyethylene Terephthalate
TPU	Thermoplastic Polyurethane
PVC	Polyvinyl Chloride
PP	Polypropylene
AM	Additive Manufacturing
RP	Rapid Prototyping
M2M	Machine to Machine
THF	Tetrahydrofuran

CTE	Coefficient Thermal Expansion
T_g	Transition Glass Temperature
T_m	Melting Temperature
FEA	Finite Element Analysis
TGA	Thermalgravimetric Analysis
SEM	Scanning Electron Microscopy
XRD	X-ray Diffraction

COMPARISON OF MECHANICAL, PHYSICAL AND THERMAL PROPERTIES OF CONVENTIONAL PLASTICS FABRICATED USING 3D PRINTING AND INJECTION MOULDING

ABSTRAK

Dalam kajian ini, sifat-sifat mekanikal, fizikal dan terma bagi produk fabrikasi melalui Terlakur Model (FDM) percetakan 3D dibandingkan dengan produk yang dihasilkan menggunakan konvensional plastik peralatan pemprosesan, acuan suntikan. Untuk memeriksa kecekapan dan keseragaman parameter berbanding, pelbagai jenis plastik telah diguna, iaitu, 'acrylonitrile butadiene styrene' (ABS), 'asid polylactic' (PLA) dan 'nylon 6' (PA6). Sifat tegangan dan kekuatan kesan diukur melalui ujian Mesin Universal dan kesan Tester Mesin masing-masing ke atas proses fabrikasi yang berbeza percetakan FDM 3D dan acuan suntikan. Sifat-sifat haba ditentukan oleh Analisis gravimetrik Thermal (TGA) yang mengukur kestabilan haba bagi setiap jenis plastik yang dicetak menggunakan FDM 3D dan acuan suntikan. Analisis SEM telah dijalankan dengan menggunakan Hitachi TM3000 'Scanning Electron Microscopy' untuk melihat kehadiran lompang dan liang dalam sampel bagi kaedah fabrikasi yang berbeza. Pengukuran penyerapan air sampel yang dicetak dan disuntik telah dijalankan mengikut ASTM D570 pada suhu bilik selama 24 jam menggunakan air suling. Ujian kelikatan telah dijalankan bagi mengukur kelikatan menggunakan 'Cannon Ubberlohde Viscometer no.1'. kekuatan tegangan, pemanjangan pada takat putus, 'Young's modulus' dan kesan kekuatan telah didapati lebih tinggi sampel yang direka menggunakan acuan suntikan berbanding sampel dicetak FDM 3D dengan perbezaan peratusan sebanyak 39.7%, 41.8%, 26.9% dan 103% masing-masing. Ketumpatan dan air diserap oleh sampel disuntik ditemui berbanding FDM 3D sampel dicetak lebih tinggi sebanyak 8.4% dan 51.6%Penghabluran, kestabilan terma dan kelikatan yang berkaitan dengan pengedaran molekul antara disuntik dan FDM dicetak sampel didapati setanding.

COMPARISON OF MECHANICAL, PHYSICAL AND THERMAL PROPERTIES OF CONVENTIONAL PLASTICS FABRICATED USING 3D PRINTING AND INJECTION MOULDING

ABSTRACT

In this study mechanical, physical and thermal properties of products fabricated through Fused Deposition Modelling (FDM) 3D printing were compared with products manufactured using conventional plastic processing equipment, injection moulding. In order to check the efficiency and consistency of both fabrication methods, therefore different types of plastics was investigated, namely, acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and nylon 6 (PA6). Tensile properties and impact strength was measured through Universal Testing Machine and Impact Tester Machine respectively. The thermal properties were determined by Thermal Gravimetric Analysis (TGA) which measure the thermal stability for each type of plastic fabricated with FDM 3D printing and injection moulding. SEM analysis was carried out using Hitachi TM3000 Scanning Electron Microscopy to observe the presence of voids and pores in the samples for different fabrication method. Water absorption for printed and injected samples was carried out according to ASTM D570 at room temperature for 24 hours using distilled water. The density of each fabricated plastics were determined using density balance at room temperature. Viscosity test was carried out for each different fabricated samples in measuring the viscosity using Cannon Ubberlohde Viscometer no.1. Tensile strength, elongation at break, Young's modulus and impact strength was found to be higher for samples fabricated using injection moulding compared FDM 3D printed sample with percentage difference of 39.7%, 41.8%, 26.9% and 60.9%, respectively. Density and water absorbed by injected samples were found higher compared FDM 3D printed samples by 8.4% and 51.6%. Crystallinity, thermal stability and viscosity related to molecular distribution between injected and FDM printed samples were found comparable.

CHAPTER 1

INTRODUCTION

1.1 Background

3D printing technology is a trendy processing method which gets attention in engineering area, particularly for fabrication of automotive parts, architecture, household appliances, aerospace and aircraft as well as medical equipment. This technology plays an important role in the recent movement of fourth industrial revolution (Industry 4.0) which introduces computerization in the designing and manufacturing process. The method can be simplified as a cyber-physical system which is controlled and monitored by the computer-based program (Stansbury and Idacavage, 2016) and therefore, a customized specific engineering design can be reproduced from the 3D model and the manufacturing process can be carried out instantaneously. The usage of 3D printing would definitely improve the success rate, cost and time saving with satisfying final products by fulfilling all the requirement of chemical, physical and mechanical properties (Howie, 2017).

3D printing technology basically referred as additive manufacturing which produces the 3D solid objects from a digital model such as CAD (computer-aided design (Howie, 2017). This printing technology applies the concept of built-up where the material is printed layer by layer until the desirable products obtained. Through this concept, reduction of waste can be achieved as the exact amount of material being used for the preparation of any product.

The oldest method of 3D printing was invented by Charles Hull was known as “stereolithography (Howie, 2017). The process of printing involves a uniquely designed 3D printing machine called a stereolithography apparatus (SLA). In SLA method, the hardened liquid plastic was converted to form 3D solid objects. The liquid plastic is solidified using the UV laser beam and the process repeated simultaneously layer by layer. This method enables several different materials to be printed in a single process. Selective laser sintering (SLS) was introduced soon after the SLA. SLS is a technique that used a laser as the main power source to form 3D solid objects (Raney et al., 2017). Next, the Digital light processing (DLP) known as optical technique was introduced. This method uses a light projector operating at UV wavelength to cure the resin and solidify followed the design (Bogue, 2013). Laminating object manufacturing (LOM) is one of 3D printing that use the mill-working system to get thin layers of material to produce 3D object (Ashley, 1993).

Another famous technique in 3D printing technology is Fused Deposition Modelling (FDM) invented by Scott Crump, Stratasys Ltd. founder, in the 1980s. FDM is widely used in 3D printing as it involves the fused filament fabrication or thermoplastic extrusion (Ahlbrandt, 2014). This method is similar to the extrusion and injection moulding but no moulds are needed. The capability of FDM to produce complicated design parts in a short period of time make FDM one of the favourable method in 3D printing technology (Howie, 2017).

FDM 3D printer is a revolution of a normal printer as it uses three robotic stages, x,y and z in producing a desirable product. FDM offers several distinct advantages when compared to conventional plastic processing equipment that includes no tools and moulds which reduce the cost and time consumption, flexibility in changing the design, easy to produce the prototype, design customization, practical and cost-effective. Furthermore, FDM method able to produce a high dimensional accuracy of parts which make it possible to manufacture complicated prototype and final products. This research work focused on FDM due to ease of operating and cheaper 3D printing process (Othman et al., 2017).

In FDM method, selection of filament material is important as the printing process involve extruding thermoplastics one layer at a time. There are a few potential plastics that are usually used in FDM such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), high impact polystyrene (HIPS), and high-density polyethylene (HDPE) (Lee et al., 2017a). ABS is the most common filament material used because of ease of processing and cheaper compare to other filament materials (Wang et al., 2017c). PLA has also become a very popular choice of filament in the FDM as it has low toxicity and is more environmentally friendly that make it expanding in medical application intensively. Other filament materials that can be used in FDM include nylon 6, polycarbonate (PC), polyethylene terephthalate (PET) and thermoplastic polyurethane (TPU) (Dilberoglu et al., 2017).

In general, 3D printing particularly FDM method aimed at replacing the injection moulding as it is one of a common method used for plastic processing in the polymer industry. Plastic injection moulding is an extremely versatile method of producing accurate plastic parts and products (He et al., 2011). It is one of the preferred methods for traditional manufacturing parts because it has multiple advantages over other methods of plastic processing such as blow moulding, extrusion and thermoforming. Injection moulding follows a few steps such as resin pellets are placed inside hopper and heated, the barrel is heated at several temperatures follows the properties of the material and the melt polymer is injected into the nozzle with aid of hydraulic, pneumatic or electronic (He et al., 2011). The mould is filled with the melted polymer and being cooled follow the cycle time. Injection moulding has the removal of excess materials in term of runner and sprue. One of a major problem that plastic injection moulding encounter is the formation of meld line and weld line. These lines are formed when the material meet up in between of the mould. The lines sometimes can be either external imperfection or structural failure (Ashley, 1993). Injection moulding also has limitation such as high initial tooling cost and part design restriction. The process of designing tools and mould fabrication is extortionate as it involves high-cost material and complex fabrication method. Apart design consideration is very important in moulding design as it leads to the quality of the products. FDM method is one of the 3D printing technique which is introduced to overcome the limitation of injection moulding.

In the present study, the performance of three different type of plastic materials, ABS, PLA and nylon 6 fabricated using two different methods fused deposition modelling (FDM) and injection moulding is compared based on their physical, mechanical and thermal properties. All three materials were chosen due to to its printing properties aligned with the available FDM 3D printer.

1.2 Context and rationale

Injection moulding is the most commonly used process in the plastic industry. The limitation of injection moulding which regularly produce defects due to fluctuation of processing parameters (He et al., 2011) such as temperature, pressure, flow rate and screw speed during the process motivates researcher to introduce much more convenient and less defective process known as 3D printing. 3D printing can work with at great range of unique and customized products based on the design. 3D printing and injection moulding are not competing, but it is a complementary way of manufacturing. Development of 3D printing in plastic processing is still in its infancy compared others plastic processing methods.

In this study, the performance of 3D printing and injection moulding are compared in term of mechanical, thermal and physical properties. As can be seen, both processing has its own limitation. Even though there are a lot of advantages to injection moulding but there are still some limitations when it comes to injection moulding process. Major limitations of injection moulding are that the initial tooling of the mould and the machinery are very costly. Mould modification is always involved in injection moulding. To make any modifications to the final part, the moulds need to be modified. However, it is difficult to modify the mould as it made of steel. Besides, the setting parameters and operating method are essential in determining the quality characteristic of the parts (Othman et al., 2017). If we do not control the parameters set up, it will lead to defects such as short mould, warpage, weld and meld lines and blister.

3D printing consists of different methods of printing. Several parameters in 3D printing play an important role in specifying the properties of printing process such as fabrication speed, quality, cost, resolution, surface finished and part strength (Lee et al., 2017a). Each technique has its advantages and disadvantages mostly depends on three criteria, material selection, a method of fabrication and resolution(Wang et al., 2017b).

However, 3D printing also lacks in time consumption aspect as the printing process for a single part takes significantly longer than a single injection moulding cycle. One of the key limitations of 3D printing is the inability to make parts with the same physical properties as conventional injection moulded parts. Besides, 3D printing also creates defect such as poor surface finish, z-wobble and bridging.

Presence of defects in both processing gives effects in the mechanical, thermal and physical properties of the plastic. Therefore, a substantial study on the mechanical, thermal, and physical performance between 3D printing and injection moulding is essential in order to understand the relative importance of processing using 3D printing compared to injection moulding.

3D printing has a great outcome in designing and optimising FDM method to achieve high-quality processing and excellent finished products. However, according to author's knowledge, no comprehensive work was dedicated to compare the performance of the different types of conventional plastics processed by FDM and injection moulding.

Therefore, it is essential to compare the performance of mechanical, physical and thermal properties for different types of plastics for both fabrication method.

1.3 Research aim and direction

The objective of this research was to compare the performance of the different type of materials fabricated using two different methods, 3D printing and injection moulding. The specific research objectives are as follows:

i. To compare the mechanical performance of the different type of conventional plastics manufactured by 3D printing and injection moulding.

ii. To investigate the difference in physical properties and microstructure of different types of conventional plastics manufactured by 3D printing and injection moulding.

iii. To evaluate and compare the thermal properties of the different types of conventional plastic manufactured by 3D printing and injection moulding

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to 3D printing

3D printing is one of the plastic manufacturing methods in which an object is made by fusing or depositing materials to form a 3D solid. 3D printing is also referred to as additive manufacturing (AM), rapid prototyping (RP) or solid free-form technology (H, 2013). There are many types of 3D printing method which varies in technologies, speed, resolution, and materials such as stereolithography (SLA), selective laser sintering (SLS), digital liquid processing (DLP), laminating object manufacturing (LOM) and fused deposition modelling (FDM) which applies the same principle of drawing of objects before printing. The drawing of objects can be transferred to 3 dimensions using computer-aided design (CAD) file. Construct the foundation of the objects and moving the print head along the x-y plane is the basic steps of CAD file (Ventola, 2014). Figure 2.1 below shows the product development using 3D printing from designation until manufacturing process. 3D printing is actually a fast, simple and economically practical method of producing models directly from 3D CAD. All type of technique producing a model of 3D printing actually follows basic steps below (Mahindru et al., 2013, Rengier et al., 2010):

i. Creation of CAD model for design.
ii. Convert CAD model into STL file.
iii. Slice STL model in thin cross-sectional layers.
iv. Construction of model layer by layer.
v. Create and finish the model.

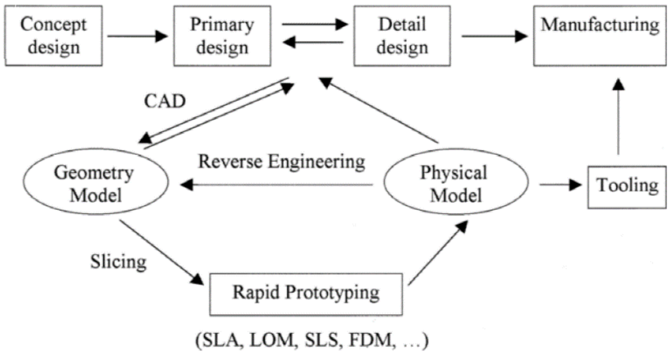

Figure 2.1: product development with 3D printing(Othman et al., 2017)

2.2 Roles of 3D printing in Industrial 4.0

3D printing is one of latest movement in Industry 4.0 as it implies the robotic technology in producing products. It also offers in the physical and cyber system as it involves in computing all the input in producing desirable parts (Dilberoglu et al., 2017). The technology of 3D printing actually gives impact to manufacturing companies through smart services such as predictive maintenance, installed data sources, field service efficiency and service profitability (Bechtold et al., 2014). It believed to reduce human-machine interaction and advanced in the machine to machine (M2M) communication by replacing the traditional equipment such as injection moulding and extrusion (Report, 2015). 3D models help in speeding the manufacturing market by creating a new desktop manufacturing which implies total digital transformation. Within five years, 85% of spare parts suppliers will incorporate 3D printing into their business due to a high level of service with low-cost manufacturing (Dr. Reinhard Geissbauer, d'Aveni, 2015). Fabrication of customized finished-products or prototypes makes 3D printing one of developing technology in Industry 4.0. The advancement of 3D printing technology by replacing the common conventional processing method such as injection moulding is due to its high production speed with an excellent accuracy of parts. Although 3D printing has its drawback in repeatability and cost which is not preferred in mass production of regular parts, 3D printing enables a large range of processing in term of materials, size and functionality (Huang et al., 2015). Figure 2.2 shows the schematic relationship of physical-cyber technologies.

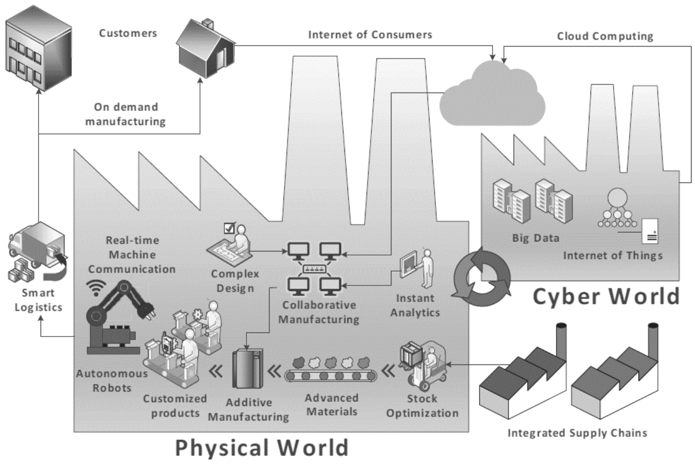

Figure 2.2: Schematic of smart factories with general properties required in Industry 4.0 (Zhou et al., 2017)

2.3 Challenges of 3D printing

As 3D printing is currently developing, it encountered several challenges in term of manufacturing and producing products or parts (Petrovic et al., 2011). Development of multi-materials and the multi-colour system is one of the challenges as favourable mechanical characteristic products need to be obtained. Furthermore, post-processing usually needed in 3D printing which helps to improve smooth surface prints (Huang et al., 2013). A certain type of 3D printing products needs a support structure before and during printing. This support structure cannot be recycled thus it needs to minimise by adjusting the good build-up orientation of the printing. Intellectual property issues regarding copyright is another main concern for engineer handling 3D printing as it only involves computing the data of the design (Berman, 2012, Chen et al., 2015, Petrick and Simpson, 2013).

2.4 Advantages of 3D printing

Current technology of 3D printing is expanding due to several advantages such as zero specialization of tooling or mould, enable to change design followed desired design rapidly, waste reduction due to the printed design followed exact dimension with high accuracy, able to customize products and equipment, short processing times for low inventories and good quality (Malik, 2017). Excellent quality of products can be predicted at the designation stage. During designation stage, the finite element analysis (FEA) can be carried out before printing to help in evaluating the manufacturability of the design in term of motion, mechanical stress, force, vibration, heat flow and physical effect. (Lipson and Kurman, 2013). Increased cost efficiency is one of the main benefit offered by 3D printing. Conventional traditional methods truly less expensive in large mass production but for small size production, 3D printing becomes more competitive as it can give large benefits through it (Ventola, 2014). Moreover, 3D printing can minimize the processing cost by reducing the non-essential resources. 3D printing also can increase the productivity of products that required milling, forging and long delivery time (Ventola, 2014). Several arrays of materials can be used in printing technology which allows the user to design their imaginary products and reduce the manufacturing cost. Evolution of 3D printing gives significantly to the price and technical specification which in future benefits the society, economy and environment.

2.5 Applications of 3D printing

Automotive, aerospace, medical and consumer goods are main industries that capitalize the 3D printing technology (Bogue, 2013). Medical sector has aimed the 3D printing in producing medical parts and human implants as 3D printers provide custom-made medical products and equipment which are fast and cost-efficient (Ventola, 2014). But in the medical sector, it has some limitations as only a few 3D printing materials are not harmful to be placed inside human body (Sons, 2016). Aerospace and automotive sectors also focus on 3D printing technology in producing products as it improved functionality and maximise performance (Bogue, 2013). Furthermore, 3D printing technology is also broadly used in food sector due to many benefits such as customized food design, reduce the complexity of food chain, personalized nutrition and expanding of available food material (Liu et al., 2017). Sectors for the military, outer space food and sweet food including ocean world mostly used products made of 3D printing (Liu et al., 2017). 3D printed component has been used quite a lot in underwater such as 3D printed coral reef is used to replace the existence of damaged coral reef (Mohammed, 2016). Table 2.1 explained current applications developing through 3D printing.

Table 2.1: Current applications using 3D printing

Application	Materials	Reference
Biodegradable scaffold and other medical device	PLA	(Kutikov et al., 2014, Senatov et al., 2016, Malik, 2017, Ngo et al., 2018, Economidou et al., 2018)
Electronic device	Carbon black/PCL	(Leigh et al., 2012, Flowers et al., 2017, Lee et al., 2017b, Sochol et al., 2018, Zarek et al., 2016)
Engine exhaust and turbine blade	Metal	(Appleyard, 2015, Watkins et al., 2013, Murr, 2016, Lee et al., 2017a)

2.6 Type of 3D printing

There are several methods of 3D printing technology available in the market for plastic processing. All method of 3D printing is additive manufacturing but only different in the way of building layers to create a specific product.

Table 2.2: the types of current 3D printing available in the manufacturing of plastic products (Lee et al., 2017b)

Technique	State of starting material	Materials	Advantage	Disadvantage
FDM	Filament	Thermoplastics such as PC, ABS, PLA and nylon	Low cost, good strength and multi-material capability	Anisotropy and nozzle clogging, required a support structure, grainy appearance
SLA	Liquid photopolymer	Photo-curable resin	High printing resolution	Materials limit, high cost
SLS	Powder	PCL and polyamide powder	Good strength and ease removal of support powder	High cost
DLP	Liquid photo-polymer	Photo-sensitive polymer	Faster than SLA	Small build size, Materials limit
LOM	Plastic film	Thermoplastic	Fast build-up, relatively cheap	Poor strength, newly printed parts required post-processing

Table 2.2 shows the types of current 3D printing available in manufacturing plastic. All types of 3D printing have its advantages and disadvantages followed their own characteristics of machine, parameters and material involved. Therefore, the advantages and limitation will be discussed specifically in the following section.

2.6.1 Stereolithography (SLA)

Commercialization of 3D printing technology started with Stereolithography (SLA) in 1986. SLA works as the polymerisation of liquid resin polymer by exposure to ultraviolet (UV) light laser to build products layer by layer at one time (Chu et al., 1998). The laser beam detects each layer of cross-section on the surface of polymer resin. The basic structure is in hanging position and for SLA, the platform is formed to support the pieces. After finished printing, the excess materials can still be used for next printing. The finished products then being cleaned from excess polymer resin and the support structure is removed (Stansbury and Idacavage, 2016). Figure 2.3 shows a schematic diagram of SLA printing.

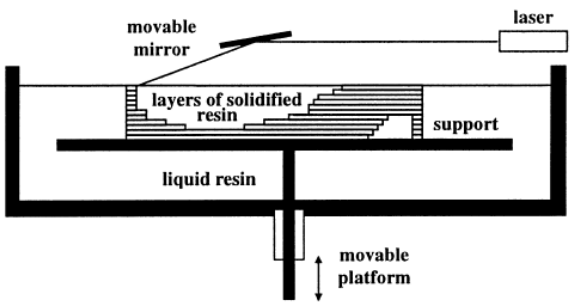

Figure 2.3: Principle of Stereolithography (Rosochowski and Matuszak, 2000)

Stereolithography method is specifically efficient for highly complex production (Barker et al., 1993). SLA is favourable in biomedicine application such as modelling for implantation of an organ inside the human body due to high-resolution printing which creates a smooth surface and enables to print with high precision and fine detail (Lee et al., 2015). Although SLA is favourable in the medical sector it has a few limitations such as fragility and unit production. The production of SLA is very low thus it is not suitable for mass production. As SLA print detailed design which resolution, it consumes high cost which leads to the disadvantage of the printing. SLA use liquid resin polymer as a starting material in their processing. Table 2.3 shows the most common liquids resin use in SLA printing.

Table 2.3: Common liquid resin polymer used in SLA printing (Latouche)

Engineering SLA resin	Advantage	Disadvantage
Tough resin (ABS)	High stiffness, Excellent resistance to cyclic loads	Relatively brittle, Not suitable for thin wall products
Durable resin (Polypropylene-like)	High wear resistance, Flexible	Low tensile strength
Heat-resistance resin	Smooth surface finish	Brittle
Rubber-like resin	Low hardness, High flexibility	Requires support structure
Ceramic filled resin	High stiffness, Moderate heat resistance	Brittle, Low impact strength

2.6.2 Selective Laser Sintering (SLS)

Selective laser sintering is introduced right after SLA in which this technique depends on two energy sources to finish the product processing. Semi-crystalline thermoplastic pre-polymer is utilized as a building material in SLS (Stansbury and Idacavage, 2016). SLS use high power laser to produce parts or object by fusing the plastic particles in a mass layer by layer as can be seen in Figure 2.4.

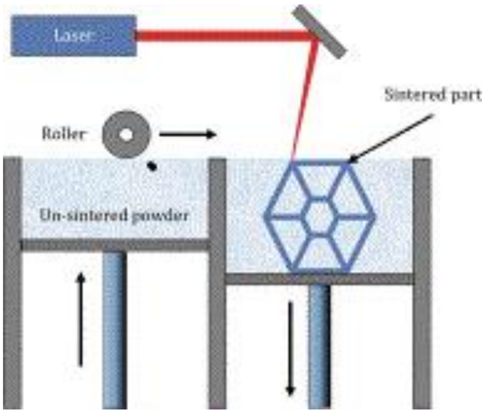

Figure 2.4: SLS approach using scanned laser (Stansbury and Idacavage, 2016)

The high power laser fuses the resin material by scanning the cross section of the products through the 3D model. The cross-section is examined and the powder bed is lowered by a layer thickness. A new layer of material is applied on top and the process is repeated until desirable products obtained (Ahlbrandt, 2014). Example of products that produced from SLS process are houseware, electronic housing, medical device and consumer products. SLS is mostly for products that require durability and functional parts, large and complex parts with economical prices. These products are suitably processed using SLS due to several advantages such as variability in the type of materials, fabricated porous components that increase their strength and surface finish and limited use of support structure (Yan et al., 2017). Material replacement for SLS process is much more difficult compared to SLA and FDM and need post-processing or finishing limits SLS as a favourable type of 3D printing. Polyamide 12, alumide, polyamide glass-filled and rubber-like thermoplastic polyurethane are common material that is used in SLS process.

2.6.3 Digital Light Processing (DLP)

Digital light processing is one of 3D printing method that utilised light and photo-sensitive polymer (Varghese et al., 2018) as can be seen in figure 2.5.

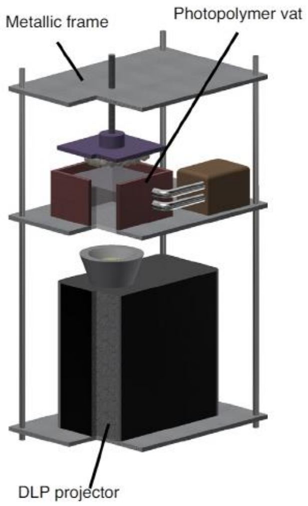

Figure 2.5: Schematic diagram of DLP(Varghese et al., 2018)

DLP is similar to SLA but the difference is that it uses light as the main source to print an object and can be photo-cure in high-speed cycle times between layers. When the platform moved up and down, the polymer resin is then solidified layer by layer (Stansbury and Idacavage, 2016). DLP can be used in a high range of monomer and resin systems. Advantages of using DLP in certain applications such as highly detailed artwork and casting for mould making is mainly because of the high printing speed which reduced the time by producing streamlined products and the end product matched accurately with CAD design with high strength and functional (Lee et al., 2017b). The main limitation of DLP is that the printed products are expensive due to outstanding printing properties. The consumable material used for DLP photo-polymer should be sensitive to ultraviolet radiation such as methacrylic acid ester and urethane acrylate (Gargitter).

2.6.4 Laminating Object Manufacturing (LOM)

The laminating object manufacturing (LOM) performed by the layering of plastic sheet or films which is then cut and laminated to form objects or prototypes (Varghese et al., 2018). This process needs to be repeated certain period of time to laminate layer by layer of plastic sheets or films until the desirable products obtained (Junk and Bambach, 2017). This method of 3D printing needs the aid of adhesive coating for bonding of individual sheet of materials to strengthen the layers. Another laminating system is known as selective deposition lamination (SDL) which is used only paper as a building material and can print numerous of material with restriction (Low et al., 2017). Figure 2.6 shows the machine structure of laminating object manufacturing that commonly used in 3D printing industry. LOM is a simple process which is very cheap, fast, good handling strength and the printing accuracy depends on the layer of thickness produced and type of material used. This printing method mainly for thermoplastic processing part such as polyvinyl chloride (PVC), composite and paper. Only limited 3D geometries can be printed through LOM and this makes it suitable for making any simple prototypes. Another major limitation of LOM is impotent in making hollow products.

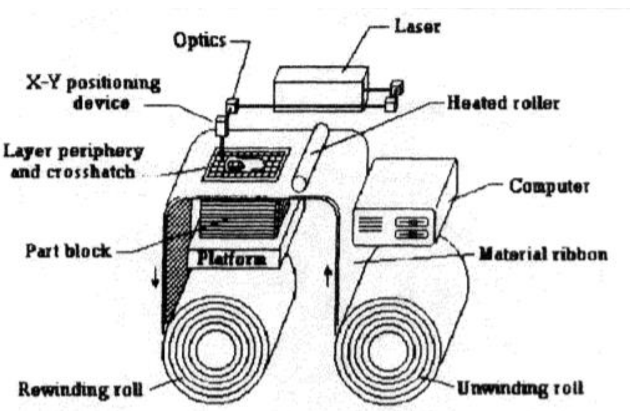

Figure 2.6: Machine structure of LOM (Feygin and Hsieh, 1991)

2.6.5 Fused Deposition Modelling (FDM)

FDM is a common technique of 3D printing, invented by Scott Crump, Stratasys Ltd. founder, in 1980 (2014, Ferreira et al., 2017). Fused filament fabrication (FFF) is another technique introduced by Scott Crump right after FDM (Balletti et al., 2017). Both FDM and FFF technique involves lamination of liquid plastic materials. In FDM, to form a printed object, the heated nozzle head moves across the cross-sectional area and the thin materials are deposited layer by layer. Figure 2.7 shows the working principle of fused deposition modelling process.

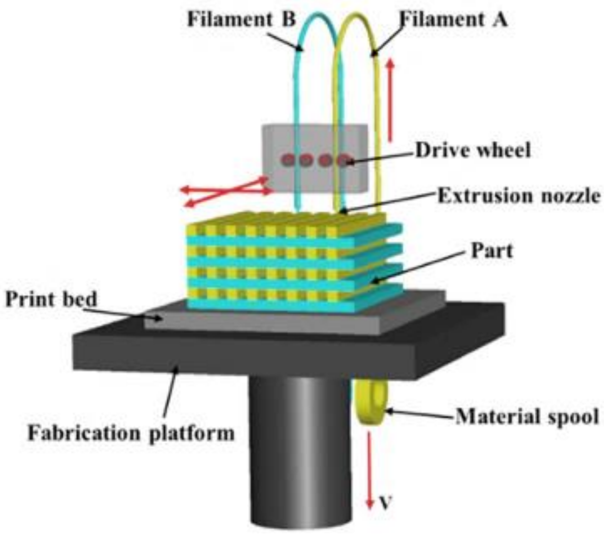

Figure 2.7: Fused Deposition Modelling (FDM) process (Wang et al., 2017c)

This technique involved two modelling materials which represent the finished pieces and a gel-like support material (Bogue, 2013). The printing process must be carried out in a closed chamber which held within the melting temperature of the filament material (Heynick and Stotz, 2006). Moreover, FDM is by far the most commonly used method for 3D printing after SLA due to low cost and user-friendly. A broad range of filament material which printing with multicolour filament is also preferable and accessibility for the user will fewer skills is possible given the standard operating procedure (Lee et al., 2017b). The major drawback of FDM is that the material must be in filament form for printing. Filament shape usually has a un-homogenous mixture of materials which create more voids and thus reduced the properties of the filament (Wang et al., 2017c). The filament material used for FDM printing process is limited to a thermoplastic polymer with proper melt properties. The polymer with low melt viscosity such as polypropylene (PP) is difficult to print through FDM because easily melt inside the nozzle and cannot be easily extruded. Example of FDM method is an automotive application which makes gearbox prototype using FDM in order to visualize the performance of functionality and accuracy of the parts in a real situation before proceeding with mass production (Novakova-Marcincinova and Novak-Marcincin, 2012).

2.7 Important Parameter in Fused Deposition Modelling

There are certain parameters that affect the properties of printed FDM parts such as air gap, a layer of thickness, raster angle, raster width, the speed of deposition and orientation of printing (Brock et al., 2000, Anitha et al., 2001) in improving dimensional accuracy and increase strength of the parts. Taguchi method is used to study the relationship between the mentioned parameter and design optimization for products properties (EQUBAL et al., Basavaraj and Vishwas, 2016). The result showed that layer of thickness and orientation of give huge impact in increasing mechanical properties of FDM 3D printed products.

2.7.1 Air gap

The air gap is between adjacent raster on the same layer which can be either positive or negative gap. As for the positive gap, the beads of material do touch and through this, a loose structure can be built faster. A negative gap of beads requires a long period of build time as it takes times for two beads occupy same space. Based on

(EQUBAL et al.), it is shown that air gap does not give significant impact on dimension and accuracy but give affects the strength of printed products.

2.7.2 Orientation of the printing

Orientation is the main critical concern during printing as it leads to good mechanical strength of the printed parts(Brock et al., 2000). Figure 2.8 explained about the orientation of printing which consists of 0^o, 45^o and z-direction. 0^o and 45^o direction create more pores compared to the z-direction. Thus, z-direction is believed to exhibit good mechanical strength compared to other orientation(Quan et al., 2018).

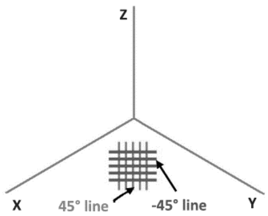

Figure 2.8: orientation of printing line (Quan et al., 2018)

2.7.3 Layer of thickness

A layer of thickness is the thickness of the layer deposited by the nozzle and the thickness depends on the size of the nozzle used during printing. This parameter affects the properties of the printed parts such as surface quality, dimension accuracy and tensile strength (Basavaraj and Vishwas, 2016). A thinner layer of printing gives better bonding strength and give good axial load capability between the printed layer which improves the elastic performance of the printed parts (Sood et al., 2010, Abbas et al., 2018). Figure 2.9 shows the example of layer thickness during printing.

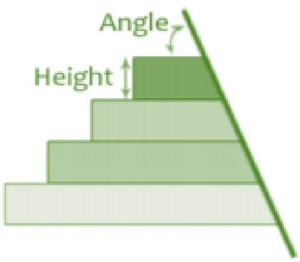

Figure 2.9: Layer thickness during printing process (Basavaraj and Vishwas, 2016)

2.7.4 Raster angle

Raster angle is known as a direction of raster relative to the x-axis of the platform plate as shown in Figure 2.10. This cause the alignment of the polymer molecules along the direction of deposition during printing which affects the tensile and impact strength of the printed sample(Sood et al., 2010).

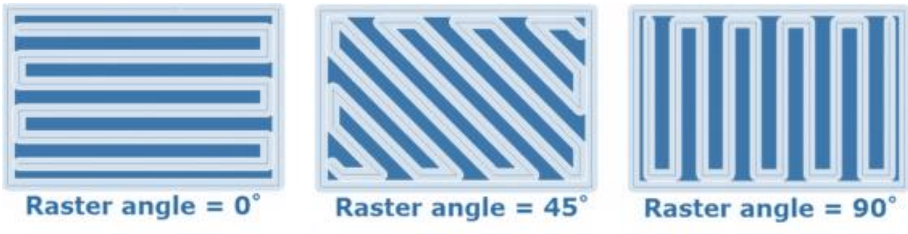

Figure 2.10: raster angle of FDM printing (Mohamed et al., 2017)

2.8 Properties of filament materials for Fused Deposition Modelling

Properties of polymers for preparation of filament materials before printing is very imperative as it affects the parameter during FDM printing. The main properties that affect the printing are that the microstructure of the polymer itself. The other properties of polymers that have large contribution are melting temperature (T_m), glass transition temperature (T_g) and coefficient thermal expansion (CTE) (Howie, 2017). During printing, the chosen polymer will be extruded through the nozzle to form a constant cross-section of filaments followed the T_m of the polymer. T_g and CTE correlated as it shows the development of thermal stress which can affect the adhesion between the support structure and the platform of printing (Hashemi Sanatgar et al., 2017). The most common materials that used in FDM printing is thermoplastic polymers consist of amorphous and semi-crystalline structure (Malik, 2017).

2.8.1 Crystalline Structure

The crystalline structure of a polymer arranged aligned and packed in a regular way tends to produce a filament with compact and straight structure shown in figure 2.8.1. A method that can be used to reinforce the interfaces is known as co-crystallization which improved through interlayer bonding between the filament. As for semi-crystalline filament, it has a core-shell structure in reducing the distortion and increase the interlayer strength through varying the crystallization temperature (Kishore et al., 2016).

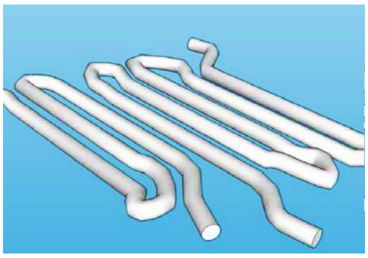

Figure 2.11: Crystalline polymer filament (Howie, 2017)

2.8.2 Amorphous Structure

An amorphous polymer is more flexible and can elongate more during extrusion of the filament. Amorphous filament tends to have more freedom of movement as the molecular chains further apart and this creates a more flexible filament. Some polymer tends to produce zig-zag filament structure as shown in Figure 2.8.2 during extrusion which gives us irregular shape and this lead to defects during printing. The inter-diffusion between the printed layer of amorphous filament is known as primary bonding which creates a strong bond between the molecules thus increases the strength and flexibility of the filament (Kishore et al., 2016).

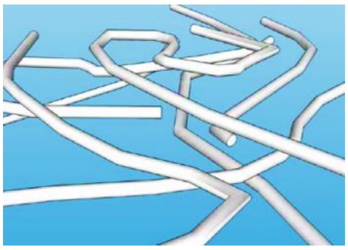

Figure 2.12: Amorphous polymer filament (Howie, 2017)

2.9 Filament Materials used in Fused Deposition Modelling

Thermoplastics with proper melt properties and thermoplastic elastomers are common types of materials that can be extruded to prepare the filament for FDM printing. Table 2.4 shows the summary of common material used in FDM process.

Table 2.4: A summary of materials used in FDM 3D printing technique (Lee et al., 2017a)

Materials	Properties	Application/ industries
ABS	Tough and strong	Automotive, aerospace and medical
Nylon 12	Good chemical resistance, high fatigue resistance and high impact strength	Ideal for impact protective component (automotive and aerospace)
PC	high tensile and flexural strength	Functional prototype, tooling and features (aerospace and automotive)
PLA	Good tensile strength and surface quality	Medical parts
TPU	Excellent wear and tear resistance, high impact strength and hardness	Industrial chemical and oil, sealant and gasket

2.9.1 Thermoplastic Polymer

2.9.1.1 Acrylonitrile butadiene styrene (ABS)

Amorphous ABS is a commonly used plastic in filament making as the plastic melt then reforms into tough, glossy and impact resistant material (Tymrak et al., 2014, Tran et al., 2017). Due to easy to shape but tough to break as it contains rubbery polymer, butadiene, ABS is very suitable for 3D printing. The major drawback of ABS filament is high glass transition temperature (T_g). This is difficult in controlling and maintaining the internal thermal stability stress at the initial stage as it causes warping and the sample tends to peel off from the platform plate. ABS filament is hazardous as it releases toxic and unpleasant gas when melting thus cause headaches. Printing of ABS filament needs to be carried out in the closed chamber as it is not an environmental friendly material in order to prevent any hazard from occurred (Howie, 2017).

2.9.1.2 Polylactic acid (PLA)

As for semi-crystalline PLA, it cools quickly to form a tough, resilient, opaque materials but cannot withstand high heat compared with ABS (Tran et al., 2017). PLA is preferred for 3D printing because it is easy to print as it filament flow according to the orientation and do not wrap. Low shrinkage and no warping of sample PLA make it beneficial in FDM printing as it can adhere to the platform tightly and low platform temperature is enough (Howie, 2017). Low thermal stability and impact strength limit this material as an excellent structural material compared to other material. PLA is preferable in medical sector as it is a natural polymer that can degrade and decompose by itself after a period of time through hydrolysis and enzyme activity (Athanasiou et al., 1998).

2.9.1.3 Nylon

Nylon is one of the popular filament material used in FDM printing process due to several factors such as good toughness, high flexibility, resistant to heat and wear and good adhesion between Z-layers. Although nylon is flexible it tends to wrap while printing because of high coefficient of thermal expansion. Furthermore, nylon is a hygroscopic material which needs to be dried first before printing to remove the presence of air moisture (Howie, 2017). Nylon is also used as commercial implant material due to good compatibility between human tissue (Rahim et al., 2016).