



A Brief Study on Three-Dimensional Printing Focusing on the Process of Fused Deposition Modeling

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<p>Abstract:</p> <p>The Main theme of this thesis is to provide technological review of the rapid prototyping techniques along with the basics of 3D printing technology, it's history and scopes in the future. An important part of the thesis is to study different types of 3D printing techniques and the materials suitable for respective techniques. Among several types of 3D printing, Fused Deposition Modeling (FDM) is one for creating new and innovative products through the process of layer by layer deposition of the material. The case part of the thesis, Minifactory III, involves experiments with a budget 3D printer kit, beginning from the assembly phase. Different Products using different kind of plastics were printed using the printer. Guidelines provided by the Minifactory III was useful for determining the physical conditions of the printer during extrusion and it also provided detailed information on how the printing should be carried. Physical conditions that was required for respective plastics was also evaluated for further experiments. This thesis is also able to explain the design considerations that need to be taken before printing and also mentions the type of problems that may occurred during the process.</p>	
Keywords:	3D printing, Laser sintering technique, FDM technology, Stereo lithography, online 3D printing services, Material extrusion, Minifactory III
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Abbreviations

3D	Three-Dimensional
AM	Additive Manufacturing
3DPT	3D Printing Technology
SLS	Selective Laser Sintering
SL	Stereo Lithography
SLM	Selective laser melting
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
RP	Rapid Prototyping
ABS	Acrylonitrile-Butadiene-Styrene
PLA	Poly Lactic Acid
STL	Stereo Lithography File Format
WAAM	Wire and Arc Additive Manufacturing
UV	Ultraviolet

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1 Introduction

Technology always signifies the innovation of new things by creating and following a system to continue the human civilization. The manufacturing sector is always giving rise to more efficient manufacturing process. Most traditional production processes require the creation of tools, patterns and molds that are used during manufacturing to shape metals and plastics into appropriate forms. Like product prototypes, items have traditionally been crafted by hand in a manner that has proven both time consuming and expensive. In order to exclude these limitations of traditional manufacturing process, various information are being gathered on new manufacturing process known as rapid prototyping (RP). (1-2)

1.1 3D Printing and Fused Deposition Modeling

Most of the traditional manufacturing systems are based on the subtraction of material involving milling or cutting of the material into small desired shapes. Rapid Prototyping is an additive manufacturing process, where the material is added layer by layer until the desired shape and size is obtained under computer control. Rapid prototyping means rapidly generating an initial prototype from concept. Rapid Prototyping reduces the need of fixed assets such as tooling and also helps to minimize the business risk. 3D printing is one of the many Rapid Prototyping processes but these days 3D printing itself is the most commonly used term for Rapid Prototyping.

3D printing is a process of formation of three-dimensional objects, components and models of plastics and other materials. 3D printing will create a tangible physical copy automatically and minimize the required number of crafts.

General principle of 3D printing starts with the creation of the object with computer software's like solid works and CAD which is followed by its printing. 3D printing technology follows the guidelines from the digital model that is created in 3D designing software's.

3D systems was the one who developed the ‘Stereo Lithographic file (stl)’ format but later its used in a standard manner to imitate the original 3D model to be defined tolerance precision. Some of the materials and processes also need finishing and curing. 3D printing has evolved itself in various forms but the transformation has been felt recently. Before, the printing equipment was very expensive so only the big projects like kick starter was able to use it but nowadays the spread of technology, standards and free software’s has made it easy for beginners to get the access.

There are several types of 3D Printing technologies available in the market each with their own unique set of competencies and their own limitations. Among them all, Fused Deposition Modelling (FDM) process looks to be more suitable for common use as it can be performed with the filament itself whereas in other rapid prototyping processes the use of resin based material is the must. The current research in this topic are being more focused on getting more and more important applications of this procedure in daily use. (1-2, 3)

1.2 History

3D printing has evolved itself in various forms for over 3 decades but the transformation in retail use has been felt in last 5 years providing this technique a breakthrough hence also called breakthrough point in the evolution of this procedure. Before the printing equipment was very expensive so only the big projects like kick starter was able to use it but nowadays the spread of technology , standards and free software’s been tailor made for the amateurs in suitable size range. This will allow every individual who are interested to fabricate their own objects at home. In early 1980s the common rapid manufacturing was inkjet printing. However the first 3D printing technique used was, Stereo Lithography, developed by Charles Hulls in 1984. The development of SLA hull stereo lithographic apparatus was developed in 1990s. Hull device made of plastics is heated to optically with a laser. The process was unclear but it showed the signs that the manufacturing could be done in a very short period of time.

The first printed organic body took place in 1999 A.D. 3D printed bladder were coated with the patient's own cells removing the chance of rejection from the body was developed by Wake Forest Institute for Regenerative Medicine. In 2002 the evolution made a big leap towards evolutionary step through the same scientists developing first effective 3D printed kidney.

Three years later, Adrian Boywery, University of Bath, England stepped up for open source Rep-Rap Project. The aim was to develop a 3D printer which is capable of printing the components required to form a new printer itself. Rep-Rap name was the derivation of English word Replication. The first Rep-Rap project was more widely published in 2008 and the printer formed was given the name of Darwin. Darwin was able to replicate the parts for 3D printer itself. In 2008, a major company called Shapeways, major force in 3D printing technique these days share the technique worldwide. Designers, architects and designers were able to share 3D printing suitable for 3D models. In 2008 the 3D printing and health sector combined well to prepare the prosthetic leg and it was handed over to the patient for use. Another company called Bespoke Innovations invented prosthetic feet and its continuing to do so these days too. First Robotics-controlled airplane was printed in 2011, university of Southampton.

Later i.materialise started to offer gold and silver jewelry printing service. In addition to 3D printing replacement human tissues outside of the body, in vivo bio printing is already in development. This involves 3D printing layers of cultured cells directly onto the wound, or even inside the body using keyhole surgery techniques. Should this kind of technology become advanced enough, one day instruments may be able to be inserted into patient's body that will remove damaged cells and replace them with the new ones. While these assumptions sound fantastical some medical practitioners and 3D printing pioneers are already taking them seriously indeed. (1, 4-5)

1.3 Scope and Objectives

The main objective of the thesis is to study one of the 3D printing processes, Fused Deposition Modeling (FDM) in detail. This thesis also focuses on finding more applications for 3D printing and to use waste plastic materials in the lab for preparing filament for further manufacturing of new innovative products. More research on different type of materials that can be used in this field could be really beneficial for modern science.

It can also bring an evolutionary jump in the different fields related. Main research idea was based upon these questions:

- What physical conditions will affect the properties of a 3D printed product?
- Will it be possible to widen the application area of the process?
- What kind of polymers will be best suited for the printing process?
- What will be the time, temperature and physical conditions of the ideal 3D printing process in accordance with the materials used? (1,4-5)

1.4 Limitations

Since this study could not focus on each and every segments of 3D Printing, there are certain limitations of this study which are mentioned below:

- This thesis is based upon Fused Deposition Modeling. This work doesn't explain more details regarding other 3D printing techniques.
- This research was based on the work of Minifactory III in Arcada laboratory so this study is unable to explain more on other 3D printers available in the market.
- Only thermoplastic material was used during the research so this work doesn't signifies use of other materials like composites and ceramics.

2 Literature Review

Literature part is explained on three different categories where first part describes about the several existing printing technologies, second one describes mainly on the fused deposition modeling and final part will provide the several applications and industries that are related to the FDM technology. This literature part also describe plastics like ABS and PLA used in Arcada Laboratory with some of their features and limitations.

2.1 3D Printing Techniques

3D printing is a process of making a 3D solid object of any shape and size from digital model under computer control. The process is said to be additive process where all different layers are created and assembled in a single geometrical shape. The process of 3D printing /3D manufacturing is different from the traditional methods used in industrial section as they were based upon simple principles of cutting, drilling or injections.

Usually in 3D printing, high power laser has been used to fuse small nanoparticle to plastic, metal (direct metal laser sintering), ceramic or glass powder into a mass that has a desired three dimensional shape. However the process of extrusion is rapidly increasing its reputation in today's world of manufacturing. Some of the 3D printing methods also uses melting or softening as its framework for production.

Clarity to this situation could only be done by flowing the information about the existing 3D printing technologies. Firstly there are printers that form object layers by extruding a semi liquid material from a computer controlled print head nozzle. Secondly, there are printers that use photo-polymerization to selectively solidify a liquid with a laser beam or other light source. And finally, there are devices that 3D print by adhering particles of powders to achieve some form of 'granular materials binding'.

The type of process that is needed in a certain situation depends upon materials to be 3D printed and the application area for it. The understanding of what kind of things can and cannot be 3D printed using a specific method is a must. For Example, if a spanner, plastic casing, an aircraft component, an item of jewelry is to be 3D printed then the knowledge of which technology to be used should be gathered down.

3D printing technology are based upon the use of laser technology or extrusion technology. Materials that are used during the printing procedure are metals, powders, ceramics, composites, polymers and bio-ink. (3, 8-9)

However, 3D Printing is categorized into six types:

1. Stereo lithography (SL)
2. Selective Laser sintering (SLS)
3. Selective Laser Melting (SLM)
4. Electron Beam Melting (EBM)
5. Laminated Object Manufacturing (LOM)
6. Fused Deposition Modeling (FDM) (3)

2.1.1 Stereo Lithography

Stereo lithography is an additive manufacturing process where each layer with photo reactive resin is being cured with Ultraviolet (UV) laser. Material extrusion is a form of 3D printing that can output quite a number of existing materials. Easy to construct and freedom of selling it for relatively lower price are the most important factors affecting today's industrial scenarios but limitations like consumption of very long time to make a single prototype of substantial size. (10)

Qualities

Stereo lithography has following advantages

- High resolution product,
- Great surface quality,
- Ability to print very complex geometries with a high level of repeatability and
- Products in very affordable price. (10-11)

To make the study more simplified, categorization of Stereo lithography took place.

1. Photo Polymerization
2. Digital Light Processing (DLP Projection)
3. Material Jetting
4. Binder Jetting
5. Two Photon Polymerization (1)

2.1.1.1 Photo Polymerization

Photo polymerization commonly known as Stereo lithography, is an additive manufacturing process where each layer with photo reactive resin is being cured with Ultraviolet (UV) laser. The process is based upon the selective solidification of materials called photopolymers which harden when exposed to an ultraviolet (UV) laser or similar controlled light source. This was the first 3D printing technique that was invented in the name of Stereo lithography. 3D printers used for this process are known as Stereo lithography apparatus or SLAs. The equipment use a computer controlled laser beam to build a 3D object within a tank of liquid photopolymer. The build platform acts as the creation point and is made up of perforated metal and initially positioned just under the surface of photopolymer in the tank.

A UV laser beam traces out the shape of the first object layer on the surface of the liquid and laser beam causes the layer to cure. Then the build platform is slightly lowered down and more liquid photopolymers are allowed to flow and other beam of light cure the next layer and this goes on until the product is finally formed, after which the build platform is returned to the surface and object is detached.

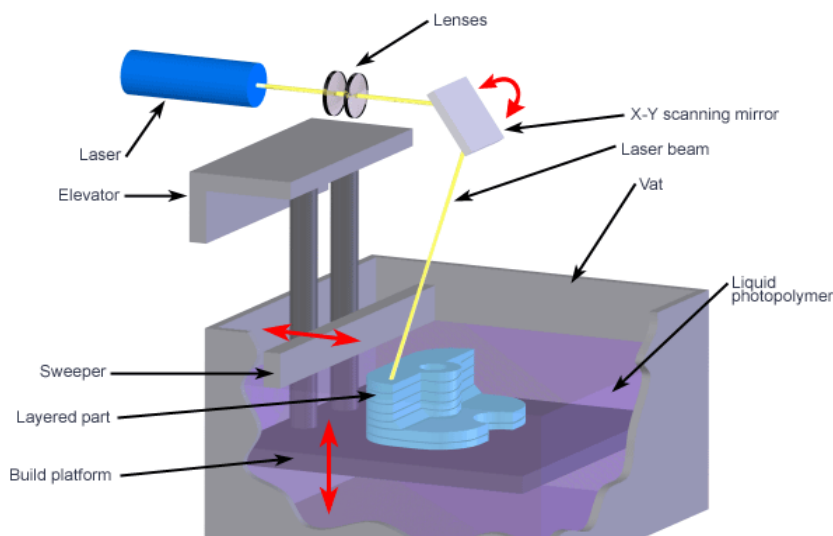


Figure 1: Stereo Lithography (10)

As in other material extrusion process, this process often require additional structures to be added to them to support overhangs or initially orphan parts, which should be broken away or removed with tools after the completion of the printout. After the printout, objects need to be cleaned with a solvent, and then water rinse, to get a completely clean object.

Curing in UV oven also often takes place for increasing the efficiency of the product formed. Items that are created in transparent resins are sometimes also varnished to prevent discoloration if they are going to be exposed to sunlight and also sometimes to improve surface quality the item are blasted with glass beads along with polishing with a fine abrasive spray in a process called 'vapour honing'. (3, 10-12)

2.1.1.2 DLP Projection

Digital Light Processing (DLP) technology is now increasingly found at the heart of many video projectors used in cinemas, lecture theatres, schools and homes too. DLP projectors can be used to selectively solidify a photopolymer liquid. This process of solidifying a photopolymer liquid with the help of DLP Projectors is known as DLP projection. In a DLP projection 3D printer, DLP projector is positioned above a tank of liquid photopolymer and is used to solidify an entire layer of an object on the surface of the liquid. The other process is like in stereo lithography as build platform is then lowered, another layer is solidified by the DLP projection method and so on. (13)

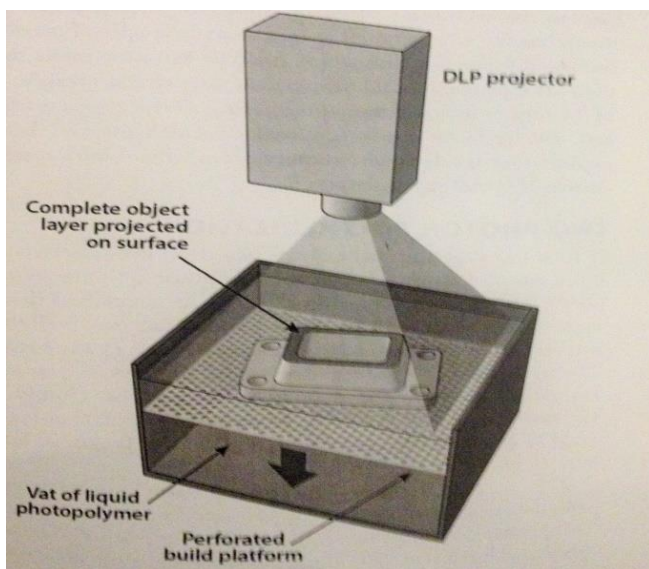


Figure 2: DLP projection (11)

2.1.1.3 Material Jetting

Material 3D printers plane drops the fluid of photopolymer onto the assemble plate. Numerous print heads plane material at the same time to make every layer, and UV light is then used to cure the layers. These layers develop each one in turn in an added substance procedure to make a 3D model. Completely cured models can be taken care of and utilized promptly without extra post-curing. Alongside the chose model materials, a gel-like bolster material encourages effective printing of confounded geometries. Bolster material can be uprooted by hand or by a high-controlled water plane station. (14)

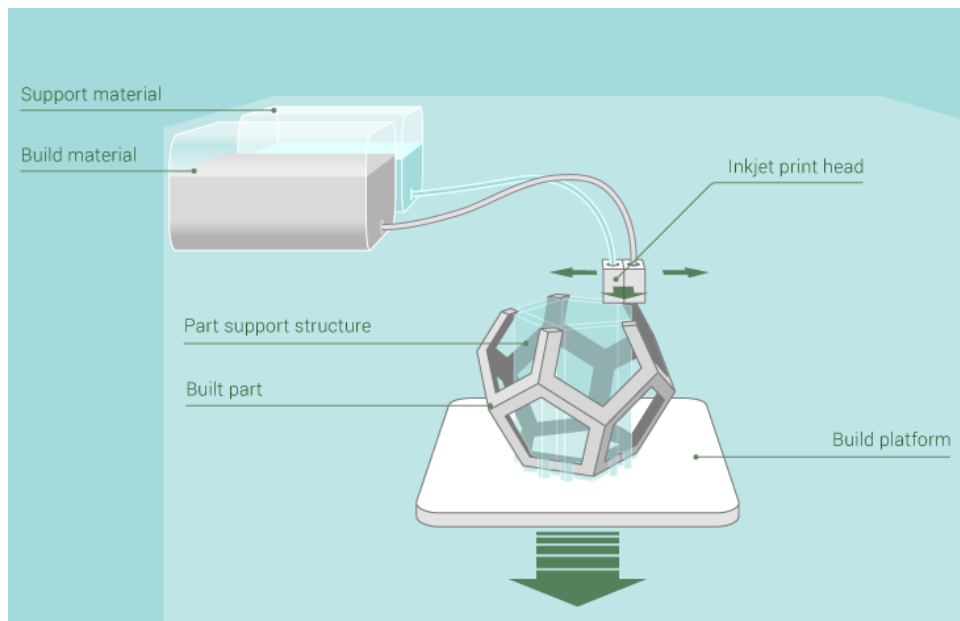


Figure 3: Material jetting processes (14)

2.1.1.4 Binder Jetting

This type of additive manufacturing process has a liquid binding agent which is selectively deposited to join powder particles and layers of materials will be bonded and after some layers deposition the object is formed. The bead where the powder is to be bonded is strategically lowered down and another layer is deposited.

Materials that can be used in this process of bonding are as:

- Metals (require curing)
- Sands (doesn't require any other additional processing)
- Ceramics (require curing)

Difference in regards to other printing processes:

- It doesn't utilise heat during the process.
- It requires significantly less material as there is near to zero waste. (15)

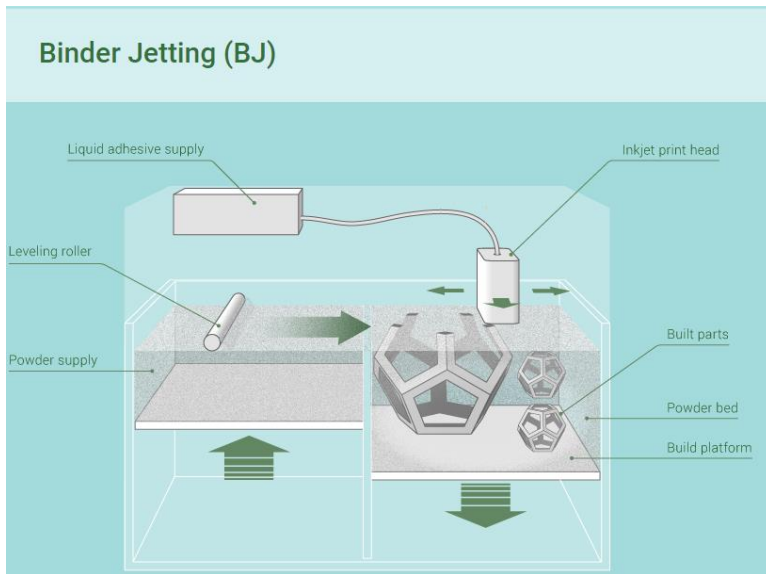


Figure 4: Binder jetting processes (15)

2.1.1.5 Two-Photon Polymerization

Two photon polymerization (2PP) is the process of formation of highly localized nonlinear light-matter interaction inside a photosensitive material. This process can be used to form 3D structures of high resolution. However this process takes hours to fabricate a single Nano device. (16)

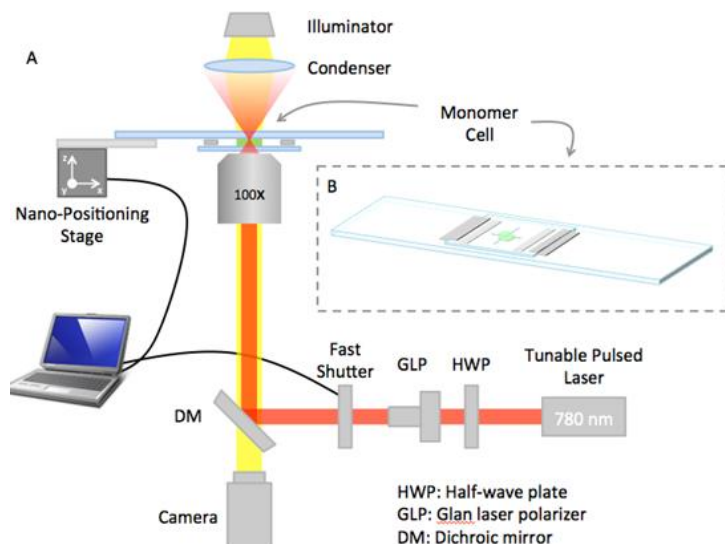


Figure 5: Two-Photon Polymerization (17)

2.1.2 Selective Laser Sintering (SLS)

Selective laser Sintering method is the process of formation of 3D product (sintered part) via laser-sinterable powder by introducing the powder to laser sintering machine. SLS technique is ideal for the product prototypes that demands very high tensile strength or make the thermoplastic properties more efficient. (1, 18-19)

High power laser of SLS technique is used to fuse small particles of plastic, metal. Laser selectively fuses powdered material by scanning cross sections generated by CAD on the surface of powder bed. After fusing, powder bed is lowered down by one layer thickness and a new layer of material is applied on its top. The process is repeated until the part is completed.

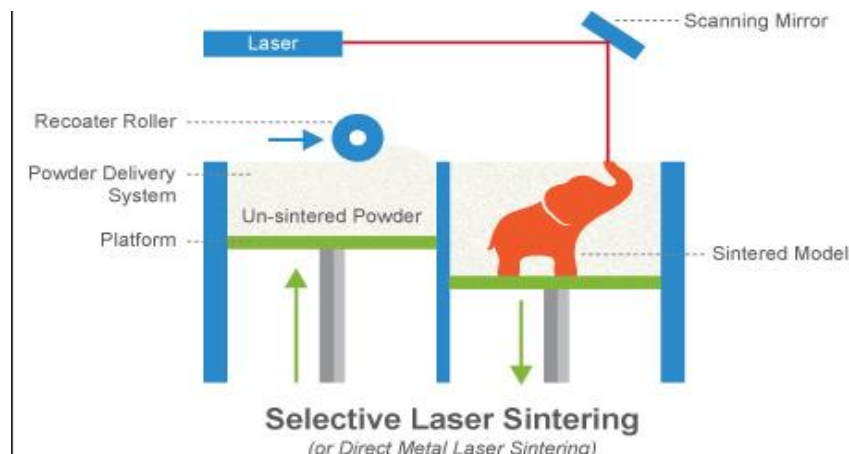


Figure 6: Selective laser sintering method (20)

2.1.2.1 Materials

The powder layers process limits the particle size to approximately 100 μm diameter and smaller. Therefore high strength composites are not suitable to the process because of the micro scale reinforcements require millimeter length fibers to reach high strength. The material that is required for clay reinforced Nano-composite is polyamide 6(Nylon -6). Commercial glass filled polyamide = 48 μm diameter making difficult for fiber reinforcement and making it suitable for the laser sintering method. 27% volume of glass in commercial composites increase its young modulus and heat distortion temperature which will reduce its strength and strain to failure making it available for this technique. (3, 18-20)

The chart for selecting materials used in selective laser sintering technique for different application is given as:

Selective Laser Sintering Materials			
LS Materials	Material Class	Application "Best Fit"	Material Data
Windform XT®	Carbon Fiber	<ul style="list-style-type: none"> • Aerospace and Military non-structural hardware • Wind Tunnel Models • Motor Racing Sports • Automotive • Direct Digital Manufacturing (DDM) • Elevated HDT 170°C • Conductivity • Increased Mechanical Properties 	Windform XT® XT Conductivity
LS Hybrid PA	Fine Polyamide (Nylon)	<ul style="list-style-type: none"> • Aerospace hardware • Thin wall, lightweight applications • Flexible part assemblies • Snap features • Rapid manufacturing 	LS Hybrid PA
LS Hybrid PAGF	Fine Polyamide (glass-filled)	<ul style="list-style-type: none"> • Robust functional prototypes • Assembly fixtures • Machining setup fixtures • Direct Digital Manufacturing (DDM) • Chemical resistant 	LS Hybrid PAGF
LS PAFR (Fire Rated)	Fine Polyamide	<ul style="list-style-type: none"> • Functional prototypes • UAS & UAV hardware • Electrical enclosure • Flame Resistant • Meets FAR 25.853 b(4) • Meets UL 94-V0 • DDM 	LS PAFR
CastForm™ PS	Polystyrene	<ul style="list-style-type: none"> • Investment casting patterns 	CastForm
Somos™ 201		<ul style="list-style-type: none"> • Soft flexible applications • Healthcare and medical custom applications • Gasket and facemask prototypes 	Somos 201
ePAC™ (engineered Polyamide Composite)	Fine Polyamide (composite)	<ul style="list-style-type: none"> • Increases part stiffness • Densifies part • Substantially eliminates salt water and other liquid absorption 	

Figure 7: Table showing applications and their polymer contents (21)

2.1.2.2 Features

- SLS machine heats the powder just below its melting point so that the laser activity to raise its temperature to its melting temperature can be reduced.
- It doesn't require any support structures so this process is easy to handle. (3,19)

2.1.3 Selective Laser Melting

Selective Laser Melting, also known as Directed Energy Deposition, creates 3D object using laser beam and metal powder. Metal powder is directed into a high power laser beam for deposition as a molten build material. This process is also called as 'Laser Engineered Net Shaping'. (1,3)

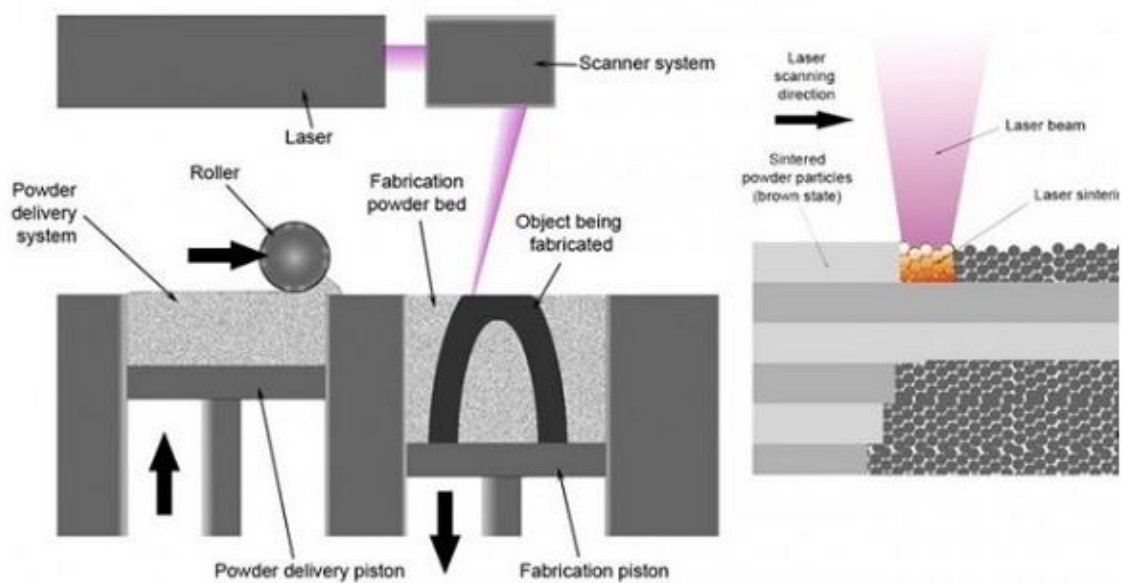


Figure 8: Selective laser melting method (3)

2.1.4 Electron Beam Melting

Electron Beam Melting is another type of 3D printing technique that uses heat to selectively solidify the powders in power bed to create 3D objects. The high results are already obtained by building metal objects layer by layer in vacuum with the help of electronic beam.

There are several stages (passes) and they are as:

- First pass of electronic beam pre-heat the build material to an optimal temperature,
 - Second pass melts the outline of object layer
 - Following passes melt the bulk of material inside the outline made by second pass.
- (1,3)

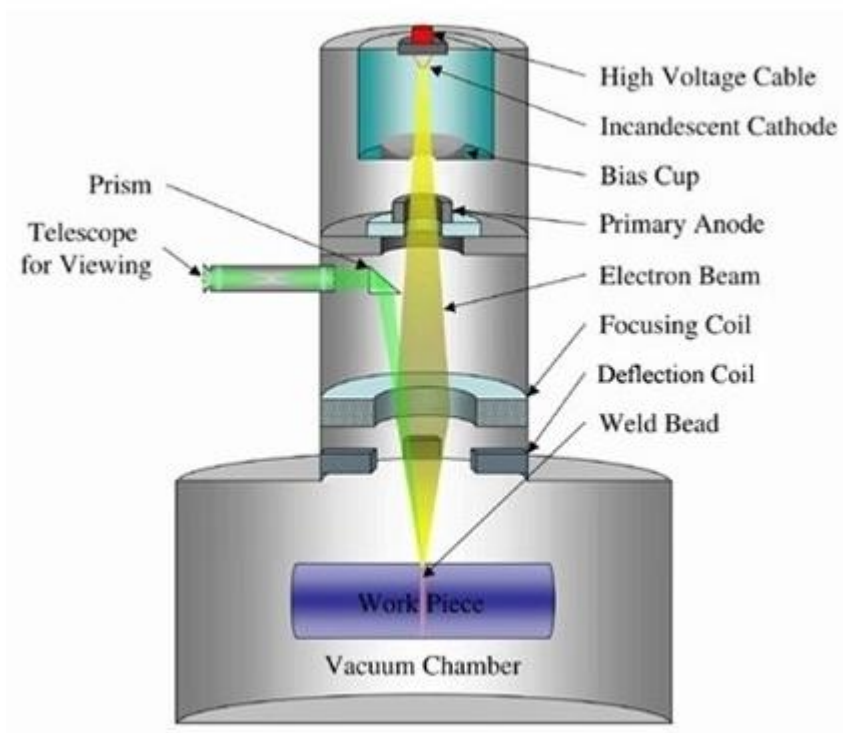


Figure 9: Electron Beam Melting (3)

2.1.5 Laminated Object Manufacturing

Laminated Object Manufacturing, invented by a company called Helisys in 1991 is a distinct 3D printing technique because this works on the basics of sheet lamination. This process builds objects in layers by sticking laser sheets of paper together, plastic or metal foil. As this system doesn't work on powder based mechanism, there is no requirement of any support structures. (3)

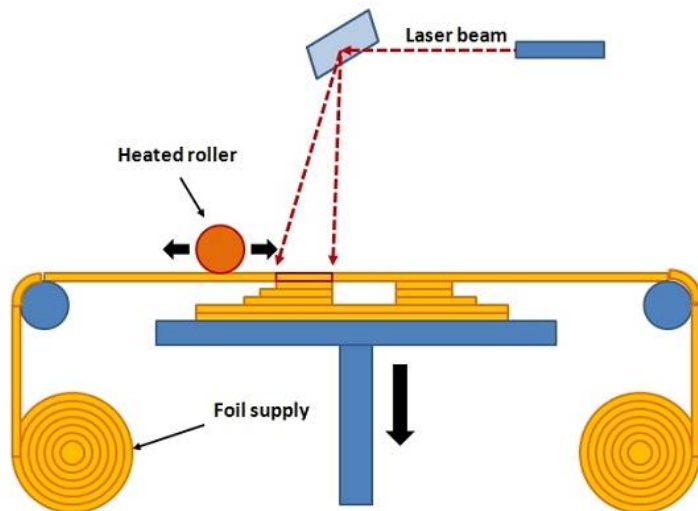


Figure 10: Laminated Object Manufacturing (3)

2.1.6 Fused Deposition Modeling

Fused Deposition Modeling (FDM) is one of the rapid manufacturing processes for creating new and innovative products through the process of layer by layer deposition of the material. Material is allowed to extrude from a nozzle head and deposited on a base plate where it is cooled down and final product can be removed from the base plate without any difficulties. This process can be used to 3D print objects in a wide range of materials including metals, concrete, ceramics and chocolate. However melted thermoplastic is the most commonly used material. So the process is named after this material itself but the name was more generically described as material extrusion in June 2012. (22)

Materials

Generally, Fused Deposition Modeling process uses the following materials:

- Plastics (ABS, PLA)
- Metals,
- Woods,
- Ceramics and Concrete (25-27)

However, Minifactory III in Arcada Lab uses plastics like Acrylonitrile Butadiene styrene (ABS), Poly Lactic acid (PLA) and Nylon-66.

2.1.6.1 Thermoplastic Extrusion

This is one of the Fused Deposition Modeling process where plastics is used as the material. Today's world is the world of plastics and Fused deposition modelling of the plastics to create new innovative models by extruding a semi-liquid material from a computer controlled print head nozzle is the most used technique. Thermoplastic extrusion was invented by a market leading company called Stratasys that labelled it "Fused Deposition Modelling (FDM)". This term FDM is widely used to refer to thermoplastic extrusion but this can only be used by Stratasys only because it is trademarked. These days other companies refer to thermoplastic extrusion as 'plastic jet printing' (PJP), 'Fused filament modelling' (FFM), 'Fused Filament Fabrication' (FFF), or 'Fused Deposition method' (FDM). (1)

Procedure

A spool of build material referred to as 'filament' is slowly fed to a print head that is heated to between 200 and 250 degree centigrade. This high temperature melts the filament, which is then extruded through a fine nozzle and flattened slightly by the print head on its way out. Initially, molten filament is deposited directly onto a smooth, flat, horizontal surface known as 3D printers 'build platform'. The filament very rapidly cools and sticks, with the print head moving in 2D space to trace out the first layer of the object being printed. Once the first layer of an object has been traced out, the build platform lowers very slightly and the next layer of thermoplastic is deposited on top of it. This process is then repeated over a period of many minutes until a complete plastic object been printed. (3, 22-23)

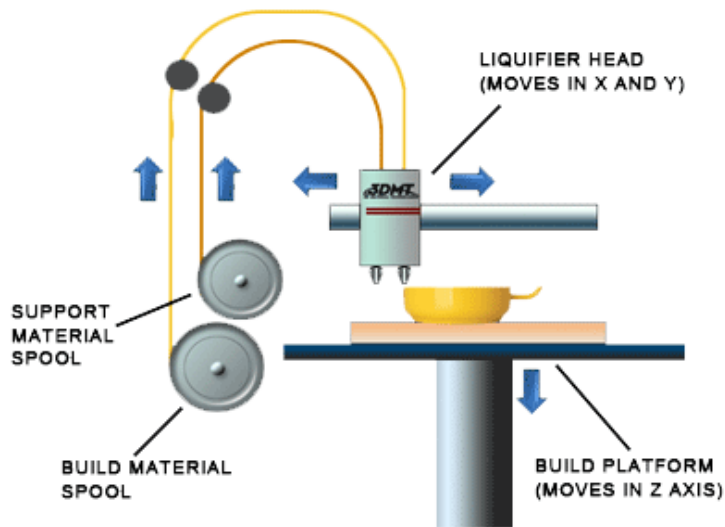


Figure 11: Fused Deposition modeling (24)

2.1.6.2 Fused Deposition Modeling of Metals

Additive manufacturing of metals (AMM) refers to any 3D printing technology that builds up metal objects in layers. Most common methods for additive metal manufacturing are direct metal laser sintering (DMLS), laser curing, and electron beam melting (EBM) and directed energy deposition. However the method of fused deposition of metals is evolving rapidly towards the top of all procedures.

Jorge Mireles, University of Texas has conducted tests using a modified printer fed with a coil of metal alloy. Used alloy has to have a relatively low melting point (of less than 300 degree centigrade). The results were successful in those objects that were just under a millimeter thick. Other researchers have successfully adapted Gas metal arc fusion welding robots to achieve fused deposition of modelling of metals. Research held in the partnerships between Cranfield University and Lockheed Martin has developed a form of FDMm that hey call ‘wire and arc additive manufacturing ‘(WAAM). The WAAM machine costs around 50000 \$ and can print hollow objects through layer formation and layers are between 0.5 and 2 mm thick. (25)

2.1.6.3 Material Extrusion of Wood

By using standard material extrusion 3D printer wooden objects can now be 3D printed. Kai Pathy, a 3D printing enthusiast created a 3 mm filament material called 'LAYWOOD-3D'. This filament is a composite of wood fibers and polymers binder. This material can be used in any thermoplastic extrusion 3D printer. The print thus formed feel and smell like wood and they can be sanded and worked on like any object made up a wood composite. The color of the product depends upon the temperature of the print head used to melt and extrude it. LAYWOOD-3D does not warp or shrink during printout. (1, 26)



Figure 12: Metablen A-3000 for wood extrusion (26)

Considerations for extrusion of wood

- Wood powder should be dispersible.
- Melt Resin in Die should be flow able.
- Haul off property and Properties of Profile should be considered. (1, 26)

2.1.6.4 Material extrusion of concrete

Unlike the most materials used in 3D printing, concrete does not need to be heated to make it melt in print head. It can be forced through a motion controlled nozzle in its naturally pre-set state to form layers that then solidify. In California in 2004, Contour Crafting, was used to manufacture the world's first 3D printed wall. Several other inventions have occurred in recent time along with large concrete objects. Benefits that surround 3D concrete printing could

be the fabrication of complex curves and designs that are hard to build with traditional building techniques. Initial crafting of walls with internal air pockets for better insulation, reduction of material usage and ducts for utilities like power and water will also be able to be 3D printed directly into a concrete wall as it is being made. (1, 27)



Figure 13: 3D printing using concrete (can withstand 4000 pounds pressure) (27)

2.1.6.5 3D Printing of Foods (Syringe Extrusion)

This Extrusion process is also known as Syringe extrusion as the head nozzle is shaped like syringe head but the main framework of this process is Fused Deposition modeling. Chocolate probably is the easiest compound to melt that is used in our daily life. So its commercial use has already been accomplished. The process of chocolate printing is mostly like the material extrusion of thermoplastics, metal or wood. Chocolate is heated so that it melts and is then extruded through a syringe style print head under computer control. Choc Edge is the main seller for 3D chocolate printer in the range about 3500 €. The main theme behind this evolution would be to explore and develop innovative opportunities of 3D printing technology in creating edible foods and providing the complicated designs more convention using this technique. (28)

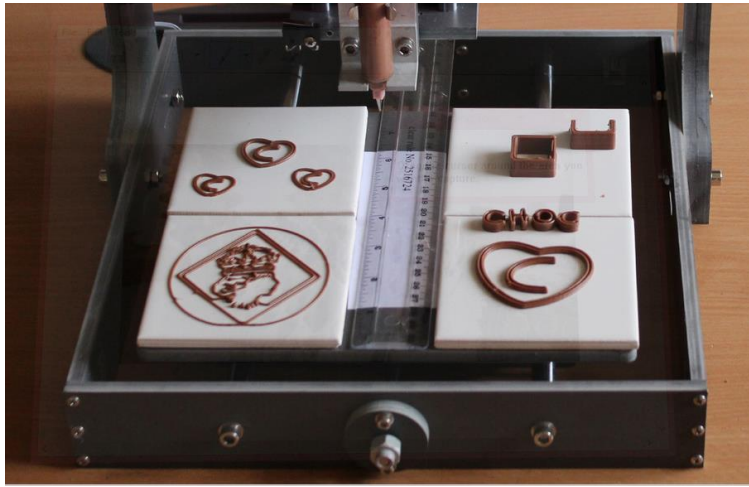


Figure 14: Chocolate extrusion by Choc Edge 3D Printer (28)

3D Printing of Pizza

NASA provided \$125, 000 to Systems and material research centre to develop a pizza printer which uses shelf-stable powdered food and oils, offering nutrition and also reducing the garbage on board. It will first print the dough onto a heated plate that bakes the dough. It then extrudes tomato which is in powder form mixed with water and oil and finally the printer will extrude some protein layer for providing the finishing touch. (1, 28)

2.1.6.6 Applications of FDM

- Functional prototypes can be used for different test.
- End use parts can be formed with low volume production without tooling expenses.
- Manufacturing tools like jigs, fixtures and tooling masters can be easily manufactured quickly without machining. (29-31)

2.1.6.7 Industries

- Aerospace Engineering: Formation of Jigs, Fixtures, Check Gauges and other Aircraft Parts.

- Automotive Industry: Manufacturing of Different parts of Cars, Buses and other Automotive Parts.
- Architecture : Sample Designs of architectural structures
- Consumer: Jewelry, Clothing and Other Households Parts Formation.
- Industrial : Models and Mold Formation
- Medical: Syringes, Gloves and several others. (29-31)

2.1.6.8 Advantages of Fused Deposition Modeling

- Freedom of Design can be noted down as the landmark feature for Fused Deposition Modeling as this process can cope with the complications of design like undercuts.
- This process allows the virtual invention to be real product. The process simply starts with designing any product with CAD and then printing it with the 3D printer. Any changes can be done easily on the screen rather than committing to the tooling process.
- This process ensures the success of the project due to easy prototype formation and its test before the complete and larger production. Any details if necessary can be changed after prototype formation and this will ensure larger production will be much more efficient. (29-31)

2.1.6.9 Limitations

Since the FDM process works as layer by layer deposition of the molten material, it often leads to rubbing and the lines are visible even after the completion of the process. Finishing touch like smoothing and polishing should be provided to remove these defects. (32)

3 Methods

3.1 Software use

Printer used: Minifactory ® III Education Edition

Materials used during the thesis: PLA and Nylon 66

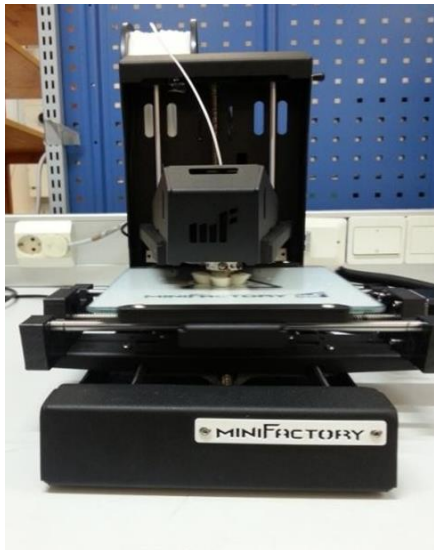


Figure 15: Minifactory III at Arcada

- Software installed: Repetier Host 0.95 (2014)
- Repetier Host 0.95 2014 software is used to connect the computer to the 3D printer which allows a spontaneous layer by layer deposition of the materials.
- Minifactory III deployment guide is recommended for a simple and proven model for the download and using the calibration.

3.1.1 Features

- It's easier to handle and get control of.
- It can also get support if there is need of multi extruder printing.
- Slice properties is advanced than any other software that ensures best printing. (33)

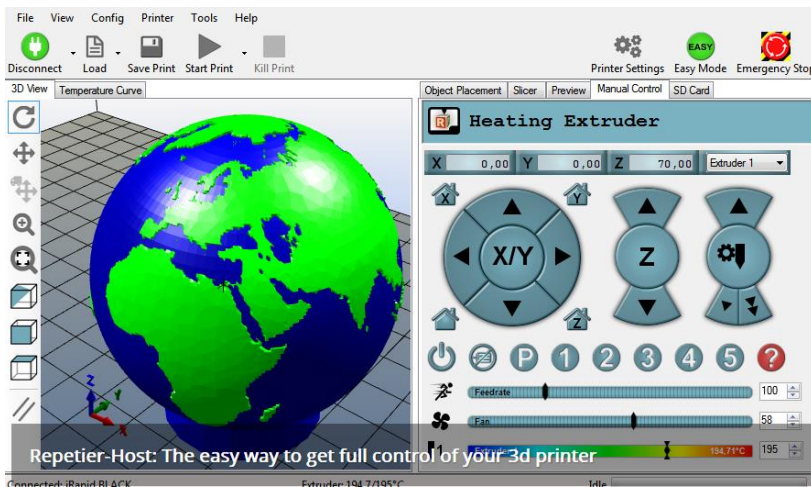


Figure 16: Repetier Host 0.95 Software (34)

3.2 Installation of software

Guideline was provided along with the hardware so that user could easily use the Minifactory III or users can easily download the pdf for software installation from the official website of the company. Each and every details that is needed for installation was given in a simplest language for efficient and proper installation. Also some problems that might occurred during the installation was also mentioned along with the suggestions of how to solve those problems.

3.3 Procedure

Designing the product is the first step of the printing process. Simplifications in the design contribute to the efficient printing. The model geometry and shape requirements go through several common references that will determine the efficiency of the final product formed.

The designs should be saved in Stereo Lithographic file (stl) format. Advantage of stl format is that most of CAD packages support it and it simplifies the job whereas its disadvantage is that increase in minor details in the modern geometry reduces the resolution of the design part.

Software Repetier Host 0.95 was opened. 3D printer and the computer in which the software is installed was connected via connect tab in the screen just after opening the software. After clicking the connect button, log option shows the connection status of the printer to the computer. Idle status is the condition where it's ready for the printing whereas any other connection status means there is some problem with the connection settings.

The printer settings and axis settings was changed according to the need of the material used. Object placement settings, Slicer settings, Filament settings, Print settings and Printer settings were controlled from the computer connected. Filament settings includes extrusion length for the printing, whereas printer settings provides the full control of temperature settings of filament extrusion and bed temperature.

After checking all filament settings, extrusion settings and printer axis, slice tab can be used to convert the print into G-codes and printing will finally start. The data's are provided along with the printing like when the printing will be completed, which layer of what thickness is being printed, at what temperature its running and several other details of axis too.

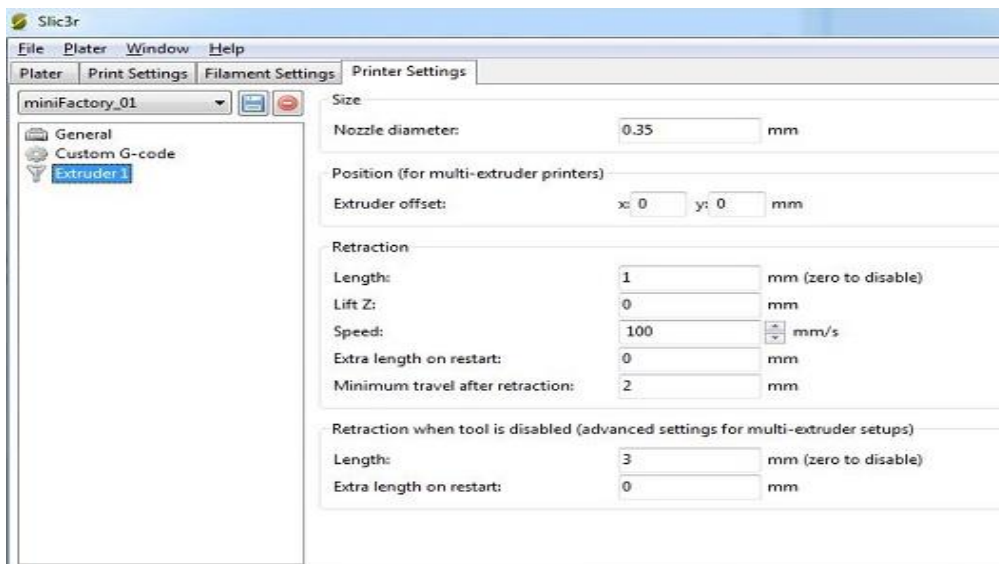


Figure 17: Printer settings of Minifactory III at Arcada

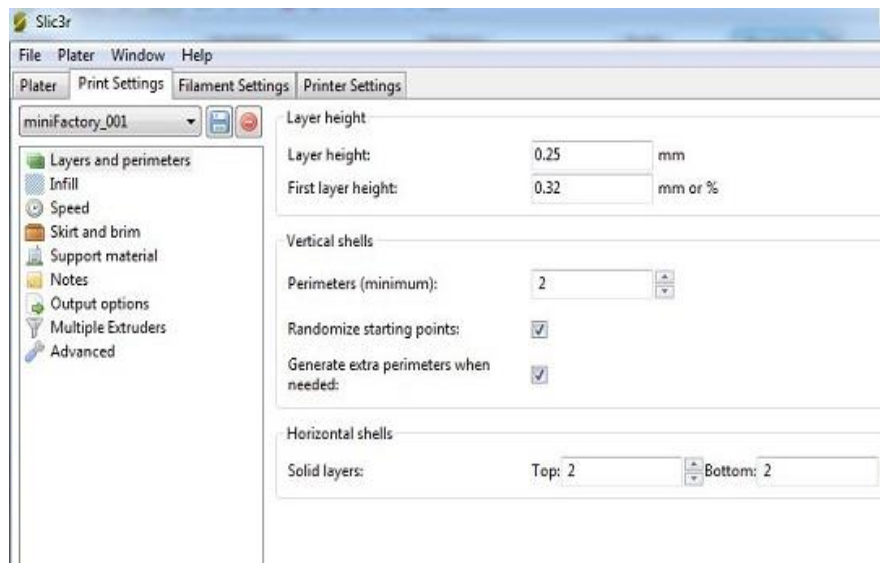


Figure 18: Print setting of Minifactory III at Arcada

3.4 First Print

Ethanol was used to clean the print bed before any print command. This cleaning will help to successfully get the print out of the print bed after completion of the printing process. If not cleaned properly, the final product may stick in the plate and may also provide irregularities during printing due to uneven layer axis.



Figure 19 : Test piece (Gear ring) provided by minifactory with the 3D Printer

3.4.1 Material used

I. Acrylonitrile Butadiene Styrene (ABS)

Among many materials available in the market but ABS, acrylonitrile butadiene styrene is the most commonly used. This is a type of thermoplastic that is widely used in industry to injection mold a great many produces and parts thereof. Lego bricks, cycle helmets and birs are all injection molded in various grades of ABS. Spools of ABS filament are available as a 3D printing consumable in a variety of colors , with a typical filament being either 3 mm or 1.75 mm in diameter. Other materials used for this process are Nylon-66, polycarbonate (PC) and ABS-polycarbonate composites. ABS, which can be sterilized with gamma radiation and ethylene oxide and the material can then be used in the food industry or for medical applications. ABS being translucent can be used for producing items that need to transmit light, such as tail lamps. ABS was discovered during Second World War and was used as an alternative of rubber.

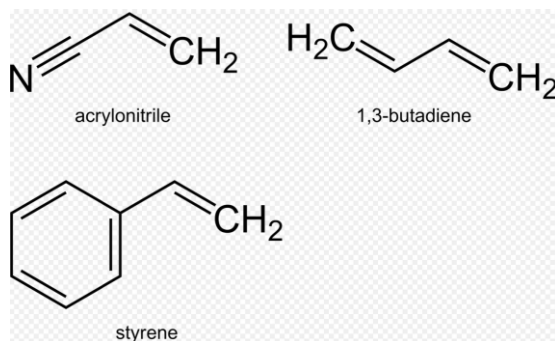


Figure 20: Monomers in the structure of ABS (39)

Advantages

- Retardant to Flame
- High heat resistance
- Good Impact resistance
- Good Process ability
- Good and high flow material property

Limitations

- Very limited weathering resistance
- Not so good heat, moisture and chemical resistance
- Expensive

(35-38)

II. Poly Lactic acid (PLA)

After ABS, thermoplastic that is highly used for fused deposition modeling process is Poly Lactic acid (PLA). PLA is a bio plastic currently made from agricultural produce such as corn starch or sugar cane , which is subsequently far more environment friendly than ABS. Since it doesn't emit toxic fumes when heated PLA is thought to be safer to use in school and colleges for experiments on 3D printing. 3D PLA filament comes in a variety of solid and translucent colors and is more popular than ABS in 3D printing because it's easier to print than ABS itself.

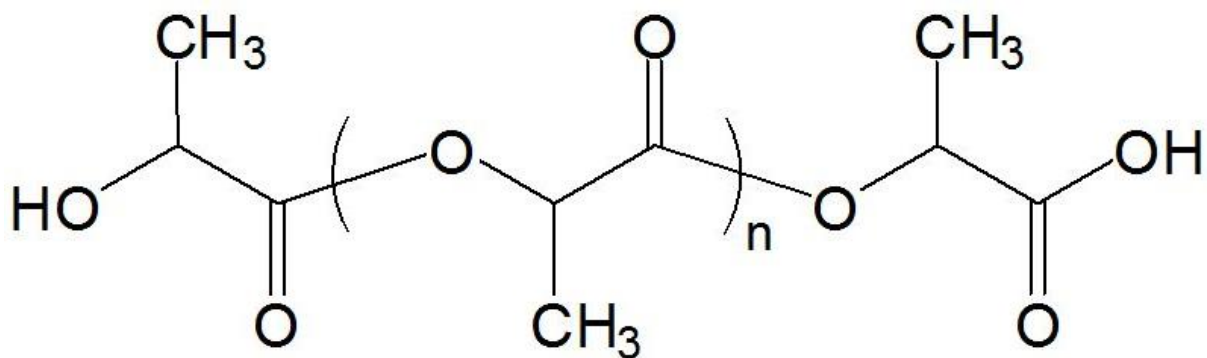


Figure 21: Chain Structure of PLA (40)

Advantages of PLA

These below mentioned properties of PLA are the main reasons that contribute to the several applications of PLA on medical field, food packaging industry and prototype business.

- Shiny and Hard
- Biodegradable
- Stronger and Flexible
- Low melting temperature (173-178 °C)
- Tensile strength (2.7-16 Giga Pascal)
- Higher 3D printing speed
- Can be printed in cold surface

Disadvantages

- Can deform in the presence of heat
- Less sturdy (37-38)

3.4.2 Material Filament Properties

Filament used : Premium Grade PLA White (ABS and Nylon-66 can also be used)

Diameter : 1.75mm

- Very good flow consistency,
- High print quality,
- Optimum flow of material,
- Strong and durable,
- Low odor and
- Free from heavy Metals and Pthalates (41)

Table 1: Printer Settings used to print Gear ring in Arcada

Bed temperature	70 °C
Bridge fan speed	100 mm/s
First layer temperature	200 °C
Maximum/minimum fan speed	100 mm/s
Minimum print speed	20 mm/s
Extruder temperature	200 °C

Some of the conditions evaluated during the printing process of prototype printing certainly helped for the further printing procedure with more efficiency. Manually controlling the machine also significantly increase the chances of getting very good product.

Conditions that can be manually controlled are:

- Extrusion Temperature
- Print bed temperature
- Feed rate
- Flow rate
- Movement speed of nozzle
- Movement of print bed through X, Y and Z axis.

Temperature curve was obtained during the process. This graph shows that the temperature change is high during initial and final stages of the process but during the middle stage which represents the printing stage, temperature change is minimum and results in required stability to the system.

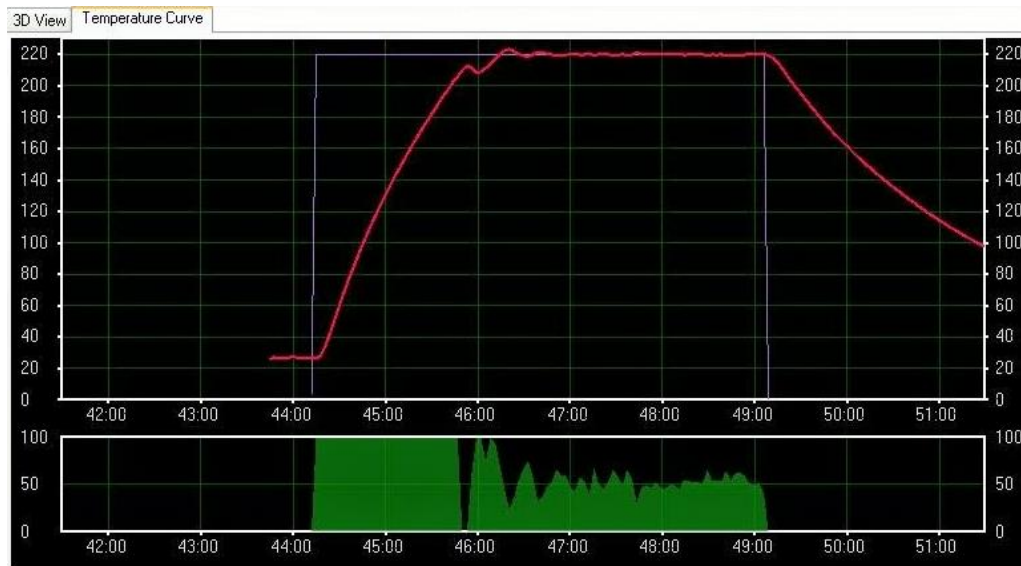


Figure 22 : Temperature curve (usually was around 200-220 during process)

3.4.3 Failures

Many failures were obtained before the near perfect gear ring was obtained. The problems were observed during the printing and after the end of the printing.

- The extruder was either depositing too much material or not depositing any material at all.
- The product was either not sticking to the build plate during the printing procedure or over sticking to the plate even after the end of the printing.

3.4.4 Reasons

- Base plate was either in low temperature or was in high temperatures that resulted un-sticking or over sticking of the extruded plastic. The successful printing had 70 degree for print bed.
- Extrusion length of the plastic was also different and caused several failures. The successful however was 4 mm.
- Several problems like printer status not being idle occurred while connecting the printer to the computer due to improper installation of the Repetier Host 0.95 Software.
- Feed rate and flow rate, however could not be directly targeted for unsuccessful printing but several other conditions did helped for the improper values of the flow rate and feed rate. Feed rate of 200 mm, Flow rate of 110 mm is preferable for PLA and ABS Filaments. (42)

Table 2: System Data for Minifactory III

Speed	80mm /s
Maximum size possible	150mm*150mm*150mm
Layer Thickness	0.1 mm (Max 100 microns)
Printing tape thickness	1.75 mm
Nozzle Diameter	0.4 mm
Printer Dimension	43,5 cm * 34 cm * 30 cm
Weight of the printer	11.2 kg

Table 3: System settings used for PLA in Minifactory III

Extruder temperature	200 °C
Bed temperature	70 °C
External perimeter speed	40 mm/s
Layer height	0.2 mm
Travel speed	60 mm/s
First layer height	0.3 mm
Fill pattern	Honey comb
Extruder clearance height	30 mm
Extruder clearance radius	40 mm
Extrusion width	0.42 mm
Fill density	0.2
Fill angle	45°

3.4.5 Design Considerations for Effective Printing

- The model designing is recommended to avoid unnecessary protrusions. Thin cantilevers, such as wings, fins, and swords can easily break or bend. As far as possible the small parts should be printed separately and pasted them into the final template closed. Character from the horns and fingers do not usually need to be removed.
- In order for the model to be firmer, thickness of the shell should be increased. A good minimum thickness on the wall of the pieces is about one millimeter. Depending on the device, the printing time may vary depending on the printer and in general the instructions are the recommended course values.

Narrow passages that affect the model already supports the modelling phase change more robust. The most important characters are printed wrists and ankles.

- The larger the print, the more it can hold the details. Since printer's accuracy is limited, highlight to the details of the model can be compensated by making the model larger.
- The model polygons should be clear. If the slicer does not understand the direction of the polygon, it can slice the model in the wrong way and cause problems. Often, such points may be printing holes.
- How the model will remain standing is the main point to take consideration because it will define the efficiency of the model and also establish the physics law regarding different sections of the model and mainly the base. (43-44)

4 Conclusion

Many applications and innovations are on the rise due to the freedom of design that has been given by this amazing technology. In recent times Fused Deposition Modeling has gained more popularity than any other technologies in 3D printing industry. Since the price of FDM printers are more affordable, its use has increased rapidly in the offices and the educational institutions. Fused Deposition Modeling is applicable to almost every material available so this certainly can be the future of rapid prototyping. New product development, model concept and prototyping are the main aspect that will surely reduce the cost and maximize the profit. The excessive use of heavy machinery will be reduced which will reduce the waste.

Minifactory III at Arcada

- Smaller and simple designs were easily printed with Minifactory 3D printer in Arcada but bigger and complex designs could not be printed because of its inability to print minor details and larger size of the product.
- Honeycomb printer settings is more useful for research propose as it consumes less material.
- Build Plate of the 3D Printer should be clean and dry before printing to avoid problems during and after printing.
- Extrusion head Nozzle should be watched carefully because it could get clotted or jammed causing problems for printing.

4.1 3D Printing Services in Internet

One of the most popular amateur printers is Maker-Bot Industries. Maker-Bot has grown around for a very large community. Maker-Bot founded *Thingiverse service* in 2008, where users can share models and experiences 3D printing related. Despite the fact that the site has a strict connection Maker-Bot, service models are the same STL format, what other printers understand. Models will be published in the service under the GNU General Public or Creative Commons license. In this way they are freely available to all 3D printing enthusiasts. The website of the models can be commented on, and if problems arise, it unconditionally cures. In addition, users upload their designs and make them improved or otherwise different versions if the original sender is a further development of terms of the license allowed. In general, a 3D printing service is easy to use. Services to support a wide scale of different file formats. All services are supported by the current organized STL format and the number of services can also be taken 3D modelling programs used by the file formats, such as 3ds.HTML5, Silverlight, and other new internet technologies have improved the 3D printing services previews significantly.

In many of its own services 3D model can be rotated and checked for potential errors still before printing, and last-minute adjustments scaling are often possible. In addition to this, viewers can also print at a lower rate, based on the product. *Shapeways* has worked since 2007 as a Dutch start-up company. The company's founders Eter Weijmarshausen, Robert Schulenburg and Marleen Vogelaar. They were originally in the Philips product design department, and developed it further. Launched in 2008, the service user was able to download the STL file Shapeways site and through this internet 3D printing service a 3D model can be downloaded and also ordered for printed ones. Currently Shapeways.com is the internet's most popular 3D printing service. At the same time there is a significant size 3D printing community. Shapeways conceptualized the site as individuals can use the site through the manufacture of 3D prints, as well as buy and sell your own 3D printed models. Shapeways print almost anything "on-demand"-on request and all output are unique and personalized according to the wishes of the customers. Material selection includes plastics, ceramic materials and metals. Shapeways has offices in New York, Eindhoven and Seattle. Shapeways workers

were in 2012 fifty. Textile printing basic white piece is \$ 1.5 each cubic centimetre of material costs \$ 1.40. The maximum printable size of 650x350x550 mm. typical delivery time is 8 days.

I. Materialise service is the most important specialty of the choice of materials as I. Materialise print on precious metals such as gold. The choice of materials varies up to 16 including various thicknesses of plastics. I.materialise printing techniques also provide a very good print quality and also a very small print of jewellery is possible. The company has a twenty-years of experience in 3D printing. Sculpteo concept is very similar with Shapeways. Distribution, selling and buying of 3D models Sculpteo service is not possible with shape ways but Sculpteo advertises concept "3D Printing Cloud Engine" - a cloud service, where companies and individuals outsource 3D printing. Sculpteo was founded by Eric Carreel Clément Moreau in 2009. The company's headquarters are located in Paris, and they have a workshop in Arreau. Material selection is as wide as Shapeways. Sculpteo works in partnership with Dassault Systems 3DVIA and taking care of – service 3D printing. It is an important source of income for Sculpteo as 3D modelling software's like SolidWorks. (1, 45-49)

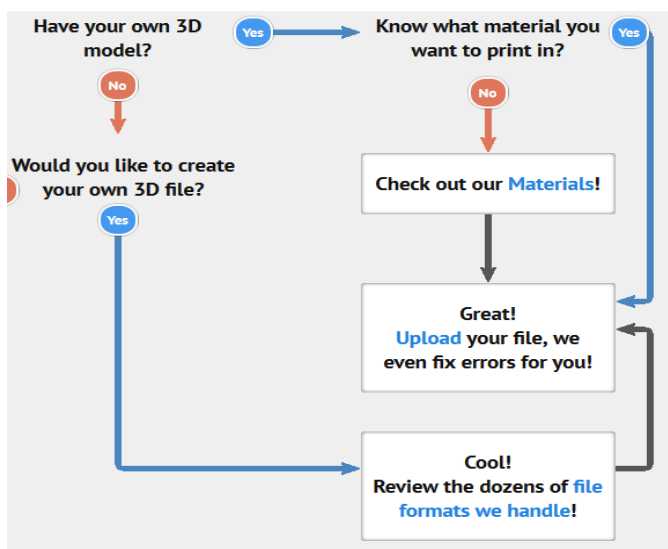


Figure 23: Sample working method of Sculpteo (46)

4.1.1 Misuse of Easy Internet Access

Easy internet most times is an advantage to have as it reaches out to the greater number of people but sometimes it does have a negative impact on the development of certain technology. Proper management of the internet access of common people for everything might be a threat that can hinder the future of the technology itself. In early 2012, the world's largest Bit Torrent trackers, The Pirate Bay -TBP, published a blog is expanding its offerings with a new "Physibles" - category. TPB believes that the future of 3D printing is a natural extension of the free software for sharing online (The Pirate Bay, 2012.). This is the biggest threats for 3D printing companies that their ideas and software's that could revolutionize the industrial section might be a victim of internet piracy. This development of improper use of technology should be closely monitored. Towards the end of 2012 Maker Bot Industries decided to pull all the parts of weapons and models thingiverse 3D library.

Addition of Terms of Use paragraph to an embargo on arms construction-promoting components to a library could be really beneficial. At present, the size of about 150 DEFCAD in article in the 3D printing model of the library can be download without any login.(1, 45-49)

4.2 Future Works

In this time of century where everything is very simplified by the use of technology, there needs to be more revolution on the field of industrial manufacturing. 3D printing is a growing industry and its importance was highlighted when the president of United States, Barack Obama mentioned in his speech to federal space USA, 3D printing to be able to revolutionize the way things are created in 2012. Indications are that the 3D printing business for moving larger amounts of investments.

There is no disagreement on the topic that the dramatic fall in the 3D printer hardware prices resembles the inevitable spread of the equipment manufacturing market. 3D printing services, easy-to-use web interfaces to calculate the threshold for 3D printing utilization.

It's obviously certain that 3D printing will surely transform industrial manufacturing. But more realistic and more grounded visions will be helpful for the future. For the breakthrough that's needed for 3D printing. Here are list of some points that should be considered.

- There is a need for a breakthrough consumer model which can just reach to millions of people. After the model is found out 3D printing should have more impact on our society.
- More work should be done to increase the speed of printing that will allow industrial manufacturing.
- While filament based printing is safe but powder based printing is messy so more safety measures should be taken. Such precautions are like using the protective gloves and mask. Avoiding the direct contact with the laser beam as much as possible is also need to be considered for safety propose.
- The most promising field of 3D Printing is the Medical field where the lives can be saved directly from organ transplants and cell regeneration technique so study should be done on that aspect.
- Along with 3D Printing services, 3D scanning services also need to be studied and updated in the regular basis for this technology to bring the impact as it's expected of it.
- More studies should be done on the characteristics of build plate needed in order for the material to stick ideally in it. The coloring and types of plastics might differ according to the build plate features.
- More studies should be done regarding particle emission from Printers to evaluate effect of 3D Printing on user and surrounding environment.

(6-7, 50-52)

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