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A Comprehensive Insight on Material Extrusion Technology: Manufacturing Process, Associated Materials, Design Considerations, Post-processing Methods and Common Applications

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Abstract – *Additive Manufacturing (AM) or 3D printing is a digital manufacturing technology that is used to create physical objects by adding material in a constructive manner from a geometrical representation which are produced using computer aided design (CAD) software. 3D printing technology manufactures objects by depositing material layer by layer directly from a digital model. This enables users to design the objects at one place and manufacturing it on the other. It is a manufacturing technology with almost zero tooling cost and no initial setup allowing the user with the freedom of mass customization of parts and producing one-off custom parts with high precision & overall cost reduction. It is disrupting various industries such as medical, aerospace, automobile, and manufacturing etc. It is a fast-emerging technology with prospects of replacing the conventional manufacturing methods in some areas if not all in near future.*

Key Words: Additive manufacturing, 3D printing technology, Material extrusion, Fused deposition modelling (FDM), computer aided design (CAD), one-off custom parts, post-processing.

1.INTRODUCTION

In recent times the most challenging tasks that the designers and engineers are facing is selecting a best suited technology for their application. For someone who is new to 3D printing, the availability of vast number of technologies and materials often puts the end user in a state of confusion as to which technology could be right for their application [1]. Selecting an optimal 3D printing process for a particular task is often difficult this is because of the range of methods and materials that are suitable to perform a particular task with slight variations in properties like dimensional accuracy, surface finish and post processing techniques that are available. For selecting an appropriate technology, one should have knowledge about how the technology works, the materials that are associated with the technology and their common applications [2] and [3]. One more important aspect that needs to governed is the designing of parts when using a particular technology [4], each technology comes with certain limitations, and this must be addressed at an early design stage so that the parts produced at the end does not fail [5] and [6]. This information coupled with the knowledge how the manufacturing process works should be enough for one to decide on which AM technology is best suited for a particular task. According to ISO/ASTM 52900 standards created in 2015 [7] for standardizing different process/methods of 3D printing were categorized into seven groups namely: material extrusion, vat polymerization, powder bed fusion, material jetting, binder jetting, direct energy deposition, and sheet lamination.

In this paper, a detailed review on material extrusion technology is presented which includes the process of manufacturing followed by different types of materials available for this type of 3D printing process, design rules and consideration that should be taken into account if material extrusion technology is opted for printing, applicable post processing methods that can be applied on a part after printing for better aesthetics, surface finish and visualization and common applications associated with this technology is discussed followed by results & discussions and conclusions section.

1.1 Material extrusion

As the name suggests, in this method of manufacturing plastic material in the form of string (filament) is dispensed through a pre-heated orifice by melting it during the process. The melted material is deposited on a build platform as the machine receives instructions from the computer to deposit it in a predetermined path to form a geometry[3] and [8]. The build platform moves up down every time it completes one layer or in some cases the platform is stationary, and the extrusion head moves a little in z-direction. This process is repeated in layers and the material deposited on the build platform cools down and layers get attached to each other forming the desired solid shape. The most common form of material extrusion technology is Fused Deposition Modelling (FDM) [9] and [10]. Below Fig-1, shows a typical material extrusion machine setup.

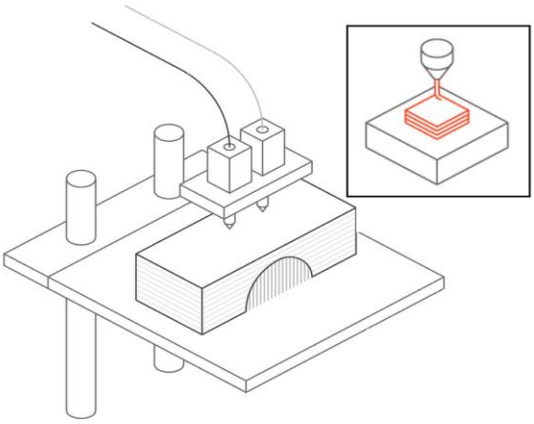


Fig -1: Typical material extrusion mechanism [11]

There are many factors that play a vital role in achieving an accurate print [12]. Factors such as material dispensing speed or extrusion speed, the orifice or nozzle temperature, layer height and build speed. These factors determine the resolution of the print and dimensional accuracy of the part. Typically, what has been observed is a smaller nozzle diameter and lower layer resolution contributes to better print resolution and smoother surface finished parts. Though all this is taken into consideration there are some limitations associated with this process [13]–[15]. Warping is one of the most common effect that is seen in FDM printed parts this occurs due to inappropriate heated bed and bad bed adhesion. A heated bed and a good adhesive bed keep the parts anchored to the build platform and limits the likelihood of warping. Second important aspect of FDM printing is layer adhesion, the layers should bond and solidify with the previously placed layer to form a solid part. To achieve this the layers are typically pressed against the previously placed layers and the hot extruded layer re-melts the previously placed layer, this downward force along with the heat, remelts the previously placed layer and forms a strong bonding. This downward force tells us that the deposited layers are not circular but oval forming small valleys which are stress concentrations and can crack when subject to load thereby leading to inherent anisotropic behavior [16] and rougher surface which can visualized as layer appearance on the surface of the part. Third aspect to consider is the support structure that is used while printing using FDM, In FDM for any overhanging structure which is shallower than 45 degrees to the build platform needs support. Usually, support in FDM are less dense structures removed after printing, but they have detrimental effect on the surface finish which makes post processing an essential part of this method of manufacturing. There are some support materials that are dissolvable in some solvents rather than removing it manually in such cases the printer uses two extruder heads and switches back and forth between two extruders to complete the print job. Lastly, the infill of the structure also plays vital role in FDM parts as it decides amount of material that is to be consumed and the build time required to finish the job. The infill density of a solid structure can be varied from 10% to filled depending upon the type of application. Typically for testing and visualization prototypes the common infill percentage in FDM printing is 20%. Infill geometries (lattice structures) and selecting an optimal infill percentage for a particular design is very critical and impacts the performance of FDM printed parts [17].

1.2 Associated materials

In material extrusion printing generally, thermoplastics are used as input material in the form of filament canisters or spools. By far printing material for FDM is way cheaper as compared to any other technology [14], and [18]. The materials range common from commodity thermoplastics to engineering grade and high-performance material. The higher the performance of the material, higher is the temperature required to print and thereby increasing the overall time and cost. Also, it is difficult to maintain the temperature when printing high temperature material as it cools down rapidly and initiates an effect of warping by creating more intense internal stress within the layers. Some of the common materials that are available for FDM printing are Acrylonitrile-Butadiene-Styrene (ABS), Polylactic Acid (PLA), Nylon, Polyethylene terephthalate glycol (PETG), Thermoplastic Polyurethane (TPU) and Polyetherimide (PEI). General characteristics of these type of materials is listed below in Table 1.

Material	Characteristics
ABS	▪ Good mechanical properties and temperature resistance ▪ Vulnerable to warping
PLA	▪ Very common & easy to print ▪ Lower impact strength, elongation, and temperature resistance than ABS
Nylon	▪ Suitable for end-use parts ▪ High flexibility ▪ Excellent chemical resistance
PETG	▪ High impact & chemical resistance ▪ Good thermal properties ▪ Vulnerable to warping

TPU	▪ Flexible and rubber-like parts ▪ Good elongation ▪ Difficult to print accurately
PEI	▪ Excellent strength to weight ▪ Fire and chemical resistance ▪ High cost

Table -1: Materials and characteristics associated with FDM printing

1.3 Design rules

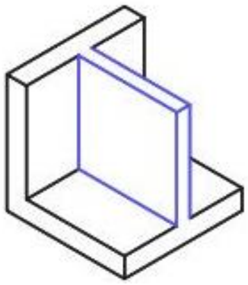
Although material extrusion is termed as the simplest form of 3D printing, there are number of limitations that are associated with this technology and as a designer one needs to take these factors into account to make sure that the part does not fail [6]. FDM printed parts display anisotropic behavior and require support material for printing, all the design rules are mostly centered around these two factors to minimize the print failure [19]. Some other common limitations include hanging structures and orientation of parts, infill density and holes. Support is required in case of hanging structures and this can be of two types: dissolvable support and breakaway support. The fundamental limitation of support material is if it is not dissolvable is it has detrimental effect on pasts surface finish. The type of support material that can be applied to a part is classified into two types: accordion support and tree-like support [15].

Hanging structures and orientation of parts: Accordion support is used in most of the cases because it offers more stability though good amount of material is consumed on the other hand tree-like structure is rarely used but one specific advantage of using this type of support is it does not deteriorate the surface of the part. Usually, a tradeoff is seen in orientating a part and obtaining a high-quality surface finish in parts because orienting a part in desired way leads to more support material and thereby increasing the time and cost and on the other side it provides smooth surface finish.

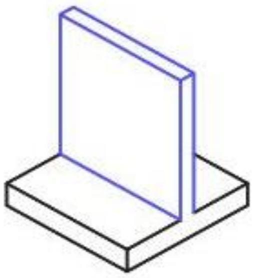
Anisotropic nature: While printing functional parts, which are subject to load in operations, a designer needs to keep in mind the anisotropic nature of FDM printing. In such cases, the build direction of the part should be parallel to the load.

Infill density: Infills allow parts to be printed faster and be more cost effective but the strength of the part is directly related to the infill [17]. There are four basic types of infill structures that are typically used are rectangular, triangular, wiggle and honeycomb. Depending upon the application weather the part is functional or demonstrative the infill density can be varied from 10% to 100 % (solid) fill.

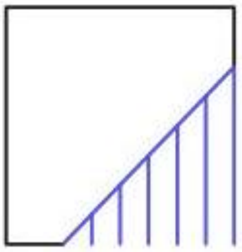
Holes: Vertical axis holes when printed in an FDM printer are typically smaller in diameter than the design intended. This is because of the force exerted on previously placed layer by the nozzle to form a strong bond making the extrusion deform into oval shape rather than being circular this increase the width of extruded segment and decrease the diameter of the hole. Moreover, FDM printing also encounters limitations when printing horizontals holes especially when the holes are large the top surface begins to sag and have poor surface quality. Fig-2. shows some common features that the designer needs to consider while designing parts for FDM printing. The values indicated below are only recommended values so that the print does not fail [20].



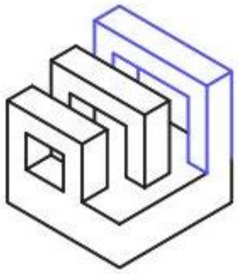
Supported wall = 0.8 mm



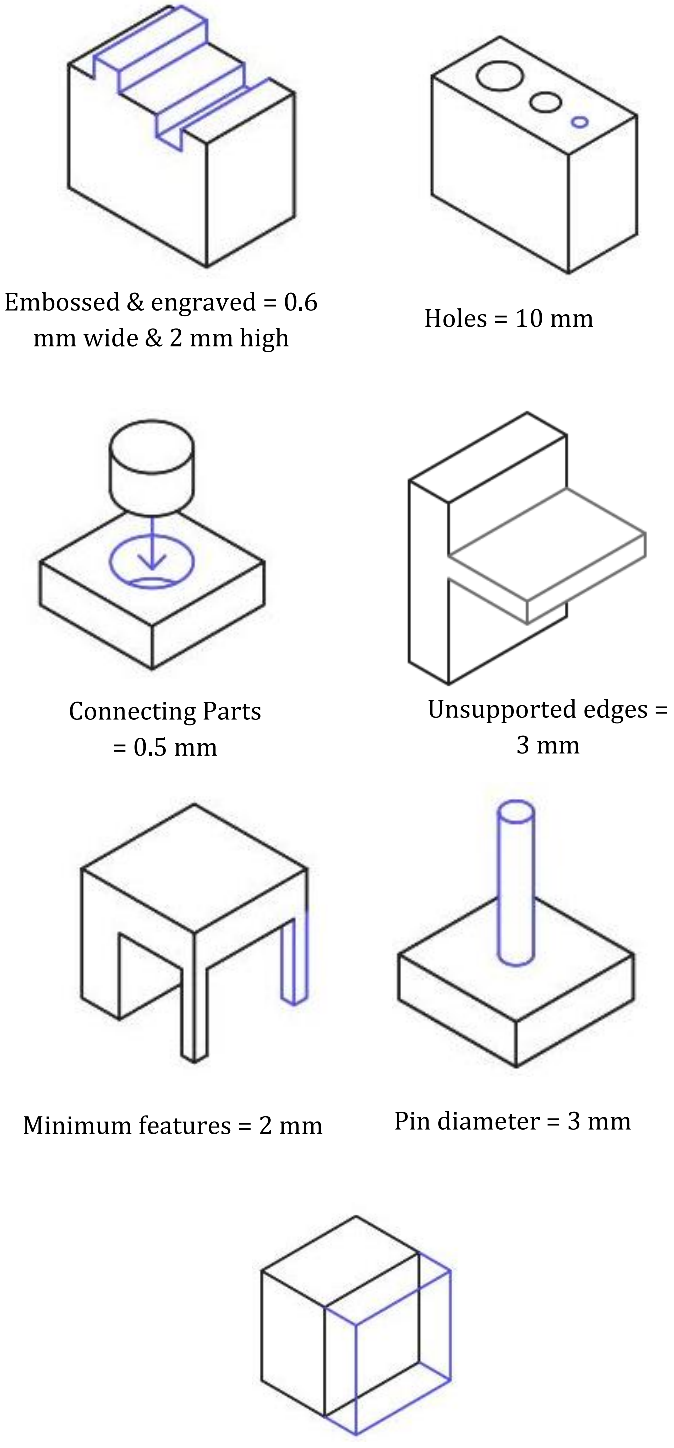
Unsupported wall = 0.8 mm



Support overhangs = 45°



Horizontal bridges = 10mm



Embossed & engraved = 0.6 mm wide & 2 mm high

Holes = 10 mm

Connecting Parts = 0.5 mm

Unsupported edges = 3 mm

Minimum features = 2 mm

Pin diameter = 3 mm

Tolerance = ±0.5% (±0.5 mm)

Fig -2: General design rules for material extrusion 3D printing [11].

1.4 Post-processing methods

Post processing is usually essential for FDM printed parts and it is important to consider how the overall dimensions of a part will have an impact if this is performed [21]. Below Table - 2 that shows common post processing options that are available for FDM.

Type	Process
Manual	Support removal
Surface finish	Sanding
	Gap Filling
Connecting	Cold Welding
Aesthetic	Polishing
	Priming & painting
	Metal Plating
	Vapor smoothing
	Epoxy coating

Table -2. FDM post processing methods

Manual - Support removal: In this process support is removed by either cutting or breaking manually by hand. The contact surface area requires sanding if a smooth surface is desired and in case of dissolvable support the support can be dissolved in solvent without loss of surface quality.

Surface finish - Sanding: Surface finish can be achieved in two ways either by sanding the part or filling the gap in parts with filler such as epoxy resin. After filling the gap and curing, the surface is sanded for better surface finish.

Surface finish - Cold welding: This is another process in which two parts are connected by melting the parts with an acetone bath. This is largely used where big designs are broken down into smaller components and are connected using this process. The joints are then sanded for better surface quality finish.

There are multiple ways in which a part can be made aesthetically pleasing like polishing, priming & painting, metal plating, vapor smoothing and epoxy coating.

Aesthetic - Polishing: After sanding, a plastic polishing compound is applied on the surface for better aesthetics. Polishing may not be suitable for designs with small intricate features.

Aesthetic - Priming & painting: This is the most common method of post processing in material extrusion 3D printing.

Like polishing, the better a surface is prepared before painting the better it will look after painting. Sanding with 600 grit sandpaper provides accurate surface. Primer is applied in two thin coats before painting. For printing, regular spray paint is suitable and will result in a smooth finish when applied correctly over several thin coats.

Aesthetic - Metal plating: If a metallic finish is desired the process of conductive coating followed by traditional metal coating processes is applied to achieve desired surface finish.

Aesthetic - Vapor smoothing: This is typically associated with parts printed in AB material. Parts are placed in a closed chamber with freezing temperature and are exposed to acetone vapor, providing the part a bath for a short period of time. This process washes away the top surface of the part and results in a smooth, polished surface. Depending on the degree of smoothing, this can result in some loss of details.

Aesthetic - Epoxy coating: Epoxy coating provides FDM parts with hard smooth outer coating. Two-part epoxies are the most common method used for epoxy coating FDM prints. As with other FDM coatings, sanding of the surface is an important initial step. The epoxy is then applied in thin layers and built up to the desired thickness.

1.5 Common applications

Material extrusion is a quick, design verification and prototyping process and is cost effective too [22]. It is well suited for functional as well as non-functional parts. Below are some of the common applications where FDM 3D printing is used widely:

Investment casting patterns: Due to the low cost of FDM materials and the complex geometries that the process can produce makes it a good solution for investment casting patterns. Also, the burnout process in case of casting becomes easier because the infill structure printed inside FDM parts is not solid.

Fig-3: Application of FDM printing in investment casting patterns.

Electronics Housing: Most popular application of FFF printing. FFF allows designers to create a prototype or final design in a matter of hours and is much cheaper compared to traditional manufacturing methods.

Fig-4: Application of FDM printed parts in Electronics Housing

Form & Fit Testing: To showcase the geometry as well as haptic feedback to the designer. FFF allows for the creation of curves and organic shapes which would be difficult to produce using conventional manufacturing techniques.

Fig-5: Application of FDM printing in Form & Fit Testing

Jigs and Fixtures: The high level of customization and complexity that FFF allows for in a design coupled with the speed and accuracy at which parts can be produced, makes it possible for creating grips, jigs and fixates

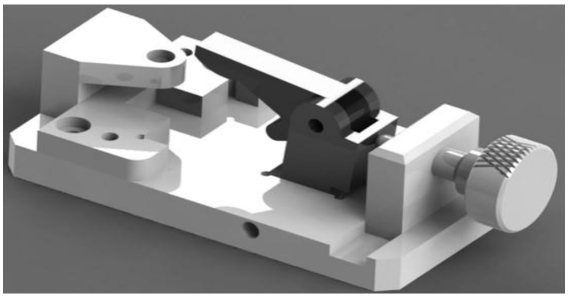


Fig-6: Application of FDM printing in jigs and fixtures.

2. RESULTS AND DISCUSSION

Material extrusion is one of the most widely process of 3D printing. Using this, prototypes and functional parts can be produced rapidly and at a low cost from a wide range of thermoplastic materials. But only knowing that the technology exist is not enough one needs to dig more into its process, operations, and applications. Due to the nature of FDM printing process, internal stresses are caused between each layer that distort the printing of parts slightly, leading to shrinkage and warping. Solution like printing rafts, a base layer printed on the bed for the build to be printed, well heated printing beds, and fillets at sharp edges and corners and avoiding large flat areas in design can help in reducing this form of occurring and provide us with better accuracy. Thermoplastics that require a higher print temperature are more at risk.

Typical build size of an FDM desktop machine is 200 x 200 x 200 mm and 1000 x 1000 x 1000 mm in case of industrial machines. Dimensional accuracy for FDM printers is ± 0.5% (lower limit ±0.5 mm) for desktop and ± 0.15% (lower limit ± 0.2 mm) for industrial machines. Common layer height is 50 to 400 microns. Support in most of the cases is essential to print an accurate part and is mandatory for overhangs less than 45 degrees and bridges longer than 10 mm.

3. CONCLUSIONS

Material extrusion technology is most popular choice of the user for rapid prototyping and developing functional prototypes for nor commercial use. As with any technology, there are certain benefits and limitations associated with it.

Benefits

- High dimensional accuracy and with intricate details.
- Ease of operations.
- Cost effective for custom thermoplastic parts.
- Largest globally exposed 3D printing technology.
- Range of materials.

Limitations

- Anisotropic nature of FDM 3D printed parts.
- Increase in infill percentage increases cost and build time.
- Visibility of layer lines which often required post processing.

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