Additive Manufacturing & 3D Printing

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Module - 3

Extrusion-Based AM Processes

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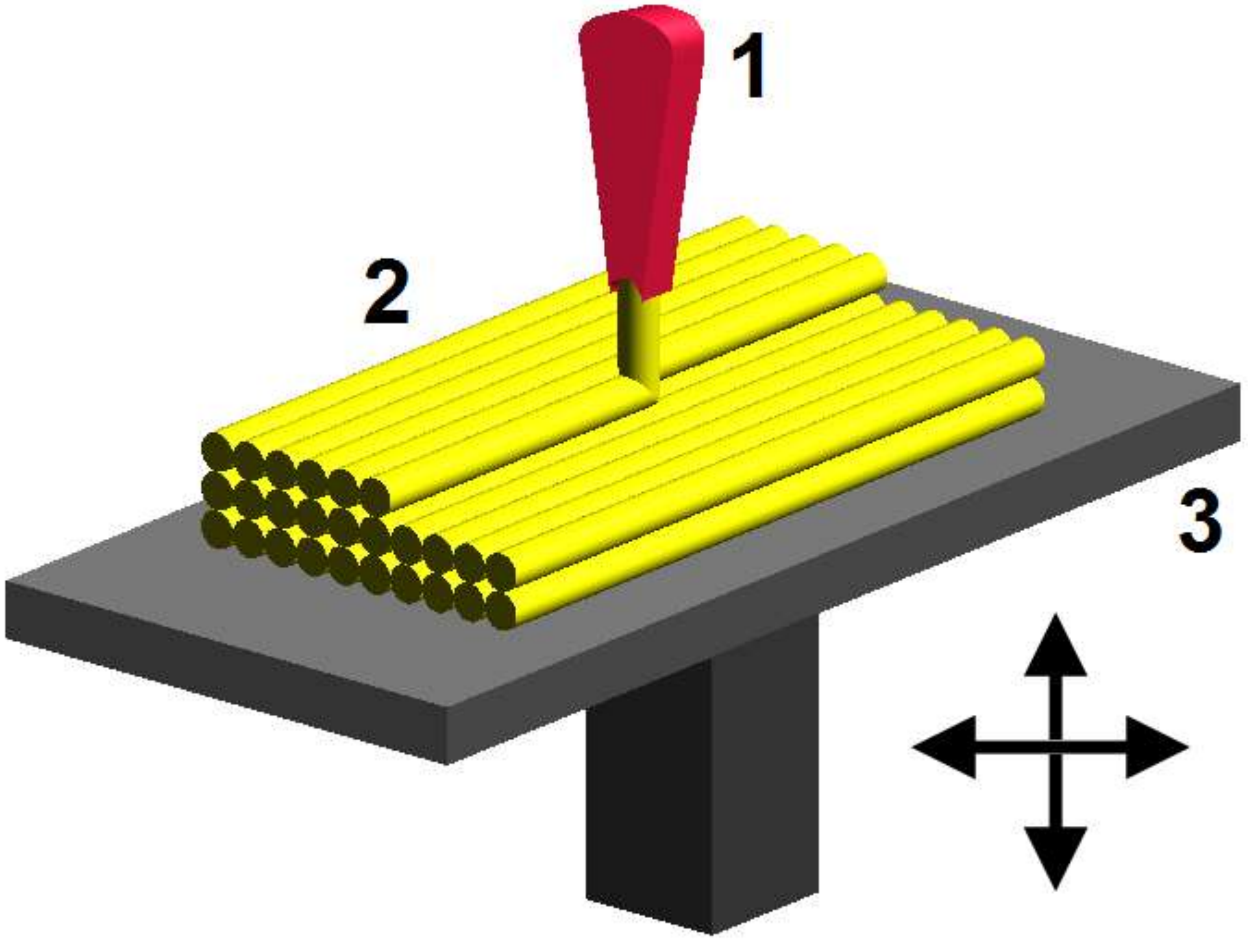
Lecture No 1

Extrusion-Based AM Processes

Introduction



Extrusion-Based AM Processes

- These technologies can be visualized as similar to cake icing, in that material contained in a reservoir is forced out through a nozzle when pressure is applied.
- If the pressure remains constant, then the resulting extruded material (commonly referred to as "roads") will flow at a constant rate and will remain a constant cross-sectional diameter.
- The diameter will remain constant if the travel of the nozzle across a depositing surface is also kept at a constant speed that corresponds to the flow rate.
- The material that is being extruded must be in a semi-solid state when it comes out of the nozzle.
- The material must fully solidify while remaining in that shape.
- The material must bond to material that has already been extruded so that a solid structure can result.

Basic Principles

- Loading of Material
- Liquification of the Material
- Application of pressure to move the material through the nozzle
- Extrusion
- Plotting according to a predefined path and in a controlled manner
- Bonding of the material to itself or secondary build materials to form a coherent solid structure
- Inclusion of support structures to enable complex geometrical features

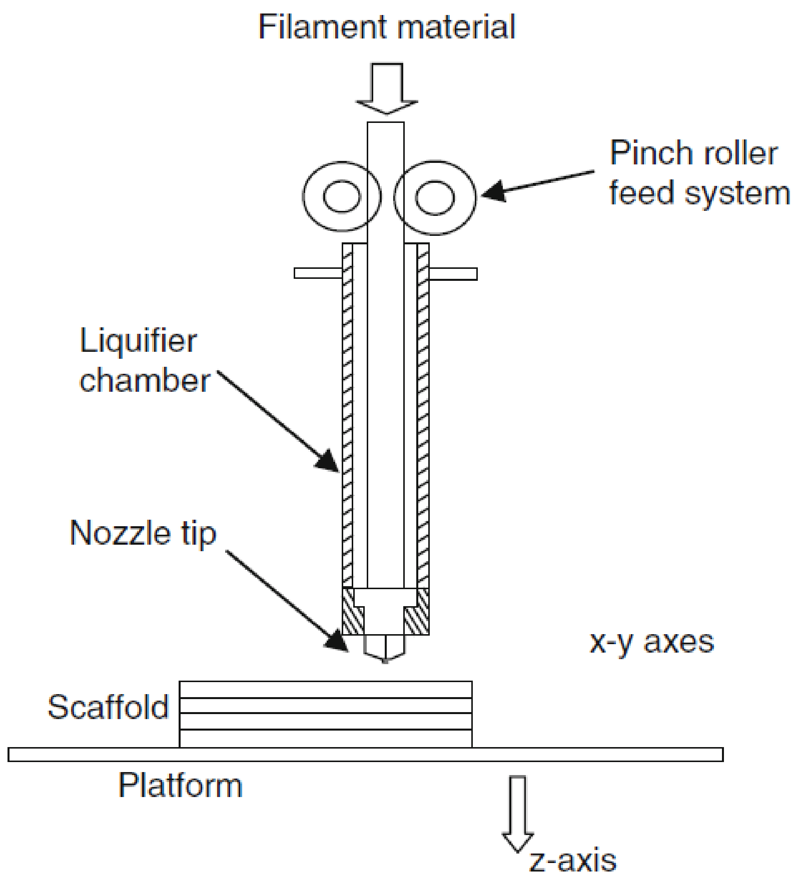
Basic Principles - Loading of Material

- Since extrusion is used, there must be a chamber from which the material is extruded. This could be preloaded with material, but it would be more useful if there was a continuous supply of material into this chamber.
- If the material is in a liquid form, then the ideal approach is to pump this material. Most bulk material is, however, supplied as a solid and the most suitable methods of supply are in pellet or powder form, or where the material is fed in as a continuous filament.

- The chamber itself is therefore the main location for the liquification process. Pellets, granules, or powders are fed through the chamber under gravity or with the aid of a screw. Materials that are fed through the system under gravity require a plunger or compressed gas to force it through the narrow nozzle.
- Screw feeding not only pushes the material through to the base of the reservoir but can be sufficient to generate the pressure needed to push it through the nozzle as well. A continuous filament can be pushed into the reservoir chamber, thus providing a mechanism for generating an input pressure for the nozzle.

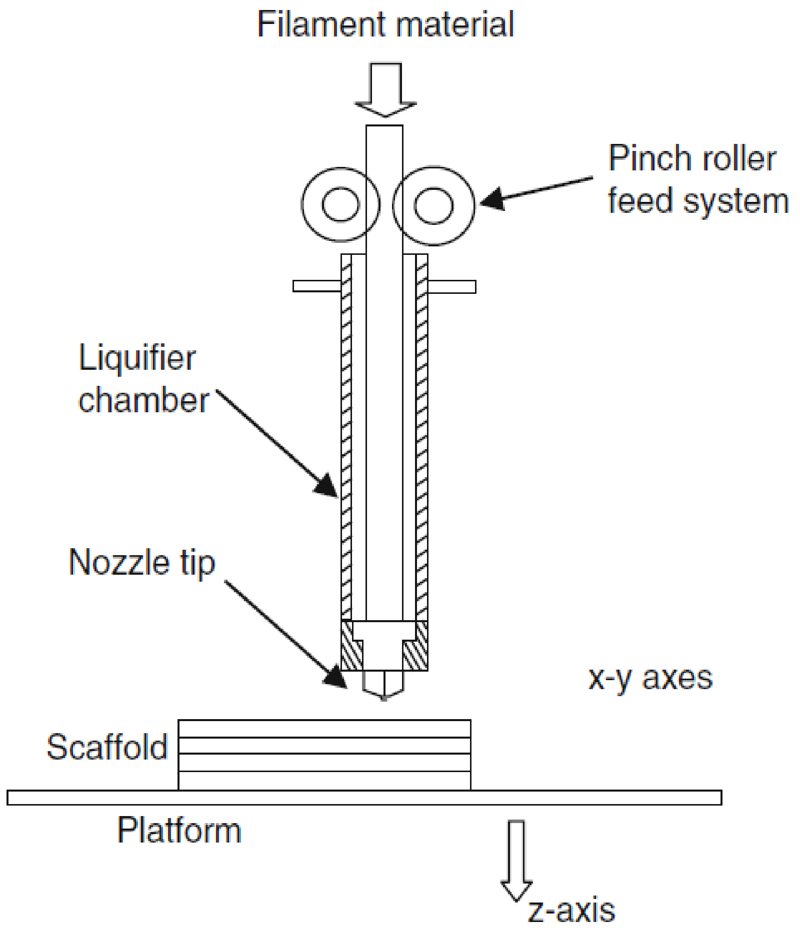
- Liquification

- The extrusion method works on the principle that what is held in the chamber will become a liquid that can eventually be pushed through the die or nozzle.
- The material could be in the form of a solution that will quickly solidify following the extrusion, but more likely this material will be liquid because of heat applied to the chamber.
- The heat would normally be applied by heater coils wrapped around the chamber and ideally this heat should be applied to maintain a constant temperature in the melt.



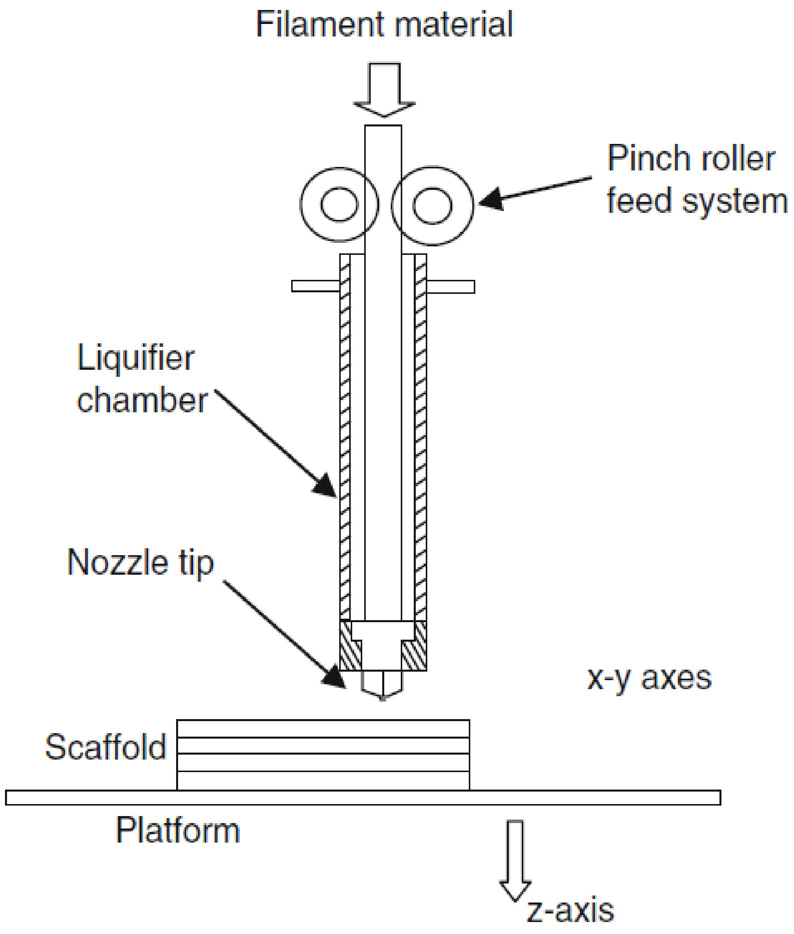
- Extrusion

- The extrusion nozzle determines the shape and size of the extruded filament.
- A larger nozzle diameter will enable material to flow more rapidly but would result in a part with lower precision compared with the original CAD drawing.
- The diameter of the nozzle also determines the minimum feature size that can be created.
- No feature can be smaller than this diameter and in practice features should normally be large relative to the nozzle diameter to faithfully reproduce them with satisfactory strength.
- Extrusion-based processes are more suitable for larger parts that have features and wall thicknesses that are at least twice the nominal diameter of the extrusion nozzle used.
- Material will flow through the nozzle is controlled by the pressure drop between the chamber and the surrounding atmosphere.



- Solidification

- Once the material is extruded, it should ideally remain the same shape and size.
- Gravity and surface tension, however, may cause the material to change shape, while size may vary according to cooling and drying effects.
- If the material is extruded in the form of a gel, the material may shrink upon drying, as well as possibly becoming porous.
- If the material is extruded in a molten state, it may also shrink when cooling.
- The cooling is also very likely to be nonlinear. If this nonlinear effect is significant, then it is possible the resulting part will distort upon cooling. This can be minimized by ensuring the temperature differential between the chamber and the surrounding atmosphere is kept to a minimum (i.e., use of a controlled environmental chamber when building the part) and also by ensuring the cooling process is controlled with a gradual and slow profile.

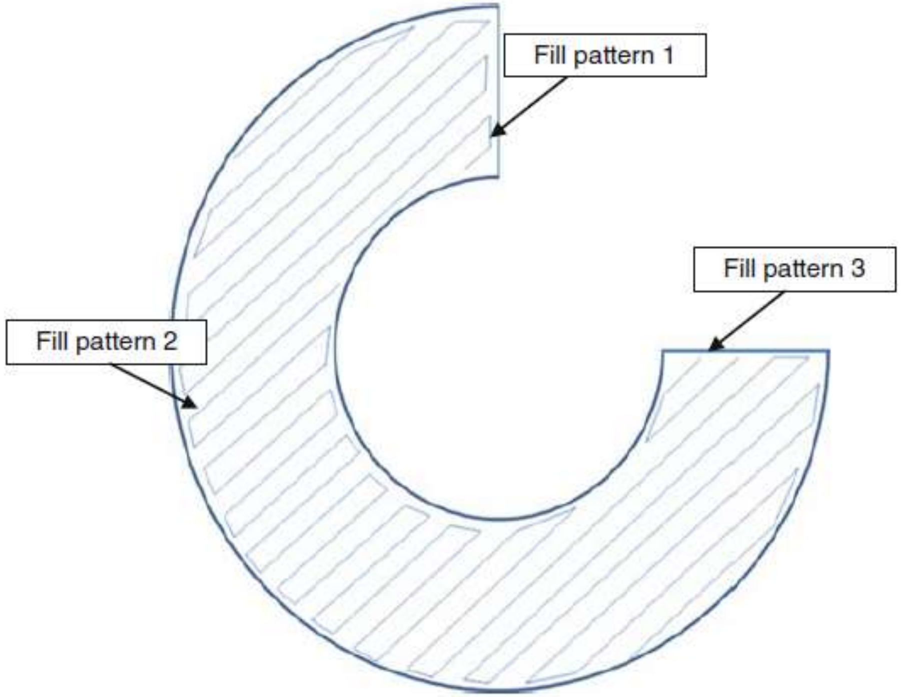


- Positional Control

- Like many AM technologies, extrusion-based systems use a platform that indexes in the vertical direction to allow formation of individual layers.
- The extrusion head is typically carried on a plotting system that allows movement in the horizontal plane. This plotting must be coordinated with the extrusion rate to ensure smooth and consistent deposition.
- The plotting head represents a mass and therefore contains an inertial element when moving in a specific direction, any change in direction must result in a deceleration followed by acceleration. The corresponding material flow rate must match this change in speed or else too much or too little material will be deposited in a particular region.
- Rapid changes in direction can make it difficult to control material flow, a common strategy would be to draw the outline of the part to be built using a slower plotting speed to ensure that material flow is maintained at a constant rate.

- Positional Control

- The internal fill pattern can be built more rapidly since the outline represents the external features of the part that corresponds to geometric precision.
- This outer shell also represents a constraining region that will prevent the filler material from affecting the overall precision.



- Bonding

- For heat-based systems there must be sufficient residual heat energy to activate the surfaces of the adjacent regions, causing bonding.
- Gel-based systems must contain residual solvent or wetting agent in the extruded filament to ensure the new material will bond to the adjacent regions that have already been deposited.
- In both cases, we visualize the process in terms of energy supplied to the material by the extrusion head. If there is insufficient energy, the regions may adhere, but there would be a distinct boundary between new and previously deposited material. This can represent a fracture surface where the materials can be easily separated. Too much energy may cause the previously deposited material to flow, which in turn may result in a poorly defined part.

Extrusion-Based AM Processes

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Lecture No 2

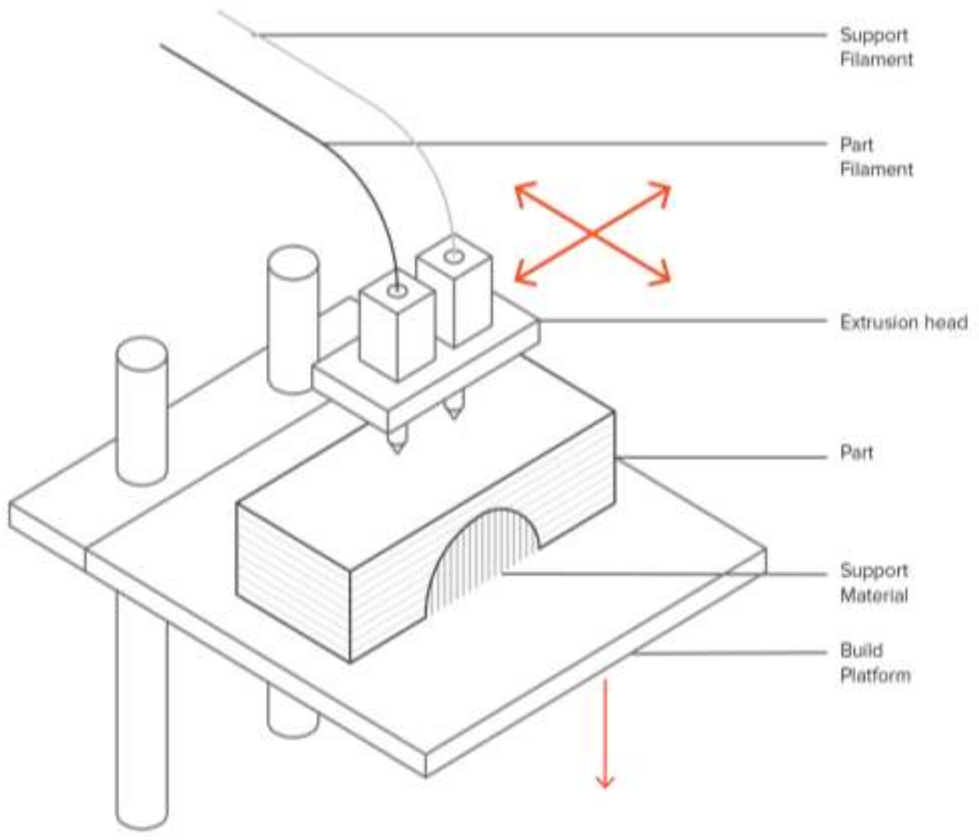
Extrusion-Based AM Processes

Extrusion-Based AM Processes

- A spool of thermoplastic filament is first loaded into the printer. Once the nozzle has reached the desired temperature, the filament is fed to the extrusion head and in the nozzle where it melts.

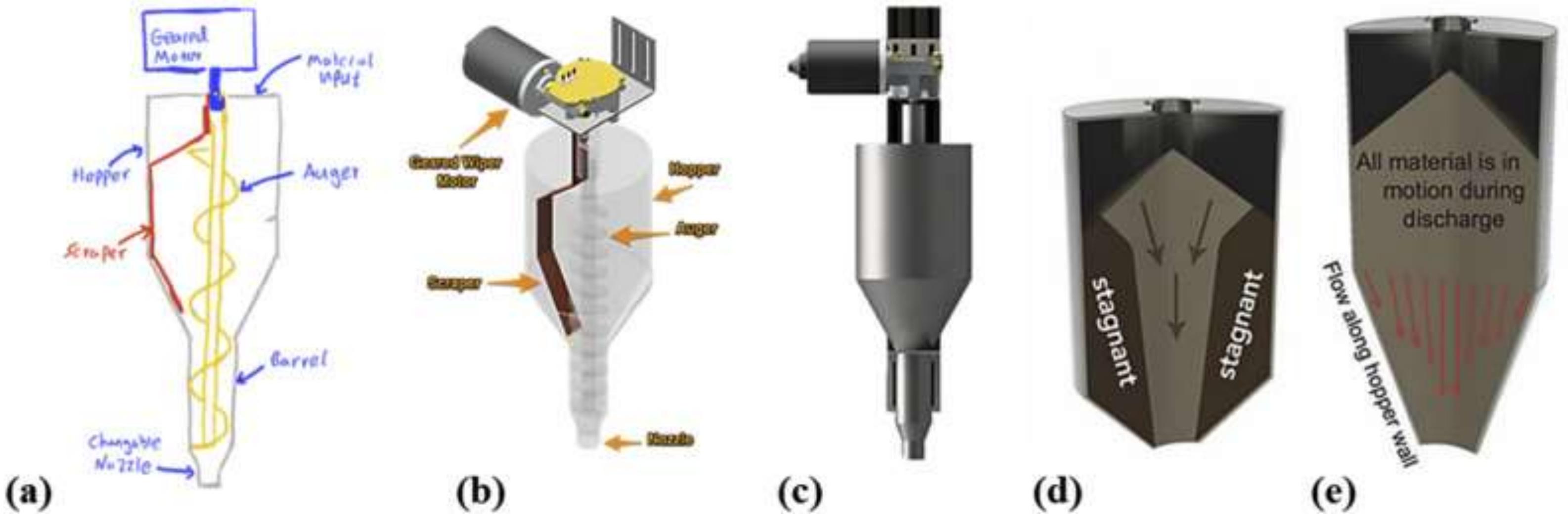
- The extrusion head is attached to a 3-axis system that allows it to move in the X, Y and Z directions. The melted material is extruded in thin strands and is deposited layer-by-layer in predetermined locations, where it cools and solidifies. Sometimes the cooling of the material is accelerated through the use of cooling fans attached on the extrusion head.

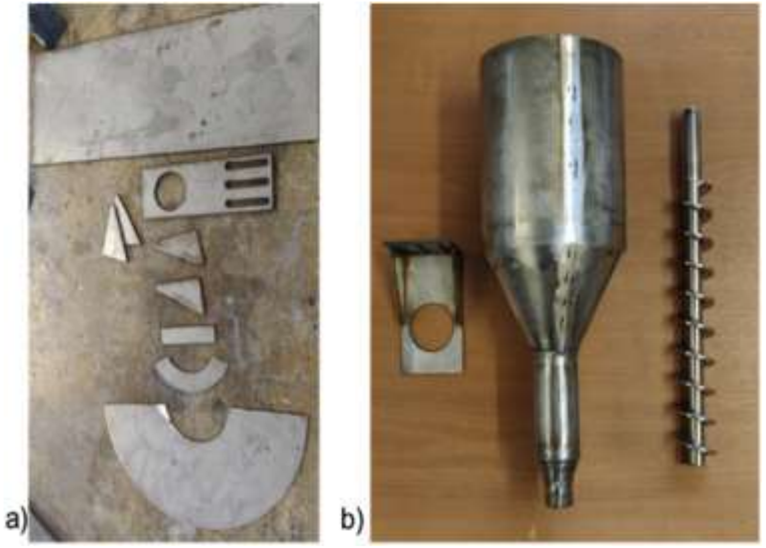
- To fill an area, multiple passes are required (similar to coloring a rectangle with a marker). When a layer is finished, the build platform moves down (or in other machine setups, the extrusion head moves up) and a new layer is deposited. This process is repeated until the part is complete.



Schematic of a typical FDM Printer

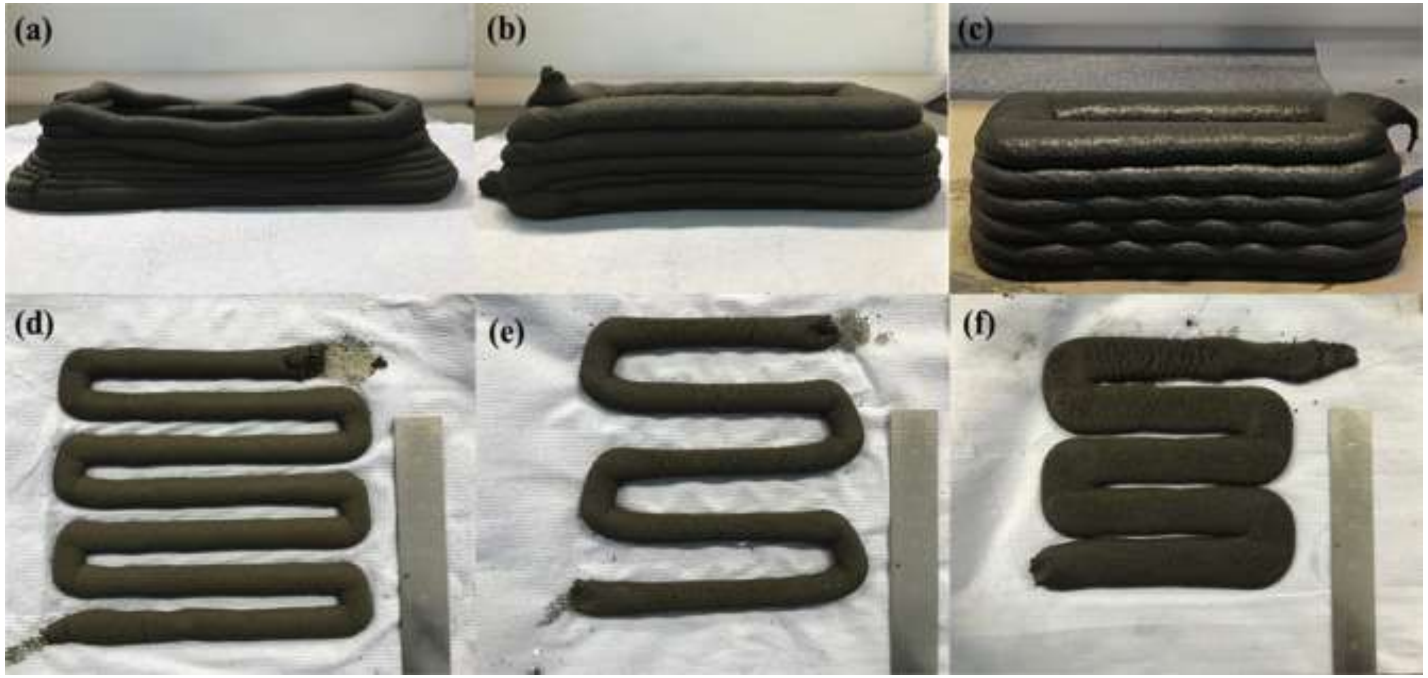
Nozzle Design





[1]Reference: Abdulrahman et. al. 2019

Nozzle Design



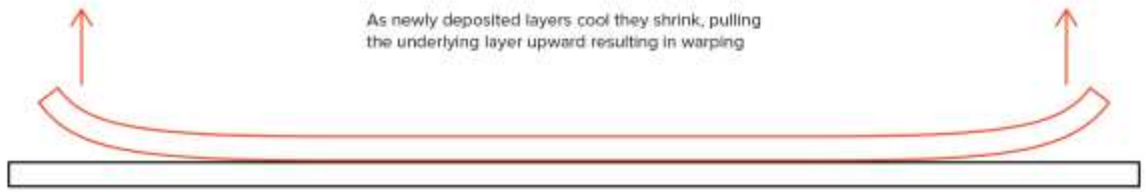
Printed samples using various nozzles dimeters (a,d) using a 10mm nozzle (b,e) 15 mm nozzle and (c,f) 20 mm nozzle.

[1]Reference: Abdulrahman et. al. 2019

Warping

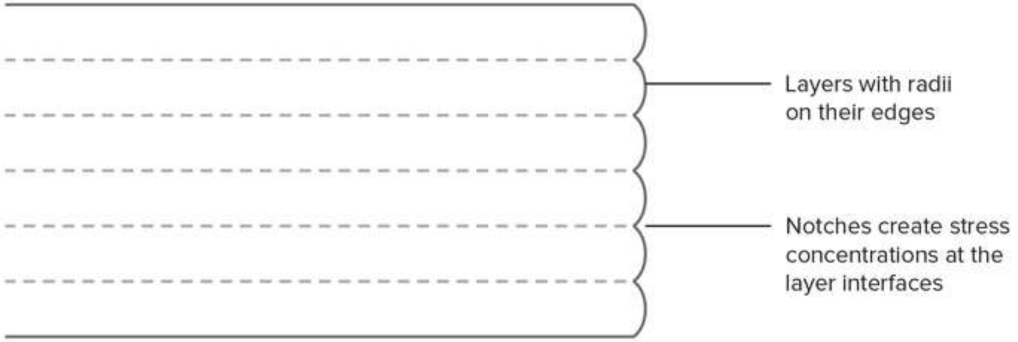
The **choices of the designer** can also reduce the probability of warping:

- **Large flat areas** (think of a rectangular box) are more prone to warping and should be avoided when possible.
- **Thin protruding features** (think of the prongs of a fork) are also prone to warping. In this case, warping can be avoided by adding some sacrificial material at the edge of the thin feature (for example a 200 microns thick rectangle) to increase the area that touches the build platform.
- **Sharp corners** are warping more often than rounded shapes, so adding fillets to your design is a good practice.
- **Different materials** are more susceptible to warping: ABS is generally more sensitive to warping compared to PLA or PETG, due to its higher glass transition temperature and relatively high coefficient of thermal expansion.



Layer Adhesion

Good adhesion between the deposited layers is very important for an FDM part. When the molten thermoplastic is extruded through the nozzle, it is pressed against the previous layer. The high temperature and the pressure re-melts the surface of the previous layer and enables the bonding of the new layer with the previously printed part.



Materials for 3D Printing Parts with FDM

Material	Description	Benefits	Applications
ABS-M30	General use "go-to" material. Variety of color options. Good for parts 1" inch cubed to parts larger than 5' feet.	•Up to 70% stronger than ABS	•Concept parts
		•High or coarse resolutions available for finer features or	•Production parts
		•Quick turn prototype and functional models	•Lightweight custom jigs & fixtures
			•Thermoform tools
ABS-ESD7	Strong ABS thermoplastic compounded with carbon resulting in static dissipative properties	•Static dissipative properties for applications where a static	•Fixtures, cases, enclosures for electronic component assembly
		•Impair performance	•Packaging
		•Cause an explosion	•Production line/conveyer parts
ABSi	Superior strength ABS; Translucent	•Superior strength vs. ABS	•Conceptual parts
		•Durable	•Light transmission
		•Translucency in three colors - Natural (clear), Amber, Red	•Material flow monitoring
			•Functional prototyping
ABS-M30i	Bio-compatible (ISO 10993; USP Class VI) NSF 51 Food-contact certification	•Good tensile, flexural & impact strength	•Medical handling
		•Gamma and EtO sterilizable	•Food handling
			•Pharmaceutical handling and tools

Materials for 3D Printing Parts with FDM

Material	Description	Benefits	Applications
ASA	General use "go-to" material UV-stable with a variety of color-fast color options	•Great heat resistance vs. ABS	•Automotive, electrical housings
		•Great aesthetics	•Sporting goods
		•Easy to work with matte finish	•Outdoor goods
		•Resists fading & significant mechanical degradation over	•Recreational vehicles
			•Tooling masters
PC	Accurate, rigid, stable	•RF transparent	•Rapid tooling
		•High tensile and flexural strength	•Concept models
		•Higher heat resistance	•Jigs & fixtures
			•Extrusion blow molding
PC-ABS	Superior strength & heat resistance of PC with flexibility of ABS	•High impact strength	•Industrial equipment manufacturing
		•High heat resistance	•Form, fit, functional prototypes
			•Low volume production parts
PC-ISO	Accurate, rigid, stable; Bio-compatible (ISO 10993; USP Class VI)	•Gamma & EtO sterilizable for medical	•Food packaging
		•RF transparent	•Drug packaging
		•High tensile and flexural strength	•Medical device manufacturing
		•Higher heat resistance	

Materials for 3D Printing Parts with FDM

Material	Description	Benefits	Applications
PPSF (aka PI	PPSF (PPSU) combines strong mechanical performance with high temperature and chemical resistance	•Suitable for steam autoclave, EtO, plasma, chemical, and	•Functional prototypes exposed to extreme conditions
		•Heat and chemical resistance	•Filter housings
		•Strong mechanical properties	•Under-hood automotive scenarios
ULTEM™ 1(	Rigid, highest heat resistance; FST certified; Bio-compatible; Food contact certified	•Steam autoclavable	•Aerospace applications
		•NSF-51 food contact	•Composite tooling
		•Bio-compatible ISO 10993/USP Class VI FST	•Medical applications
			•Food contact applications
ULTEM™ R	High strength, high heat resistance; FST certified per "14 CFR/FAR 25.853" & "ASTM F814/E662"	•High strength to weight ratio	•Aerospace applications
		•High thermal and chemical resistance	•ECS ducting
			•Metal forming tools
ULTEM™ 9(	FDM Pro - Low coefficient of variance and increased mechanical properties vs. the standard ULTEM™ 9085 Resin. FST certified per "14 CFR/FAR 25.853" &	•High strength to weight ratio	•Aerospace applications
		•High thermal and chemical resistance	•Aircraft interior replacement parts
		•Leading repeatability part to part	•ECS ducting
			•Metal forming tools

Materials for 3D Printing Parts with FDM

Material	Description	Benefits	Applications
Nylon 12	High elongation at break, fatigue resistance; Resistance to moderate solvents, alcohols, chemicals	•High fatigue resistance	•Panels, covers, housings with snap-fit clips
		•Exposure to shock, repeat load cycles, stress or vibration	•Environmental control ducting or venting
			•Drill guides
			•Parts exposed to high vibration, repetitive stress
Nylon 12CF	Chipped Carbon Fiber filled Nylon 12 combined with Electrostatic Discharge (ESD) Properties	•Highest Strength & Stiffness to weight ratio	•Tooling applications
			•Metal replacement
			•Lightweight functional prototypes
			•Select end use parts
Antero 800N	Antero™ 800NA PEKK-based thermoplastic combines FDM's design freedom and ease of use with the excellent mechanical properties and low outgassing	•High strength to weight ratio	•Aerospace applications
		•High thermal and chemical resistance	•Aircraft interior replacement parts
		•Leading repeatability part to part	•ECS ducting
			•Metal forming tools
Antero 840C	Antero™ 840CN03 is a PEKK-based FDM thermoplastic combining the excellent physical and mechanical qualities of PEKK with electrostatic	•Exceptional chemical and wear resistance	ESD values range from 104 – 109 ohms per square inch. This makes the material particularly suitable for space and industrial applications where these qualities are critical.
		•Ultra-low outgassing properties	
		•Consistent ESD performance	

Applications

- Concept or Design Visualization.
- Direct Use Components.
- Investment Casting.
- Medical Applications
- Flexible Components

Advantages

- Strength and temperature capability of build materials.
- Safe laser free operation.
- Easy Post Processing.

Disadvantages

- Process is slower than laser based systems.
- Build Speed is low.
- Thin vertical column prove difficult to build with FDM.
- Physical contact with extrusion can sometimes topple or at least shift thin vertical columns and walls.

Thanks