# FDM Process

The fused deposition modeling process uses a heated nozzle to melt the material before extruding it. Commonly used materials are nylon, ABS plastic and wax. These materials are supplied as a rod or filament and driven with the help of rollers and a motor. The nozzle is moved according to the G-Codes obtained from CAD files to 3-D print the object point by point and layer by layer.

# Desired Material Properties

## Thermo-physical properties

* Acceptable melting and solidification temperature range
  + Melting point should be high enough to have a high softening or heat distortion temperature
  + Melting point should be low enough to avoid high temperatures for processing. Temperature within the range of 70°C to 100°C is preferred
  + Solidification temperature range should be 5°C to 10°C below the softening temperature
* Low thermal expansion coefficient: This is critical for achieving dimensional accuracy in the manufactured part. The linear shrinkage within a part between build and end-use temperatures should be lower than 1 percent.
* Low shrinkage
* Good resistance to heat
* No or very less volatile molecules when material is liquid
* No phase transformation in solid form: Semi-crystalline polymers consist of a crystalline as well as amorphous part. The transformation from solid to liquid for amorphous part is gradual in nature without any fixed temperature

## Mechanical properties

* A material must have adequate strength, flexibility and ductility so that it can be drawn into filaments and used to push out the melted or fused portion near the nozzle.
* In order to retain the surface quality, the material needs to be rigid. This helps to guard the part against surface wear and tear
* Initial raw material for FDM is usually a thermoplastic which needs to be melted. Thus, it should have low viscosity in liquid form so that it can be easily dispensed from the nozzle
* After being deposited, the material must be able to solidify in a short amount of time for acceptable build speed. However, a layer which is solidifying needs enough time to properly attach to the layer beneath it
* Process of solidification should lead to low or acceptable internal stress otherwise the mechanical properties of the part will be compromised

# Preparation and characterization of 3D printed continuous carbon fiber reinforced thermosetting composites

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## Introduction:

* Due to high specific strength and stiffness along with good fatigue performance and corrosion resistance, continuous carbon fiber reinforced thermosetting composite structures are widely used in fields of aeronautics and astronautics.
* High manufacturing costs limit their application to industries requiring high production rate.
* Owing to recent developments in additive manufacturing and 3D printing, methods have been developed for manufacturing metallic and ceramic materials along with plastics, biological materials, flexible films etc.
* Relative mechanical properties and performance of 3D printed materials have been characterized.
  + <https://www.sciencedirect.com/science/article/pii/S0142941816312946>
  + <https://www.sciencedirect.com/science/article/pii/S0142941817300065>
* Short fiber reinforced 3-D printed composites:
  + <https://www.sciencedirect.com/science/article/pii/S1359836816321230>
  + (Access Required for complete paper) <https://www.scopus.com/record/display.uri?eid=2-s2.0-0032131003&origin=inward>  
    Gray et. al, used FDM to reinforce polypropylene(PP) strands using thermotropic liquid crystalline polymer(TLCP) through a process using a dual extruder. Process allowed PP with a melting temperature of 165°C using TLCP (Vectra A950) which has melting temperature of 283°C. Strands were extruded again using a capillary rheometer to form monofilaments which simulated a piston actuated FDM process. Tensile properties of strands improved with the draw ratio. Upon compression at temperature just above the melting point of matrix, the tensile modulus was reduced by 20 percent. Tensile properties of the extruded monofilament depend upon capillary’s diameter and length to diameter ratio along with the shear rate caused due to alignment of TLCP fibrils. *Capillary rheometer forces fluid through a tube of constant cross-section. One among flow rate and pressure drop is fixed while the other is measured. Flow rate converts to shear rate and pressure drop to shear stress.*
  + <https://www.sciencedirect.com/science/article/pii/S0921509300018104>  
    Zhong et. al. modified Acrylonitrile-butadiene-styrene(ABS) using short glass fibers to increase strength. This caused a reduction in flexibility and ease of handling. This was overcome using agents to increase plasticity and compatibility.  
    **Equipment** used consisted of:
    - A twin screw extruder TE-34 with diameter 34mm and L/D ratio 34
    - A single screw extruder with diameter 30mm and length 800mm
    - Multifunctional rapid prototyping and manufacturing machine MEM-250

**Sample** was prepared by mixing raw materials in twin-screw extruder which gave out granulated small pellets. These pellets were fed into the single screw extruder and drawn into filament of diameter between 1.75 to 1.90 mm by adjusting single screw’s rotational speed and tractor’s filament pulling speed. This filament was rolled onto a drum and fed to the MEM 250. Nozzle temperature was 250°C and build chamber was maintained at 60°C. Two samples were obtained of 90mm length and 20mm width. However, for the first sample, the direction of sample length was same as the nozzle movement whereas for the second sample it was perpendicular.  
**Modification** by addition of short glass fiber, led to higher heat distortion temperature and surface rigidity whereas the shrinkage decreased. However, the surface toughness was reduced making the filament brittle and unsuitable for FDM process. Changing the glass fiber content was not feasible. process included addition of an engineering plastic with softening temperature of around 100°C. Since ABS begins to flow at 200°C, there was ample range for making changes. Next approach added LLDPE which is a linear flexible polymer into GFABS-30(Glass Fiber – 30%) with GF weight content of 10.2 and 13.2 percent. Composite filaments were successfully extruded and it was observed that toughness and appearance of filaments with only 10 percent LLDPE was better than those with higher percentages of LLDPE. This could be attributed to limited compatibility between LLDPE and ABS. LLDPE mixes well with ABS when it’s only 10 percent but higher percentages lead to phase separation. On observing through a microscope, it was indicated that the core and surface of drawn filament were separated into two layers for samples having higher LLDPE percentages. The incompatibility was overcome through addition of 10 grams of hydrogenated Buna-N in 13.2 and 18 percent GFABS. Buna-N has butadiene and acrylonitrile groups similar to ABS along with a main chain structure which is similar to LLDPE. Thus, it makes ABS and LLDPE compatible (no separation between core and surface regions) and improved the properties such as toughness and appearance of composite material. Scanning electron microscope (SEM) pictures were taken by soaking filament samples in liquid nitrogen which froze the structure and allowed the filament to be broken in a brittle manner. It was seen that phase particles of LLDPE are much larger in size without the Buta-N to create interfacial compatibility. Buta-N also promotes the uniform dispersion of LLDPE through ABS resulting in better mechanical properties and surface quality.  
**Mechanical properties** indicated that the strength of modified GFABS is much higher than unmodified and normal ABS. [Doubt regarding correct interpretation] Addition of short glass fiber reduced the adhesive strength between layers but increased with the increment of GF content. It is speculated that this occurs due to bridging together of glass fibers through adjacent layers before solidification.

Increasing glass fibers results in more input force required for extrusion or injection. This leads to a higher tool wear rate and needs to be balanced.

* + Tensile and thermomechanical properties of short carbon fiber reinforced polyamide-6 composites prepared using FDM have been studied  
    <https://www.sciencedirect.com/science/article/pii/S135983681300125X>
  + Mechanical properties in short carbon fiber reinforced plastics have been studied.  
    <https://www.sciencedirect.com/science/article/pii/S0266353814003716>  
    <https://www.sciencedirect.com/science/article/pii/S1359836815003777>
* Continuous carbon-fiber reinforcement:
  + Methods for 3D printing of continuous carbon fiber reinforced plastics  
    <https://link.springer.com/chapter/10.1007%2F978-3-642-41329-2_17>
  + Using MakerBot  
    <https://link.springer.com/chapter/10.1007%2F978-3-642-41329-2_17>  
    <https://scholar.google.com/scholar_lookup?title=Evaluation%20of%20dimensional%20accuracy%20and%20material%20properties%20of%20the%20MakerBot%203D%20desktop%20printer&author=W.M.%20Garrett&publication_year=2015&pages=618-627>  
    <https://www.sciencedirect.com/science/article/pii/S0263822316311497>  
    <https://www.sciencedirect.com/science/article/pii/S0264127516305196>
  + Carbon fiber reinforced polylactide to investigate interfacial performance and mechanical properties  
    <https://www.sciencedirect.com/science/article/pii/S1359835X16301695>
  + Continuous carbon-fiber reinforced polylactic acid composites using rapid prototyping  
    <https://www.sciencedirect.com/science/article/pii/S0924013616302515>

## Equipment

The 3D printing platform consists of a fiber bundle conveying pipe, epoxy pool, printing head and building platform along with guide rails and a control panel. Software used to control the 3D printing is Repetier-Host which is open source. The 3D printer is modified to prepare components in 3 axes by controlling rotational angle position. Four stepper motors are used to control nozzle path, X,Y,Z axes and rotation angles in XY, XZ and YZ planes. Displacement and control of rotation angle have an accuracy of ±0.2mm and 0.1 ̊ respectively.

**Material** used was epoxy resin (E-54(616)) for thermosetting matrix and carbon fiber bundle for reinforcement containing 3000 fibers of HF10 in a bundle. The viscosity of epoxy is 5000 to 10000 mPa s at 25°C. The carbon fiber bundle has a density of 1.78 g/cm3, tensile strength of 3530 MPa and elastic modulus of 221 GPa.

**Manufacturing** was done using three schemes of a lamina, honeycomb and grid. Fiber bundle went to the epoxy resin pool from supply coil and then to the printing head. Nozzle tip diameter was 2mm, layer height was selected as 1mm and the feed rate of filament was 100 mm/min. The distance between centers of two adjacent fibers (hatch spacing) was set to 1 mm. Speed of printing head or transverse speed was set to 200 mm/min. Epoxy content can be controlled using three rods in epoxy resin pool. Software controlled the printing speed and path. After printing, the samples were cured in a high temperature chamber.

## Mechanical properties

Three point bending and tensile tests were done on 5 specimens of dimension 250mm x 25mm x 3mm. Speed for tensile test was 2mm/min, the three point bending test had the same loading velocity with a loading rod diameter of 5mm. The tensile strength observed was 792.8 MPa which is much higher as compared to the reported tensile strength values for continuous carbon-fiber-reinforced polylactic acid composites (91 MPA Li. Et. al. and 464.4 MPa Klift et. al.). Tensile elastic modulus was calculated as 161.4 GPa which is much higher than the Young’s modulus of SiC/C-filled thermosetting composites reported by Compton et al. at 24.5 GPa. Flexural strength was 202.0 Mpa whereas that of fiber-reinforced polylactic acid composites and short carbon fiber thermoplastic composites was 156 Mpa and 68 MPa respectively. Elastic modulus was 143.9 GPa. Thus, the mechanical properties of 3D printed continuous carbon fiber reinforced thermosetting composites were better as compared to printed continuous carbon fiber thermoplastic composites or printed short carbon fiber thermosetting composites.