Analyzing the effect of nozzle diameter in Fused Deposition Modeling using open source 3D printer

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Abstract: This report provides brief information about advances that has been made in the past years in the field of Fused Deposition Method. Many open source research papers have been reviewed and complete perception has been taken in account that is covered in here. This field still under being research, a primarily focus only on specific objectives to be presented through research gap needs to be achieved by the end of this review. A short account is provided on the working related to 3D printer. The Process parameters described in various papers are noted and a brief description of their behavior with various properties has been given. The ASTM standards D638 and D780 are used For testing. The specimen were created using Tarantula 3D printer. The testing was carried out at ISO certified Institute 'ALEKH Plastic Testing Center'. The observations and measurement of all related parameters is carried out and an optimal diameter of nozzle is derived which needs to be manufactured and test to compare results in future.

Keywords : Process Parameters, 3D Printing, Fused Deposition Method (FDM), Carbon Fiber, PLA, ABS.

I. Introduction

In this section, theories related to proposed dissertation work is discussed in detail.

1.1 3D Printing

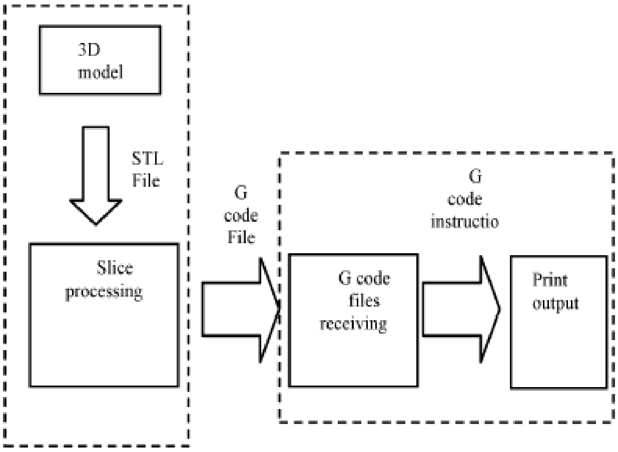


Figure 1: The process flow of 3D printing [1]

Every 3D print starts as a digital 3D design file – like a blueprint – for a physical object. Trying to print without a design file is like trying to print a document on a sheet of paper without a text file. This design file is sliced into thin layers which is then sent to the 3D printer. All 3D printing technologies create physical objects from digital designs layer by layer, but each using its own proprietary method. To shed the confusion, we've created an infographic highlighting all the main technologies starting from the high level grouping, guiding through the printing process, exact technology titles, material options and ending with the key industry players.

The main components of a 3D printer:

1. Print Bed (Tray):This is the flat surface where the 3D models are layered during printing. The print bed may be ambient or heated Depending on the filament types used in the printer. Heated print beds are used to keep the printed section of the print warm during the layering process to prevent warping.
2. Extruder : The extruder is the part that thrusts out and feeds the plastic filament (or any other filament) into the ‘hot-end’. Extruders are typically incorporated into the hot-end, however in some types it can be remote, pushing the filament through a tube, called a Bowden cable, into the hot-end. In some types a dual extruder is used, which provides the ability to print two different materials at the same time. This added feature result in increased price, as it requires an extra extruder, and hot end.
3. Hot-end :The hot-end is composed of a heat source, a temperature sensor, and an extrusion tip where plastic filament is fed though to deposit molten material, it is often confused with the extruder. The hole in the slot may range in size, typically between 0.2mm and 0.8mm. The smaller the nozzle, the more detailed the print, but the longer it takes for the thinner layers to stack up.
4. Filament: The filament is the input material which is formulated as a 3D solid object by the printer. Like an inkjet inject ink, a 3D printer emits melted filament.

Current 3D printing technologies are as follows:

Stereo lithography (SLA): Position a perforated platform just below the surface of a vat of liquid photo curable polymer. A UV (Ultra Violate) laser beam then traces the first slice of an object on the surface of this liquid, causing a very thin layer of photopolymer to harden. The perforated platform is then lowered very slightly and another slice is traced out and hardened by the laser. Another slice is then created, and then another, until a complete object has been printed and can be removed from the vat of photopolymer, drained of excess liquid, and cured.

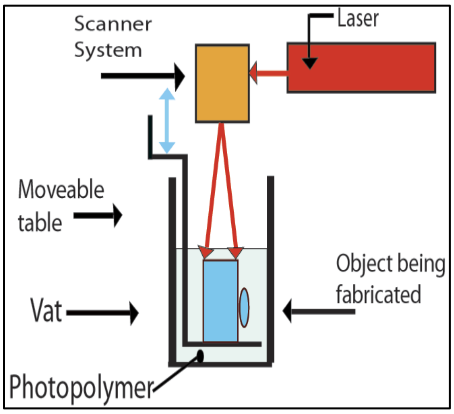


Figure 2: The Stereolithography process[17]

Fused deposition modelling (FDM) : Here a hot thermoplastic is extruded from a Temperature-controlled print head to produce fairly robust objects to a high degree of accuracy.

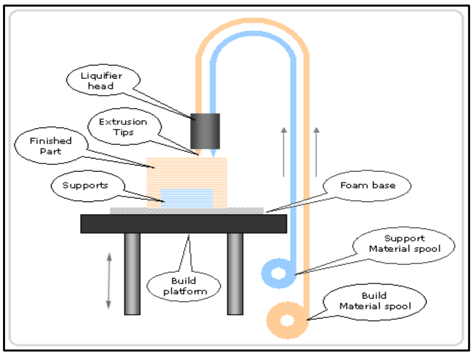


Figure 3: The FDM process setup and working[18]

Selective laser sintering (SLS): This builds objects by using a laser to selectively use together successive layers of a cocktail of powdered wax, ceramic, metal, nylon or one of a range of other materials.

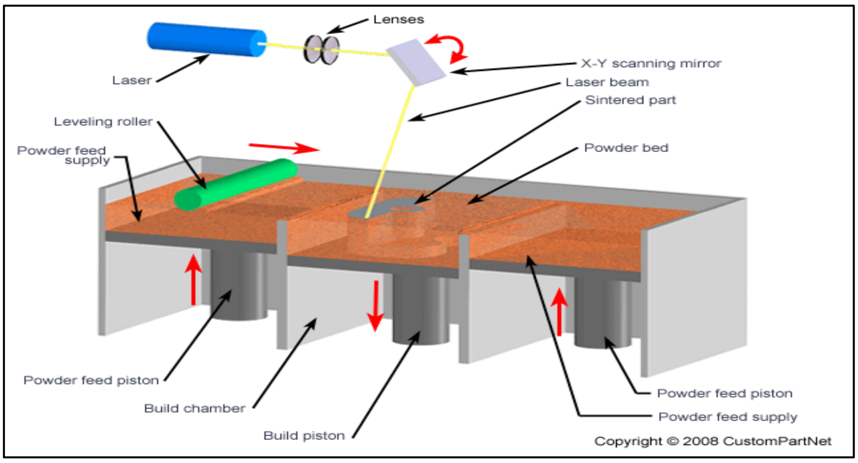


Figure 4: The process of SLS[19]

II. Literature Review

The Field of Rapid Prototyping has developed since last two and half decades from a research oriented practice to a more commercialized Industry so much that now it is being incorporated in field besides those directly affected by it. Already existing Industrial machines are now being customized to improve their output and performance to an extent. Though very expensive with many material constraints are difficulties to be overcome in studying process parameters. Fused (FDM) is a process of surface bonding, Heat energy transfer in Rapid Prototyping usually regarded in Additive layer manufacturing technology. In this, thermoplastics filaments are heated and pushed through a extruder that moves in the x-y directions. The processor is controlling the extruder head which deposits very tiny beads of material on the base plate to form the first layer then continues to do it layer after layer. The base plate or platform is maintained at normal degrees of temperature thus material swiftly hardens. Then the platform is moved downwards or head is moved upwards by the specified distance (i.e., layer thickness). The process is repeated again until the desired design of specified dimensions. This paper reviews the specifically selected papers from a variety of different sources in this decade.

Literature Review: The literature review comprises of few selected papers that are highly relevant for understanding the process parameters that are highly important for process of FDM.

At best all that is necessary for developing a quantitative model for optimization of process is described in here.

The invention of 3D printing had a large impact on various field since the requirement for a various types of materials which can be utilized in any particular application. An artificial biomaterial such as polylactic acid (PLA) is bio-degradable which is needed especially in orthopedics because it has the ability to be a base as platform for generating natural tissues. A study investigated the suitability of extruding PLA to observe various physical properties of the final design and its use in scaffold design.

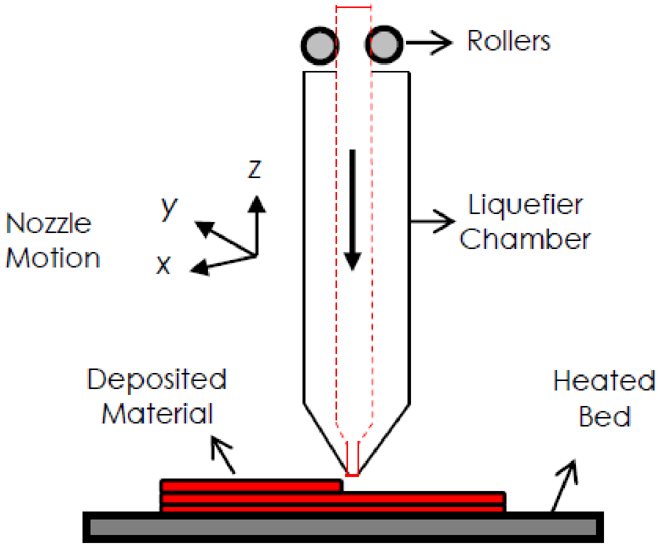


Figure 5: The basic process of FDM[1]

The working as shown in above image shows that the force from the stepper motor pushes the filaments from the liquefying heater at a constant rate. The pressure drop from the motor needs to be watched and control along with the nozzle's geometry is needed to be found. The current research has been focused on studying the effect of the pressure drop using FEA by changing the nozzle diameter and nozzle diameter's effect on the printing speed and time as well. The model's precision and accuracy relies on the pressure drop and hence, observing the pressure drop is vital. Additionally, to carry out an efficient extrusion, it is important to focus on the extrusion time. This study suggests the optimum nozzle diameter for open-source 3D printing, which was developed for this research, using PLA as a material[1].

The flow chart for selection of material was studied using FEA by considering all the necessary boundary conditions. By changing the diameter, the flow of the material inside the liquefying heater was observed. The difference in nozzle diameter also affects the printing time.

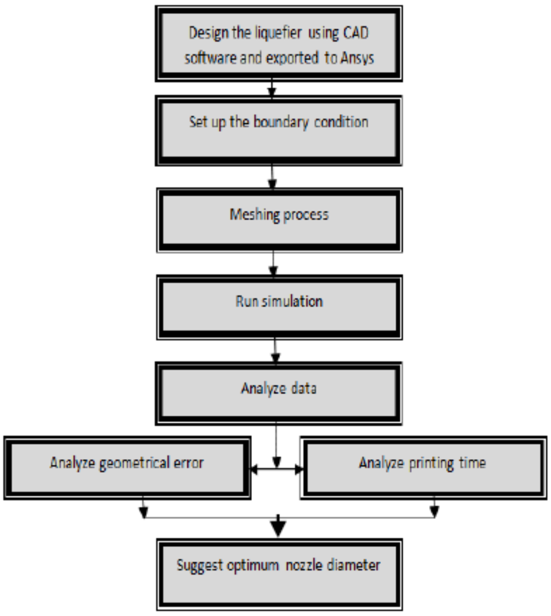


Figure 6: The Flow diagram for optimization[2]

The boundary condition is highly important for carrying out a successful FEA simulation. The 3D printing process is taking place in an unsteady-state, but it is presumed the process to be in a steady state having no changes in the material flow over time. Some other presumptions are also considered in this[1]:

1. The flow is considered laminar flow;
2. The material flow rate near the wall of heater is considered as zero because melting the material is assumed to be adhesive to the wall;
3. The heater temperature is at stable value and it is perfectly insulated.

Table 1 Properties and measurements

Specification		**Testing Condition (Mode)**	**Measurement for Testing**	**Measurement Unit**
Physical Capability	Density	-	1.25	g/cm3
	Specific Heat	-	1800	J/kg-K
	Thermal Conductivity	-	0.13	W/m-K
Machine Capability	Film Thickness	Tested	25	Mm
	Tensile Strength	MD:25 µm	103	Mm
		TD: 25 µm	145	Mm
	Elongation	MD:25 µm	180	%
		TD: 25 µm	100	%
Thermal Capability	Glass transition Point (temperature)	DSC	57.8	°C
	Melting Point (temperature)	-	160	°C
Optical Capability	Gloss	20°C, 25.4 µm	90	-
	Transparency	25.4 µm	2.1	%

The prime important result here is change of the pressure drop effect when the diameter of extruder is changed from 0.2 mm to 0.4 mm[1].

In another aspect the research focused different parameters which can be control before production using IDE of given commercial machine. Material ASTM D638 & ASTM D790 is used for the printing of tensile and flexural samples, respectively. The main objective is to create the sample with different process parameters like varying layer thickness (0.2 mm, 0.25 mm and 0.3 mm) and varying printing speeds (30 mm/s. 40 mm/s and 50mm/s). It was observed that varying in printing time of preparation of test samples with the different built parameters. For all experiments, 0.6 mm diameter nozzle was used. The nozzle was maintained a temperature of ~190 ºC for the extrusion of the ABS + hydrous magnesium silicate composite material and the build platform was maintained at ~70 ºC. A UTM (universal testing machine) having tensile and flexural fixtures with 10 kN load cell capacity was used to perform tensile and flexural tests. For ASTM D638, the test is stopped when the specimen reaches 2.5% elongation or the specimen breaks. For ASTM D790, a 3 point load conditions were followed for the flexural strength.

From the present research work, the following conclusions were drawn:

1. A maximum tensile and flexural strength values are reported for samples which has low layer thickness of 0.2 mm and printing speed of 30 mm/s.
2. The other samples with maximum printing speed of different layer thickness of 0.25 and 0.3 mm has exhibited a marginal reduction in strength values.
3. A low printing speed with low layer thickness gives a better bonding with the ,previous layer due to that it exhibited a better tensile and flexural strength.

In other paper [2] the optimum die angle has been found out using trial and error method. Extruding PLA material effectively is utilized under simulation method and the data obtain has been recorded. Die angle has been varied from 80° until 160° and it shows a different effect in pressure drop. Pressure drop need to be observed as it affects the road width of scaffold design, thus affecting the quality of the extruded part.

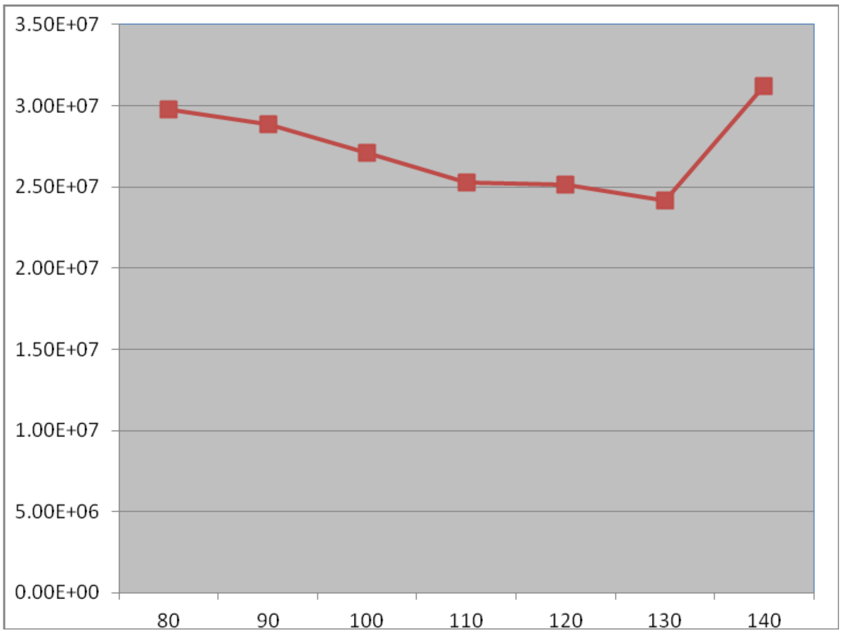


Figure 7: Nozzle angle versus the pressure drop[2]

Simulation has been conducted by using FEA to find the natural convergence angle ($2\theta^o$) for PLA material. It is very important to determine the natural convergence angle as the closer the $2\theta^o$ value to the 2α (die angle), the stable and consistent extrusion process would be. In addition, pressure drop varied as the die angle varied and minimizing the pressure drop is the key to have consistent and accurate scaffold design. This paper suggests that the optimal angle for the extruding PLA material using the FDM use in this research found to be 130°.

Conclusion and Objective: Form all the above papers it can be concluded that various unique and same parameters under the same condition for different type of design model produces varying results which tells the optimization must be performed for all the specific produce where the final result must be compared with the desired outcomes of the pre-requested values or requirements of the model or product.

Following objective has been deducted from the above study of various literatures.

- An Explicit study regarding process parameters based on recent material advancement is needed. [3].
- Optimization suggestion must be universally applicable [4].
- A uniform experiment with various parameters needs to carried for a specific mass produced product.

III. Method and Setup

There are a variety of processes, equipments, and materials used in the synthesis of a three-dimensional object. 3D printing is also known as additive manufacturing, therefore the numerous available 3D printing processes tend to be additive in nature with a few key differences in the technologies and the materials used in this process.

Some of the different types of processes include extrusion, light polymerization, continuous liquid interface production and powder bed. Each process and piece of equipment has pros and cons associated with it.

These usually involve aspects such as speed, costs, as well as a mechanical and appearance properties of the material like strength, texture and color.

The variety of processes and equipment allows for numerous uses by amateurs and professionals alike. Some lend themselves better toward industry use whilst others make 3D printing accessible to the average consumer. Some printers are large enough to fabricate buildings whilst others tend to micro and nano-scale sized objects and in general many different technologies can be exploited to physically produce the designed objects.

Machine and Setup: Fused deposition modeling (FDM), derives from automatic polymeric foil hot air welding system, hot-melt gluing and automatic gasket deposition. Such principle has been further developed by S. Scott Crump in the late 1980s and was commercialized in 1990 by Stratasys. After the patent on this technology expired, a large open-source development community developed and both commercial and DIY variants utilizing this type of 3D printer appeared. As a result, the price of this technology has dropped by two orders of magnitude since its creation, and it has become the most common form of 3D printing.

In fused deposition modeling, the model or part is produced by extruding small beads or streams of material which harden immediately to form layers. A filament of thermoplastic, metal wire, or other material is fed into an extrusion nozzle head (3D printer extruder). The nozzle head heats the material and turns the flow on and off. Typically stepper motors or servo motors are employed to move the extrusion head and adjust the flow. The printer usually has 3 axes of motion. A computer-aided manufacturing (CAM) software package is used to generate the G-Code that is sent to a microcontroller which controls the motors.

Plastic is the most common material for such printing. Various polymers may be used, including acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polylactic acid (PLA), high-density polyethylene (HDPE), PC/ABS, polyphenylsulfone (PPSU) and high impact polystyrene (HIPS).

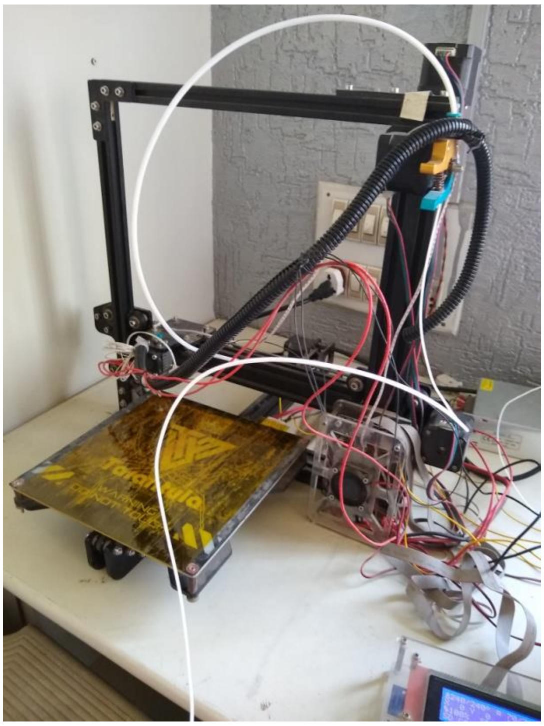


Figure 8: The Assembled DIY printer frim Tarantula

Above machine has a base working area of 200 mm X 200 mm with height of 180 mm. The machine is highly customizable with already available interface for programming and developing. The machine has traditional FDM based system with extruder moving in all 3 directions on XYZ axis.

The cad model generated must be oriented as per the process of layering hence over-hanged parts and hollow parts must be also supported whenever required. Once the orientation and other aspects are finalized.

Once completed, the STL file needs to be processed by a piece of software called a "slicer," which converts the model into a series of thin layers and produces a G-code file containing instructions tailored to a specific type of 3D printer (FDM printers). This G-code file can then be printed with 3D printing client software (which loads the G-code, and uses it to instruct the 3D printer during the 3D printing process).

Printer resolution describes layer thickness and X–Y resolution in dots per inch (dpi) or micrometers (µm). Typical layer thickness is around 100 µm (250 DPI), although some machines can print layers as thin as 16 µm (1,600 DPI).] X–Y resolution is comparable to that of laser printers. The particles (3D dots) are around 50 to 100 µm (510 to 250 DPI) in diameter. For that printer resolution, specifying a mesh resolution of 0.01–0.03 mm and a chord length ≤ 0.016 mm generate an optimal STL output file for a given model input file. Specifying higher resolution results in larger files without increase in print quality.

Construction of a model with contemporary methods can take anywhere from several hours to several days, depending on the method used and the size and complexity of the model. Additive systems can typically reduce this time to a few hours, although it varies widely depending on the type of machine used and the size and number of models being produced simultaneously.

An STL file describes a raw, unstructured triangulated surface by the unit normal and vertices (ordered by the right-hand rule) of the triangles using a three-dimensional Cartesian coordinate system. In the original specification, all STL coordinates were required to be positive numbers, but this restriction is no longer enforced and negative coordinates are commonly encountered in STL files today. STL files contain no scale information, and the units are arbitrary.

Before printing a 3D model from an STL file, it must first be examined for errors. Most CAD applications produce errors in output STL files, of the following types:

- Holes;
- Faces normal;
- Self-intersections;
- Noise shells;
- Manifold errors.

A step in the STL generation known as "repair" fixes such problems in the original model. Generally STLs that have been produced from a model obtained through 3D scanning often have more of these errors. This is due to how 3D scanning works-as it is often by point to point acquisition, reconstruction will include errors in most cases.

The Model: The ASTM Standards D638 Type 1 was used for testing of the material published by ASTM, 2010. The model dimensions are as per shown below

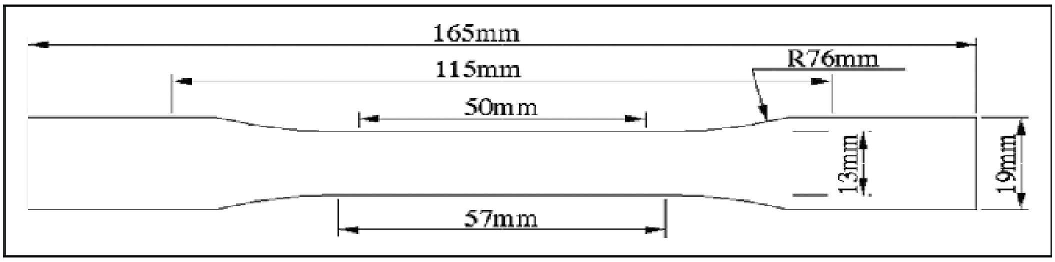


Figure 9: Specimen Dimension as per ASTM D680

Above shown is a CAD rendered image from solidworks of the impulsor which is then turned into STL geometry which creates a facet of triangles all across the model dividing into very large chunks of meshes which generates vertices and edges data which is later on feed in to a slicing software.

Similarly the dimensions used for bending test are according to ASTM D790, ‘Flexure test of plastics’, ASTM International, 2010.

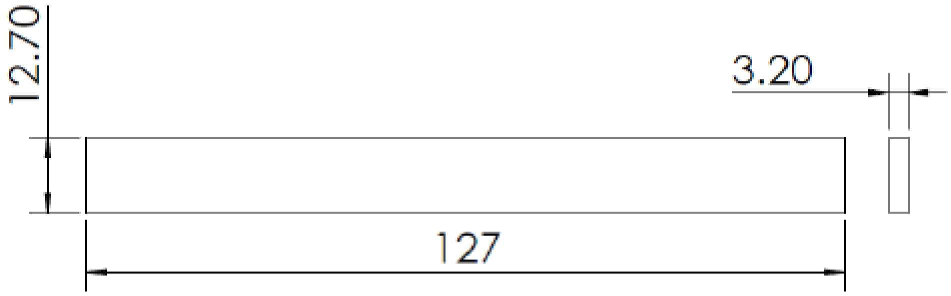
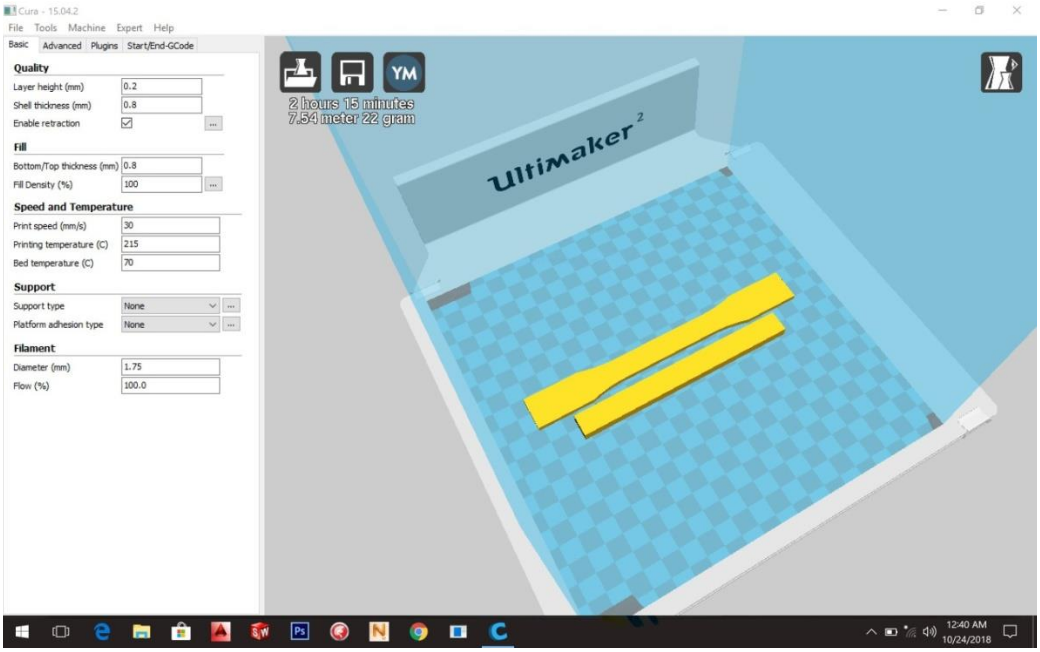


Figure 10: Specimen Dimensions as per ASTM D790

The Slicing:



Cura - 15.04.2

Quality

Layer height (mm)	0.2
Shell thickness (mm)	0.8
Enable retraction	☑

Fill

Bottom/Top thickness (mm)	0.8
Fill Density (%)	100

Speed and Temperature

Print speed (mm/s)	30
Printing temperature (C)	215
Bed temperature (C)	70

Support

Support type	None
Platform adhesion type	None

Filament

Diameter (mm)	1.75
Flow (%)	100.0

2 hours 15 minutes
7.54 meter 22 gram

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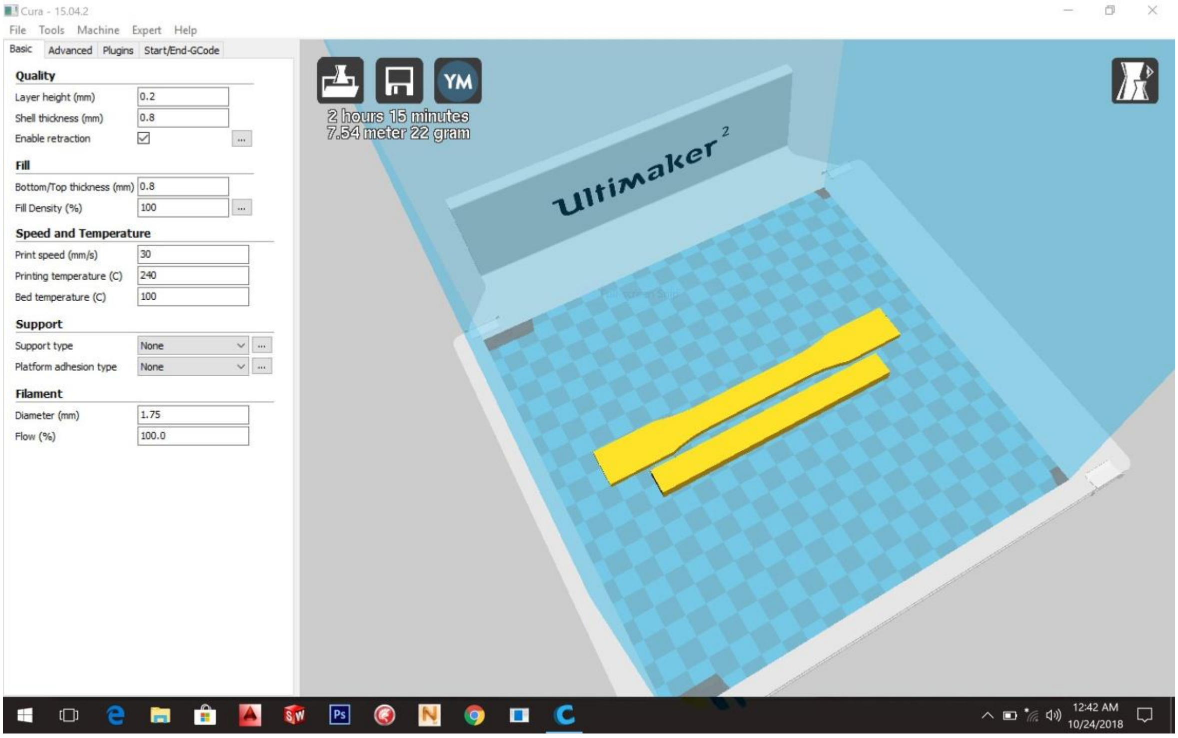
Figure 11 The Slicing software used 'ULTIMAKER 2' showing PLA print settings

For this study, software available with the machine product has been utilized to create a slicing model of the impulsor as shown above. This software as show is ‘ULTIMAKER 2’.

According to the required thickness of layers, the 3D model can be sliced into a series of parallel cross-section. The triangular facets are grouped. The intersecting lines between the tangent planes and triangular facets are computed. The intersecting lines with a specific algorithm in the same tangent plane and form the contour of slicing layer are sorted.



Quality
Layer height (mm): 0.2
Shell thickness (mm): 0.8
Enable retraction: ☑

Fill
Bottom/Top thickness (mm): 0.8
Fill Density (%): 100

Speed and Temperature
Print speed (mm/s): 30
Printing temperature (C): 240
Bed temperature (C): 100

Support
Support type: None
Platform adhesion type: None

Filament
Diameter (mm): 1.75
Flow (%): 100.0

2 hours 15 minutes
7.54 meter 22 gram

Figure 12 The 0.4 mm Nozzle diameter generated slicing model for ABS

Following are few the input parameters as shown in above images for all materials with 0.4 Diameter:

Table 2 : Input parameters for 0.4 mm Diameter Nozzle

Parameter specification	CARBON FIBER	ABS	PLA
Layer height	0.2	0.2	0.2
Shell thickness	0.8	0.8	0.8
Fill thickness	0.8	0.8	0.8
Fill Density %	100	100	100
Print Speed (mm/s)	30	30	30
Printing temperature (degree Celsius)	225	240	215
Bed Temperature (degree Celsius)	80	100	70

These parameters are the idle input which will be measured along with the output parameters for accurate optimization. The model created based upon them is as shown below:

Figure 13: The PLA material reel (spool) with 1.75mm thickness

Figure 14: The ABS white material reel

Figure 15: The Carbon fiber material reel

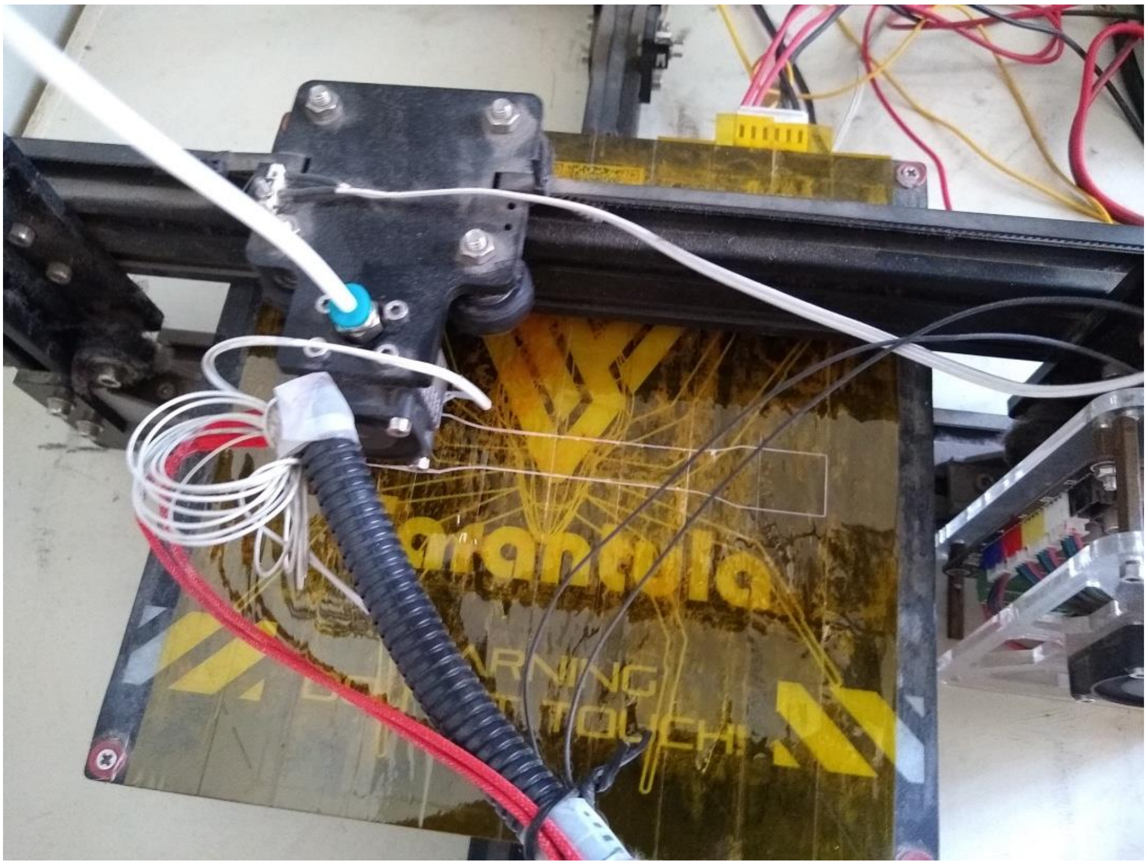


Figure 16 : The First level of 0.4mm ABS material

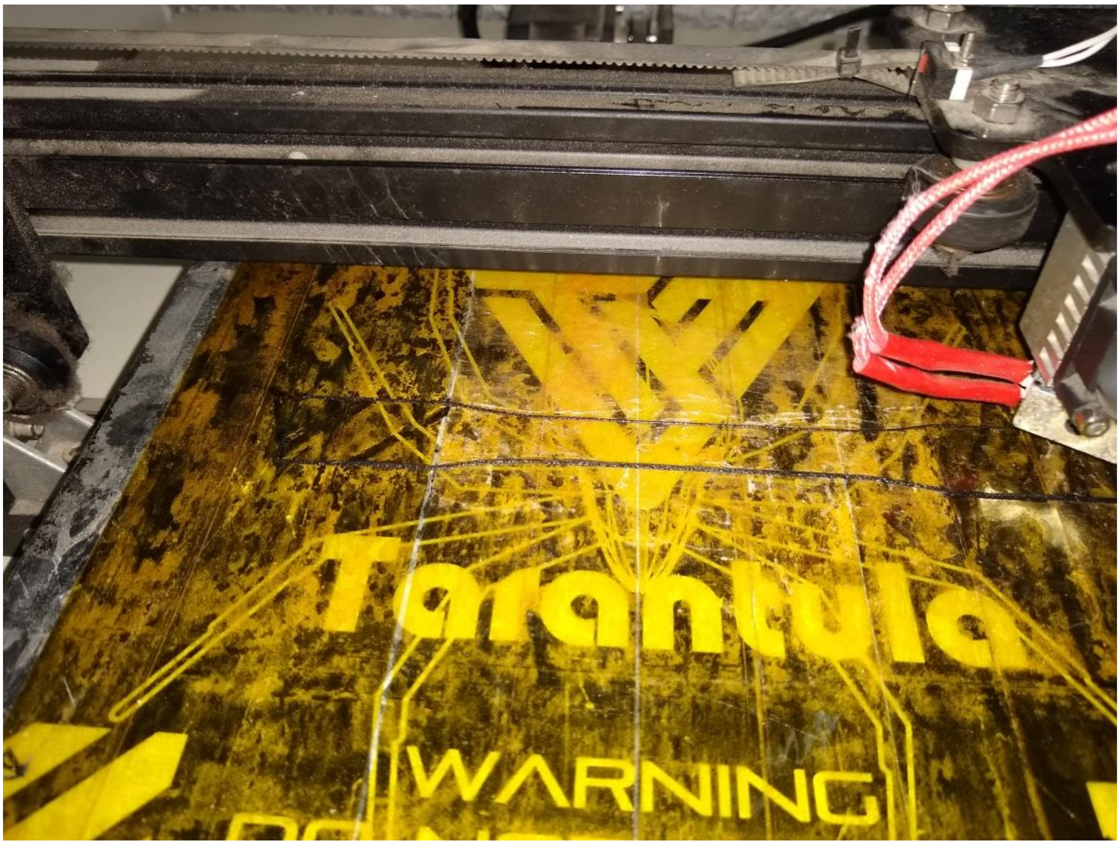


Figure 17: The First layer of Carbon fiber set after bed leveling

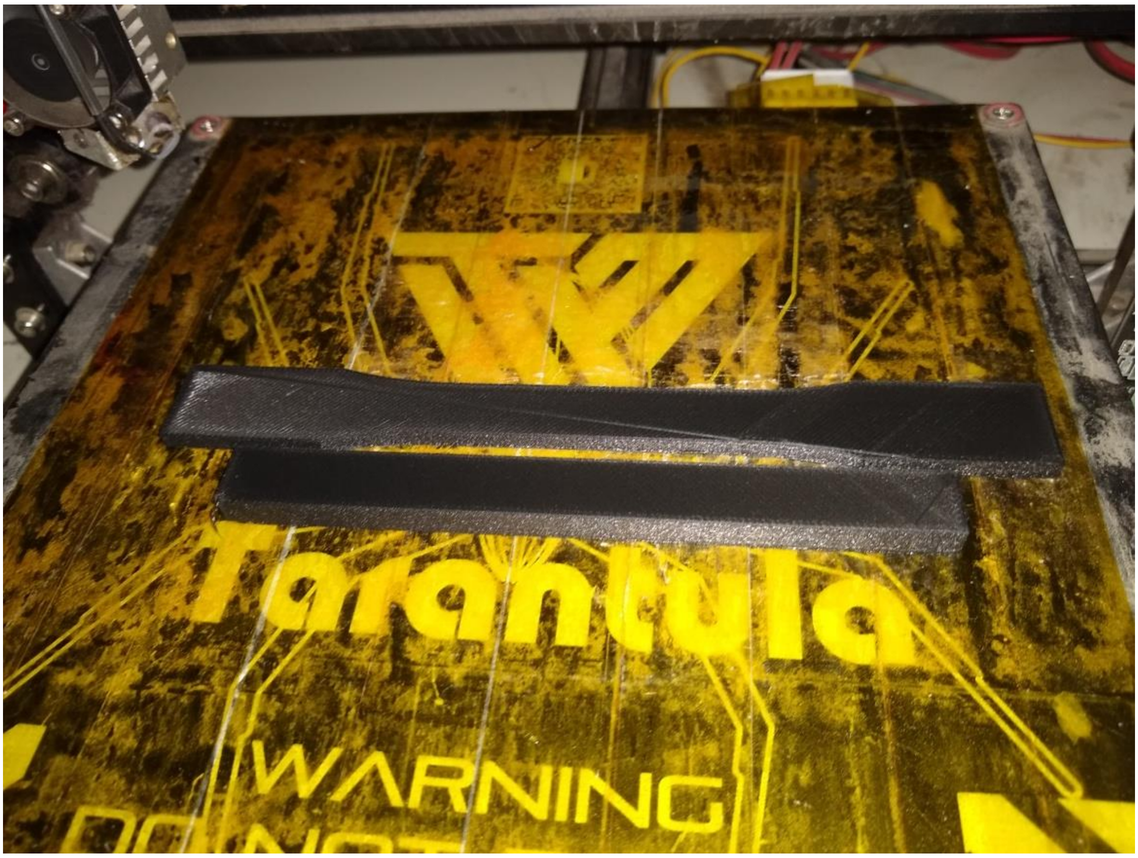


Figure 18: The finished Layer of Carbon Fiber set

Figure 19: The module showing total time with 100% fill

IV. Conclusion

The Results: The Specimens produced as shown previously were tested as per standard procedure guidelines from ASTM D638 and ASTM D790 for Tensile and bending respectively. These specimens were tested by an ISO certified institute, 'ALEKH PLASTIC TESTING CENTER' at Vatva GIDC, Ahemdabad, Gujarat

The following data has been produced from the data:

Table 3: The experimental data

Material	Nozzle Diameter (mm)	Average Ultimate Stress (MPa)	Average Elongation at Break (%)	Average modulus of Elasticity (GPa)
ABS	0.4	42.03	24.05	2.21
	0.5	43.56	23.98	2.20
	0.6	44.32	24.05	2.20
PLA	0.4	57.59	11.01	4.09
	0.5	59.03	12.02	4.11
	0.6	60.51	13.05	4.10
Carbon Fiber	0.4	120.05	18.01	6.22

0.5	120.64	17.89	6.16
0.6	121.35	17.80	6.56

The Conclusions: From above results we can conclude that the carbon fiber has the highest tensile strength value for highest nozzle diameter but also least surface finish which makes it difficult for prototype if aesthetic is of prime importances.

Also the Margin of error for actual dimensions are highest compared to the other diameters. This means tolerances are in multiples of 0.6mm every time.

Following are the objective of future work.

- Create specimen for Impact test and Fatigue test.
- Create a comparable chart with derivative values for further different nozzle diameter if required.
- Manufacture a modified diameter nozzle if necessary.
- Manufacture and test the nozzle for the optimal diameter to cross relate with the input values.

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