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# Printing Parameters and Material Characteristics Affecting Mechanical Properties of FDM Printed Parts

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**Abstract**: Using additive manufacturing to create mechanical models could be challenging. To achieve successful mechanical models using additive manufacturing, various factors such as material selection, design optimization and printing constraints must be carefully considered. These factors play a crucial role in ensuring the functionality and structural integrity of the printed mechanical models. Several tests and experiments have been conducted to study the mechanical properties and performance of additive manufactured parts. Challenges include specimen shape and printing parameters emerged as key factors influencing the mechanical properties of additive manufactured parts. Furthermore, the microstructure of the printed parts and their relationship to mechanical properties is still not fully understood. Therefore, further research and development are needed to improve the understanding of these factors and optimize the additive manufacturing process for creating mechanical models with enhanced functionality and structural integrity. In order to thoroughly understand and optimize the mechanical properties of additively manufactured parts, it is essential to conduct mechanical tests to assess these properties.

**Keywords** :FDM, Additive Manufacturing, Layer Thickness, Seam Position.

## 1. INTRODUCTION

Additive manufacturing has revolutionized the field of manufacturing by enabling the creation of complex three-dimensional objects with unprecedented levels of customization and efficiency. One of the most widely used additive manufacturing technologies is Fused Deposition Modeling. Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), is a technique that utilizes the process of extruding thermoplastic material through heated nozzles to create cross-sections of a part (Valerga et al., 2023) [1].

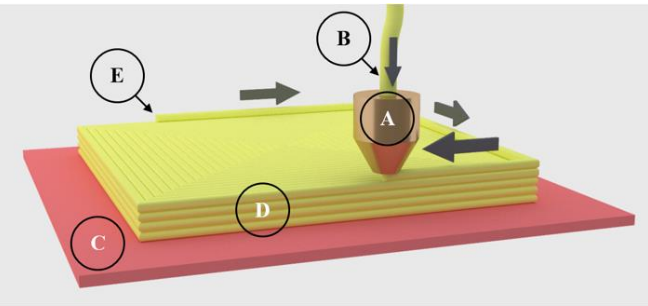


**Fig 1.** The process of FDM printing must include a heated nozzle (A) through which the filament (B) is fed. Molten material extruded from nozzle is deposed on a hot platform (C) where the first layer is adhered to. Multiple layers (D) constitute the printed part. Each layer has a starting point (E) which is called the Z-seam position.

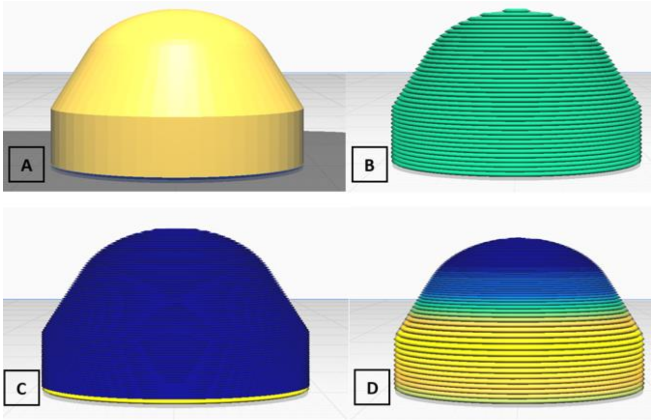


**Fig 2.** Using an opensource slicing software (UltiMaker Cura V5.3.1), a bullet shaped part (A) is sliced into layers as shown in (B), (C) and (D). All layers of (B) have a thickness of 0.3mm, while they are 0.1mm in (C). In case of (D), the thickness varies from 0.35mm at the bottom of the part and, starting from the inclined surface, it decreases gradually to 0.1mm.

As shown in Fig.1, this method involves the deposition of layers of extruded thermoplastic material on a heated platform, resulting in the production of three-dimensional structures. Fused Deposition Modeling has become a popular choice due to its simplicity, cost-effectiveness, and versatility in various industries.

On the other hand, printing models on FDM machine could face many challenges. Figure 2 shows how a part is sliced and printed. The CAD model (which must be in .stl format) is exported to slicing software, where it breaks down the 3D model into multiple number of layers with a certain height stacked over each other. On top of layer thickness, other parameters are defined including but not limited to nozzle temperature, bed temperature (the platform above it the first layer is printed), printing speed, etc. After all parameters are set, the slicer software generates a G-code which will be sent to the printer to control the bed and the nozzle motion, as well as temperature.

The number of layers depends on the layer thickness of each layer, e.g., if the part height is 10mm and each layer is 0.1mm thick therefore 100 layers are needed to build the part. It is not mandatory to have a fixed thickness for each layer, e.g., the first layer may be assigned a thickness of 0.1mm and the second layer a thickness of 0.15mm. The variable layer height may be adopted for many reasons, but it concerns mainly the surface topology of the printed part. As shown in Fig.2, the curved wall is smoother in case (C) and case (D) where the variable layer height is applied (ranges from 0.1mm up to 0.35mm).

The reduced layer thickness increases the surface quality of the printed part, especially if the surface is deviated from the vertical axis. But the layer height has an impact on the printing time, as well as the mechanical properties of the printed part, which will be discussed later. The time consumed to print the part using layer thickness of 0.1mm (as in case C) is 3 times more than the time consumed to print it using a layer thickness of 0.3mm (as in case B). However, case D (variable layer thickness is adopted) consumes the same amount of time consumed in case B, as the vertical portion (Yellow) of the part is sliced into 0.35mm layers to compensate for the time taken to print the dome (Blue) with a thickness of 0.1mm.

Time is a critical factor when it comes to 3D printing. A simple cube having a side length of 20mm would take up to 150 minutes from start to finish. The bullet shape mentioned previously, demonstrates how to reduce the printing time by changing the layer heights according to shape, where vertical walls are thick to accelerate the operation meanwhile the dome layers are thin to preserve the aesthetic features. On the other hand, the cube doesn't have any curves so the layer thickness could be maximized to reduce the time needed.

However, to achieve lower printing time or even lighter products, some modifications must be made to the sliced design itself. One of them is to reduce the infill density. The infill is the core of the printed part, it may be fully solid with no voids (100% infill density) or, it may have lower densities. Also, the infill may be built with one of various patterns.

## 2.TESTS SPECIFICATIONS

As mentioned before, layer height has an impact on the time consumed for printing. Meanwhile a series of tension tests is carried out to evaluate the impact of layer height on mechanical properties of the printed part.

### 2.1 Printer and Specimens

The tensile test specimens have the conventional dog bone shape. Specimens are printed according to ASTM D 638-02a type I and type IV. The printer used to print those specimens is Anycubic I3 mega. It has a square platform of 484cm$^2$ available for printing.

**FIG3.** Three dog bone specimens are printed consecutively with the same layer height which is indicated by the number. Each number is assigned to a certain layer height while the letter determines whether it is printed on the left region (A), middle region (B) or the right region (C).

All the specimens are printed under the same environmental conditions. The printer is surrounded by a wooden/Acrylic enclosure to stabilize humidity and control the temperature. The tip of a heat gun is inserted in a vent drilled in the wall of the enclosure and it is connected to a temperature sensor installed inside the enclosure to maintain the ambient temperature around the printed part.

### 2.2 Material Used

FDM machines are fed with thermoplastic filaments wound around spools. Typically, a spool is 1Kg in weight and could be available in a large variety of materials like ABS, PETG, PLA, Nylon …etc. Those materials could be reinforced using fibers with appropriate amounts.

PLA (Poly Lactic Acid) has emerged as a popular material for FDM 3D printing due to its numerous benefits compared to other alternatives. Single used plastics used in packaging only costs the worldwide economy USD 120 billion each year (Matthews et al., 2021) [2].

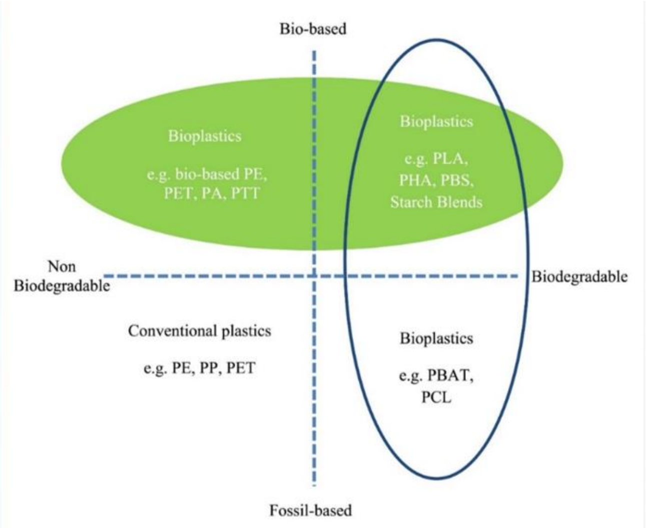


**Fig4.** Classification of common bioplastic/synthetic polymers and their biodegradability (European Bioplastics, 2017) [3].

PLA is a biodegradable and, also, biobased material as shown in Fig.4 (European Bioplastics, 2017) [3]. PLA is fabricated mainly from lactic acid which is obtained from plant-derived resources such as sugar beets and corn, hence its name Polylactic Acid (Chong et al., 2022) [4]. All test specimens are printed using the same spool. Calibration cubes are printed, at first, to adjust the printer flow rate. The material used is commercially known as (PLA+). The filament diameter coming out of the spool is 1.75mm. The filament has a Tensile Strength of 63 MPa (Manufacturer specifications). The specimens are printed just right after ripping off the vacuum seal of the spool. The prints are run consecutively with minimal break time between each print to avoid ruining the filament which is exposed to air humidity. The filament color is white as different colors can affect the specimen properties as well as its coefficient of friction (Hanon and Zsidai, 2021) [5].

### 2.3 Printing Parameters and Test Conditions

Two sets of tensile tests were performed. The first set's objective was to assess the impact of printing temperature on the tensile properties of the specimen. The second set's objective was to assess the impact of the specimen printing layer height on the specimen tensile properties.

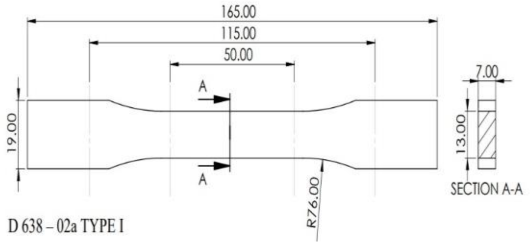
#### 2.3.1 The First Set Printing Parameters, Test Conditions and Specimens Variables.

The specimens printing parameters and test conditions are listed in Tables (1) and (2).

TABLE 1. First Set Printing Parameters.

| Parameter | Value/ State |
|---|---|
| Layer height | 0.2mm |
| Printing speed | 50mm/s |
| Platform temperature | 60°C |
| Infill density | 50% |
| Infill pattern | Lines |
| Wall thickness | 1.2mm |
| Top/ bottom thickness | 1.2mm |
| Top/ bottom pattern | Lines |
| Raster angle | 45° (Alternate layers) |
| Line width | 0.4mm |

TABLE 2. First Set Test Conditions.

| Condition | Value/ State |
|---|---|
| Ambient temperature | Range (55°C - 60°C) |
| Specimen | ASTM D638-02a Type (I) |
|  | |
| Specimen weight | 16g |
| Printing time | 60mins |
| Test Elongation Rate | 2 mm/min |

As noted, the first set was meant to assess the effect of printing temperature on the tensile properties of specimens. The manufacturer of the filament used recommended a temperature between 210°C and 230°C. Six specimens were printed according to Table (3).

TABLE 3. Specimens Printing Temperatures of the First Set.

| Specimen number | Printing temperature |
|---|---|
| 1 and 2 | 210°C |
| 3 and 4 | 220°C |
| 5 and 6 | 230°C |

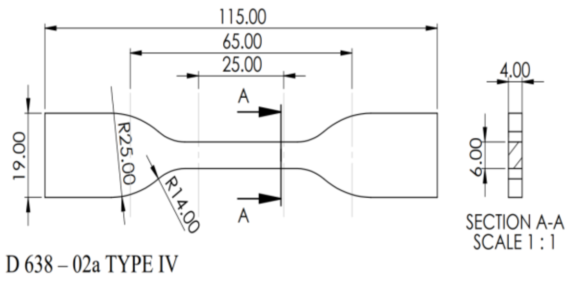
#### 2.3.2 The Second Set Printing Parameters, Test Conditions and Specimens Variables.

The specimens printing parameters and test conditions are listed in Tables (4) and (5).

TABLE 4. Second Set Printing Parameters.

| Parameter | Value/ State |
|---|---|
| Printing temperature | 220°C |
| Printing speed | 50mm/s |
| Platform temperature | 60°C |
| Infill density | 100% |
| Infill pattern | Lines |
| Wall thickness | 1.2mm |
| Top/ bottom thickness | 1.2mm |
| Top/ bottom pattern | Lines |
| Raster angle | 45° (Alternate layers) |
| Line width | 0.4mm |

TABLE 5. Second Set Test Conditions.

| Condition | Value/ State |
|---|---|
| Ambient temperature | Range (55°C - 60°C) |
| Specimen | ASTM D638-02a Type |
|  | |
| Specimen weight | 7g |
| Printing time | 31mins |
| Test Elongation Rate | 2 mm/min |

As noted, the second set was meant to assess the effect of printing layer height on the tensile properties of specimens. Fifteen specimens were printed according to Table (6). The platform is divided into 3 imaginary regions. For each layer height to be tested, a set of 3 specimens are printed consecutively (one in each zone as shown in Fig.3). They are labeled A, B and C from left to right.

TABLE 6. Specimens Printing Heights of the Second Set.

| Specimen number | Printing layer height |
|---|---|
| 1A, 1B, 1C | 0.1mm |
| 2A, 2B, 2C | 0.15mm |
| 3A, 3B, 3C | 0.2mm |
| 4A, 4B, 4C | 0.25mm |
| 5A, 5B, 5C | 0.3mm |

## 3.TESTS RESULTS

### 3.1 First Set of Specimens

The yield and ultimate strengths obtained from the first set of tests are plotted on chart (1). While testing the specimens printed with nozzle temperature of 210°C, failure occurred, and layers were separated before yielding (as shown in Fig.5). Meanwhile specimens printed at 220°C have, slightly, higher than those specimens printed at 230°C. Therefore, the second set of specimens were printed at 220°C

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CHART 1. Yield and Ultimate Strength of the First Set of Tests

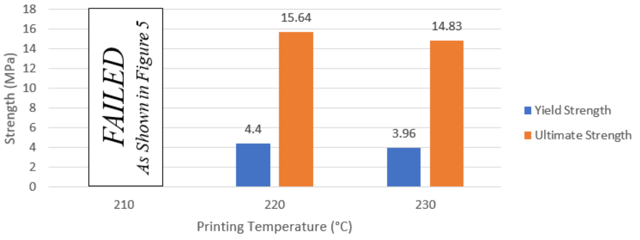


**Fig 5.** Specimen printed at 210°C failed before yielding where layers were separated

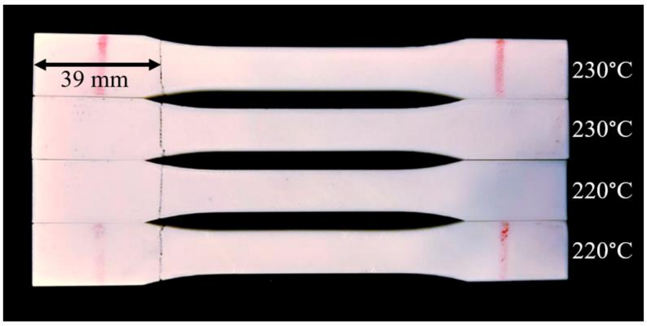


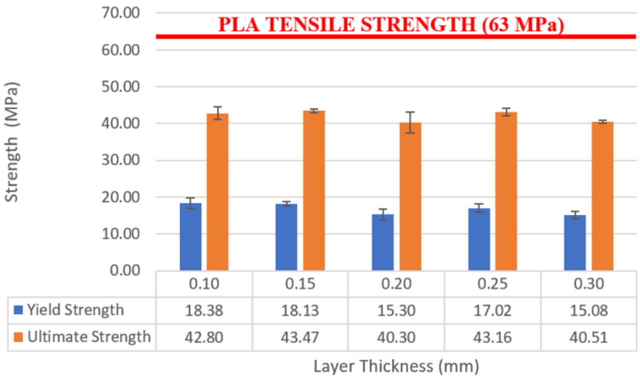
**Fig 6.** Specimens printed at 220°C and 230°C failed exactly at the same location (39mm from the edge).

Specimens number 3 to 6 failed exactly at the same location, which is located at 39mm from the edge (As shown in Fig.6). On the other hand, the failure occurred outside the borders of the gauge length. By examining the sliced model of the specimen introduced to the 3D printer, it is concluded that the failure occurred at the location of the Z-Seam position. The Z-Seam position was introduced in Fig.1, and it could be defined as the location where the nozzle starts printing a new layer. Hence, in the following specimens, the seam position was relocated to the corner of the specimen where minimal tension stress is generated.

### 3.2 Second Set of Specimens

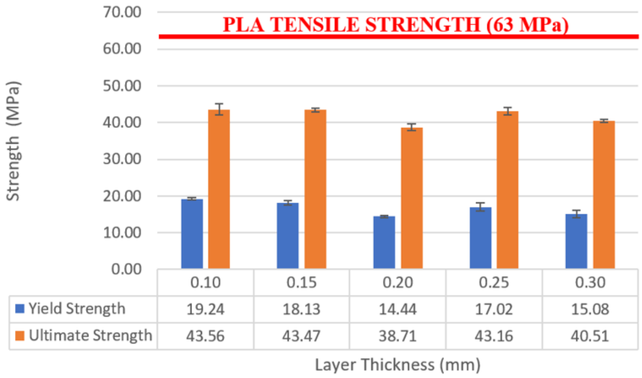
The yield and ultimate strengths obtained from the second set of tests are plotted on chart (2) and chart (3) where the outliers are excluded.

CHART 2. Yield and Ultimate Strength of the Second Set of Tests. Error bars are plotted.



| | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 |
|---|---|---|---|---|---|
| ■ Yield Strength | 18.38 | 18.13 | 15.30 | 17.02 | 15.08 |
| ■ Ultimate Strength | 42.80 | 43.47 | 40.30 | 43.16 | 40.51 |

CHART 3. Yield and Ultimate Strength of the First Set of Tests (Outliers Excluded). Error bars are plotted.



| | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 |
|---|---|---|---|---|---|
| ■ Yield Strength | 19.24 | 18.13 | 14.44 | 17.02 | 15.08 |
| ■ Ultimate Strength | 43.56 | 43.47 | 38.71 | 43.16 | 40.51 |

The strength of specimens, both yield and ultimate, decreases as the layer thickness increases. A drop in strength is spotted at specimens of layer thickness 0.2mm.

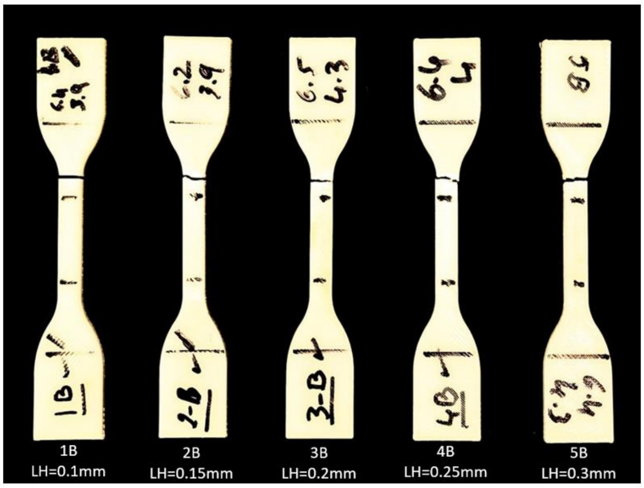


**Fig 7.** Some Specimens of the second set of tests failed outside the gauge length zone

The specimens failed just at the end of the fillet of the narrow section of the specimen (As shown in Fig.7). The fillet is introduced in the dog bone shaped specimen to reduce stress concentrations and ensure smooth flow of tension from grip to grip during test, so, repetitive failure at the fillet portion of the specimen could not be tolerated. However, using mechanical gripping for fixing the specimen prior to the test may have caused twisting in the specimen which may have caused specimen damage.

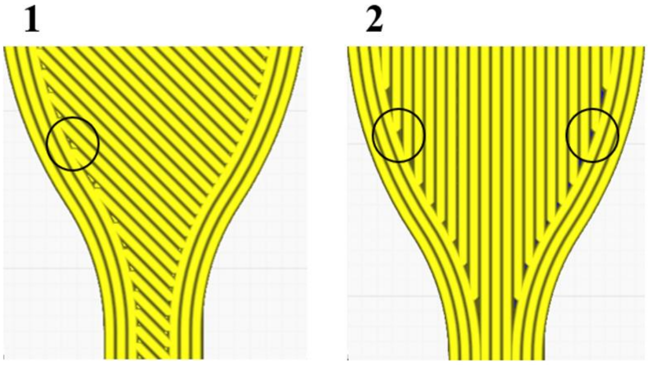


**Fig 8.** On the left (Case 1), the sketch shows a specimen sliced with a raster of 45°, while on the right it is sliced with a raster of 90° (Case 2). The encircled parts in both sketches show voids between the external wall and the internal infill

As shown in Fig.8 (Case 1), slicing the fillet introduces voids in the specimen. It is even worse in the second case where the raster is 90°, therefore no specimen was printed with a 90° raster. The nozzle diameter is 0.4mm in diameter as well as the line width. The printed line having a circular shape, it cannot fill the whole area unless an overlap is introduced between the end of each line and the wall to over fill these voids. But that overlap will increase the amount of material deposited, therefore, geometry distortion may occur.

According to (Sola et al., 2023) [6], existing standards for tensile tests are not applicable in case of testing specimens manufactured using additive manufacturing. Due to the layered approach of additive manufacturing, the printed specimen may have different mechanical properties along X, Y, or Z axis independent from the used material mechanical properties (Monzón et al.,2014) [7]. The need for AM standards is urgent. ASTM and ISO organizations signed a Partner Standards Developing Organization (PSDO) cooperative agreement to adopt an additive manufacturing standard (Kabir et al., 2022) [8].

## 4.CONCLUSIONS

- Printing PLA at 210°C may cause inconsistencies within the printed layers, while printing at 220°C and 230°C gave good results (Tensile strength at 220°C is slightly higher than at 230°C). However, at 230°C probable nozzle oozing may occur, as well as more energy consumption. So, printing PLA at 220°C is preferable.
- While slicing the part, the position of the Z-Seam shall be moved to a location where minimal stresses are generated.

- Printing thin layers produce stronger parts at the expense of printing time.
- Fillets introduced in the specimen to reduce stress concentrations will, in fact, increase the stresses due to voids formed within the part and cause part failure.
- Hydraulic gripping is preferred over mechanical gripping, as it may cause damage to fragile specimens.
- The strength of specimens of the first set, printed at 50% infill, is on average 24 % that of the filament in its raw form.
- The strength of specimens of the second set, printed at 100% infill with different printing temperatures, compared to that of the filament in its raw form ranges from 61.4% (0.2mm) to 69.1% (0.1mm).
- The existing standards may not comply with specimens manufactured with AM. New standards, especially for AM, are needed.

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