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THESIS

**EFFECTS OF 3D PRINTING PROCESSING
PARAMETERS ON MECHANICAL PROPERTIES OF
POLYMERIC MATERIALS**

by

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June 2021

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**EFFECTS OF 3D PRINTING PROCESSING PARAMETERS ON MECHANICAL
PROPERTIES OF POLYMERIC MATERIALS**

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ABSTRACT

Additive manufacturing has been used for many years to create complex shapes and designs that would otherwise be difficult for traditional machining methods to produce. However, little is known about the mechanical properties of objects produced via such methods and, as a result, these objects rarely find their way into structural applications. To better understand the applicability of additive manufacturing in structural applications, specimens were created using variations of 3D build parameters. Influence of basic parameters such as build direction, infill pattern (± 45 -degree lines, longitudinal lines, transverse lines, concentric lines), and printed layer height (0.2 mm, 0.16 mm, 0.1 mm) were explored on several types of polymers, to include PLA, PETG, and polycarbonate. Tensile testing was used to evaluate the effects of the 3D printing parameters on mechanical properties. Regardless of material tested, infill raster patterns that were oriented in line with applied stress axis resulted in samples with superior strength and strain properties. Additionally, printing with smaller layer heights produced denser samples, which generally exhibited better mechanical properties compared to samples printed with larger layer heights. While some mechanical trends held true across material type, others did not, indicating there are no ideal print settings that can be universally applied to all materials.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
ABS	acrylonitrile butadiene styrene
AM	additive manufacturing
ASTM	American Society for Testing and Materials
COMSUBPAC	Commander, Submarine Force, U.S. Pacific Fleet
FDM	fused deposition modeling
PC	polycarbonate
PETG	polyethylene terephthalate-glycol
PLA	polylactic acid
PLLA	poly(l-lactic) acid
SE2	Everhart-Thornley secondary electron detector
SEM	scanning electron microscope
XRD	X-ray diffraction

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I. INTRODUCTION

A. MOTIVATION

Fused deposition modeling (FDM) additive manufacturing (AM) provides an efficient method to rapidly prototype “one-off” parts of both simple and complex geometries. The initial fascination with the FDM AM technology therefore was primarily focused on its rapid prototyping abilities and not so much with exploring the mechanical properties of the produced parts. However, technology advancements and increased accessibility have allowed for FDM AM to potentially become a standard means of production. As a result, the amount of published research on this technology has increased over six-fold in the past twenty-plus years [1]. However, with this change, a need has arisen to understand the effects of varying FDM parameters on the mechanical properties of parts for use in structural applications [2].

B. NAVAL APPLICATION

In current Navy supply systems, replacement parts must be sourced from backstock stored onboard the ship; if no spare is available, the replacement must be sourced via a relatively slow and complex supply chain. Ready spares take up extensive amounts of space on U.S. Navy platforms, and if the ship is actively deployed, the part acquisition via the supply chain becomes even slower and more complex. FDM AM provides a solution to the downfalls of the current supply chain processes by possessing the unique ability to produce parts at the point and time of need. This inherent benefit to the technology reduces the space requirement to store ready spares onboard ships, and it practically eliminates the time delay to acquire a new part if one needs to be sourced or manufactured. Currently, little consideration is given to FDM AM for use in structural military applications. Non-load-bearing parts have been printed and put in use, but the true benefits of FDM AM will be realized when it is used to produce structurally viable components.

Commander, Submarine Force, U.S. Pacific Fleet (COMSUBPAC), a stakeholder and sponsor of this research, has indicated a desire to use small footprint FDM printers

onboard submarines. The data produced from this research could be used by military end users to validate predictive models created in the future.

C. STATE OF THE ART

Current ASTM standards do not cover how to characterize the mechanical properties of FDM manufactured components, so independent research and studies, like this thesis, have been necessary in order to understand the feasibility of FDM components in structural applications. Earlier FDM research was centered around acrylonitrile butadiene styrene (ABS) due to it being the most available and mechanically feasible neat polymer for use in FDM applications at the time [3]. Other previous FDM AM research has been heavily focused on the use of polymer matrix composites because these materials tended to exhibit better mechanical properties in terms of strength, strain, creep, and wear resistance [4], [5], [6]. With advances in FDM printer technology and filament production over the past 35 years, research has shifted focus to studying more modern filaments such as polylactic acid (PLA) and polyethylene terephthalate-glycol (PETG) [2], [3]. Commercially available FDM printers capable of printing at temperatures hot enough to utilize polycarbonate (PC) filament have become more affordable and available, adding viability to studying FDM manufactured PC components for use in structural applications. The chemical structures of these materials are shown in Figure 1.

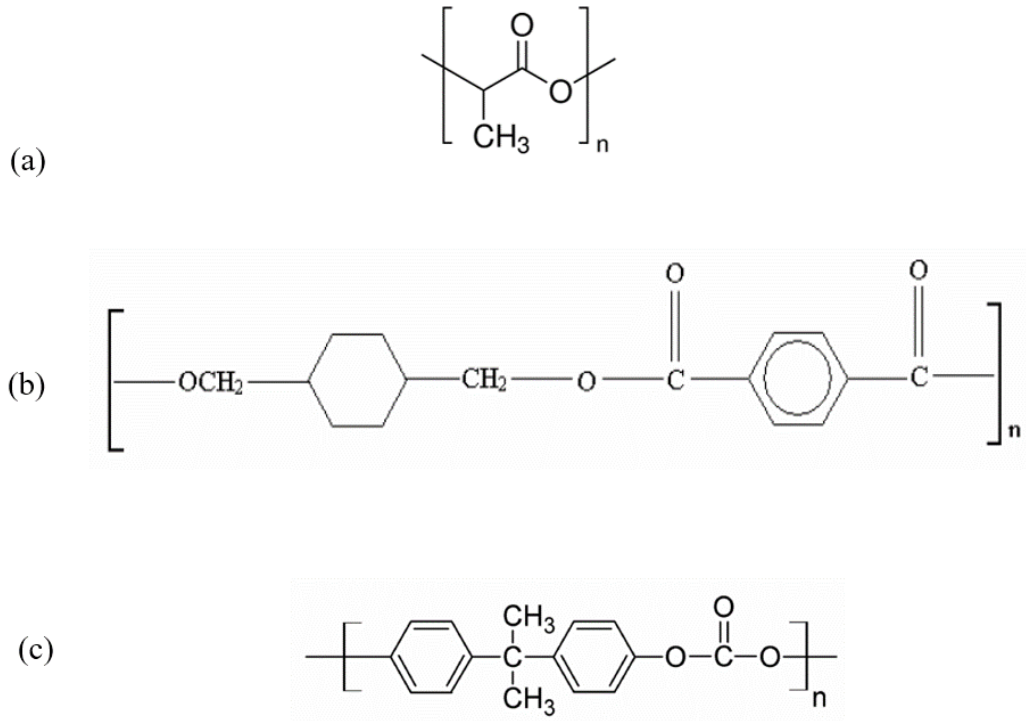


Figure 1. Chemical structures of PLA (a), PETG (b), and PC (c). Sources: [7], [8], [9].

1. Infill Orientation

A unique aspect of FDM manufacturing is the ability to tailor specific component properties by adjusting the various printing parameters. While the outer walls of the component are fixed to specified dimensions, the infill material can be printed in an almost infinite number of direction and pattern combinations. Kiendl and Gao [10]. studied how mechanical properties of FDM printed PLA samples were influenced by the printed infill parameters. In their first series of tests, samples with unidirectional infill were tensile tested. The infill for each printed layer was oriented in the same direction. Sample sets were made with varying infill directions from zero to 90°, where 0° meant orientation in line with the stress axis, and 90° meant orientation perpendicular to the stress axis. Their results concluded tensile strength increased as the infill orientation decreased to be more in line with the stress axis (i.e., parallel to loading direction). Also observed was the lack of toughness with unidirectional infill regardless of orientation [10].

Kiendl and Gao did a second test with samples possessing alternating infill orientations, meaning subsequent infill layers were printed 90° offset from the previous layer [10]. This created infill sequences of $0^\circ/+90^\circ$, $+45^\circ/-45^\circ$, and $+30^\circ/-60^\circ$. Tensile testing of these sample sets resulted in a relatively isotropic strength. When compared to their unidirectional counterparts, these anisotropic patterns varied in strength by $\pm 15\%$, but all patterns exhibited an increase in strain ranging from 200–500%. Additionally, it was observed samples with more perpendicular infill orientations exhibited brittle failure mechanisms, whereas samples with more inclined infill orientations exhibited greater toughness and more ductile failure mechanisms [10]. Considering the failure in these tensile tests initiated at the interfacial bonds between layers, the inclined infill was able to rotate and reorientate in line with the stress axis, increasing the observed ductility before failure [10].

2. Layer Thickness

FDM manufacturing allows the user to control the level of detail possessed by a part by adjusting the printed layer thickness parameter. Large layer thicknesses, such as 0.4 mm, allow for parts to print more quickly at the cost of detail resolution. Small layer heights, as low as 0.05 mm, allow the printer to print in very fine detail, but the part may take many hours or even days to print. Rankoui et al. [11]. explored how adjusting the printed layer thickness might affect the mechanical properties of the part. They printed two sets of ABS tensile specimens with two different layer thicknesses, 0.2 mm and 0.4 mm. All other parameters were held constant between the two sets. Their tensile test results showed the samples with the 0.2 mm layer height exhibited greater ultimate strength values than the samples printed at 0.4 mm. Using optical and scanning electron microscope (SEM) imagery, seen in Figure 2, they concluded the greater strength was caused by a reduction in the inter-fiber porosity, which resulted in an increase densification of the sample [11].

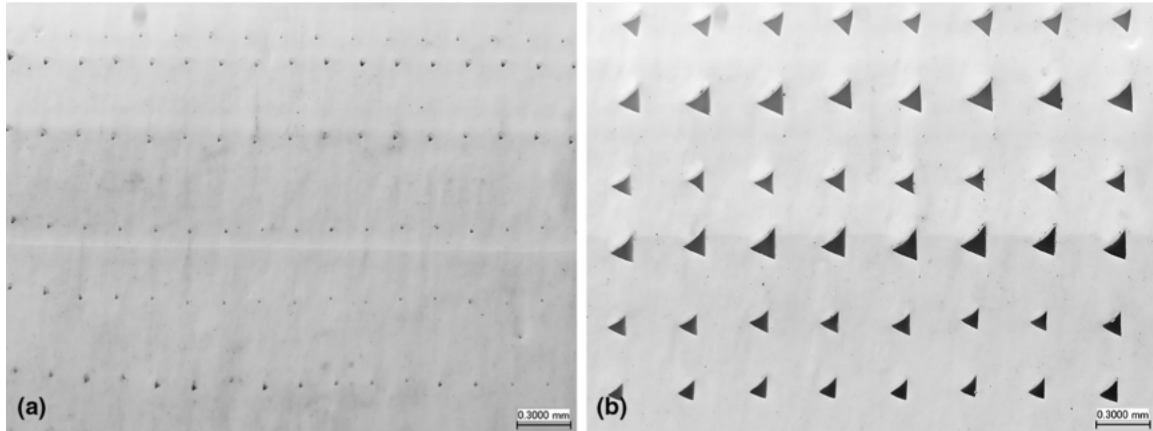


Figure 2. Sample cross-sections printed at 0.2 mm (a) and 0.4 mm (b). Source: [11].

3. Crystallinity

The inherent processes of FDM AM expose the printer filament to heating, physical extrusion, and cooling. Filaments used in FDM printers are either amorphous or semi-crystalline in their raw state. The inherent FDM AM processes previously mentioned can invoke crystalline artifacts in once raw amorphous polymers or change the crystalline phases within semi-crystalline polymers. Wasanasuk et al. [12] melted, cooled, and stretched films of Poly(l-lactic) Acid (PLLA) to explore how crystalline phases change as a result of those processes. Using x-ray diffraction (XRD), they observed how randomly oriented polymer chains (δ -phase), after being subjected to heating at temperatures greater than 120 °C, were aligned into a regular crystalline orientation (α -phase). Additionally, they used XRD to further observe how the crystalline phases of the heated and cooled samples changed after undergoing tensile loading. Their research revealed a third crystalline phase that presents itself as the regular oriented polymer chains are broken and shift as a result of tensile loading [12]. Figure 3 depicts the crystalline phase transformations of PLLA.

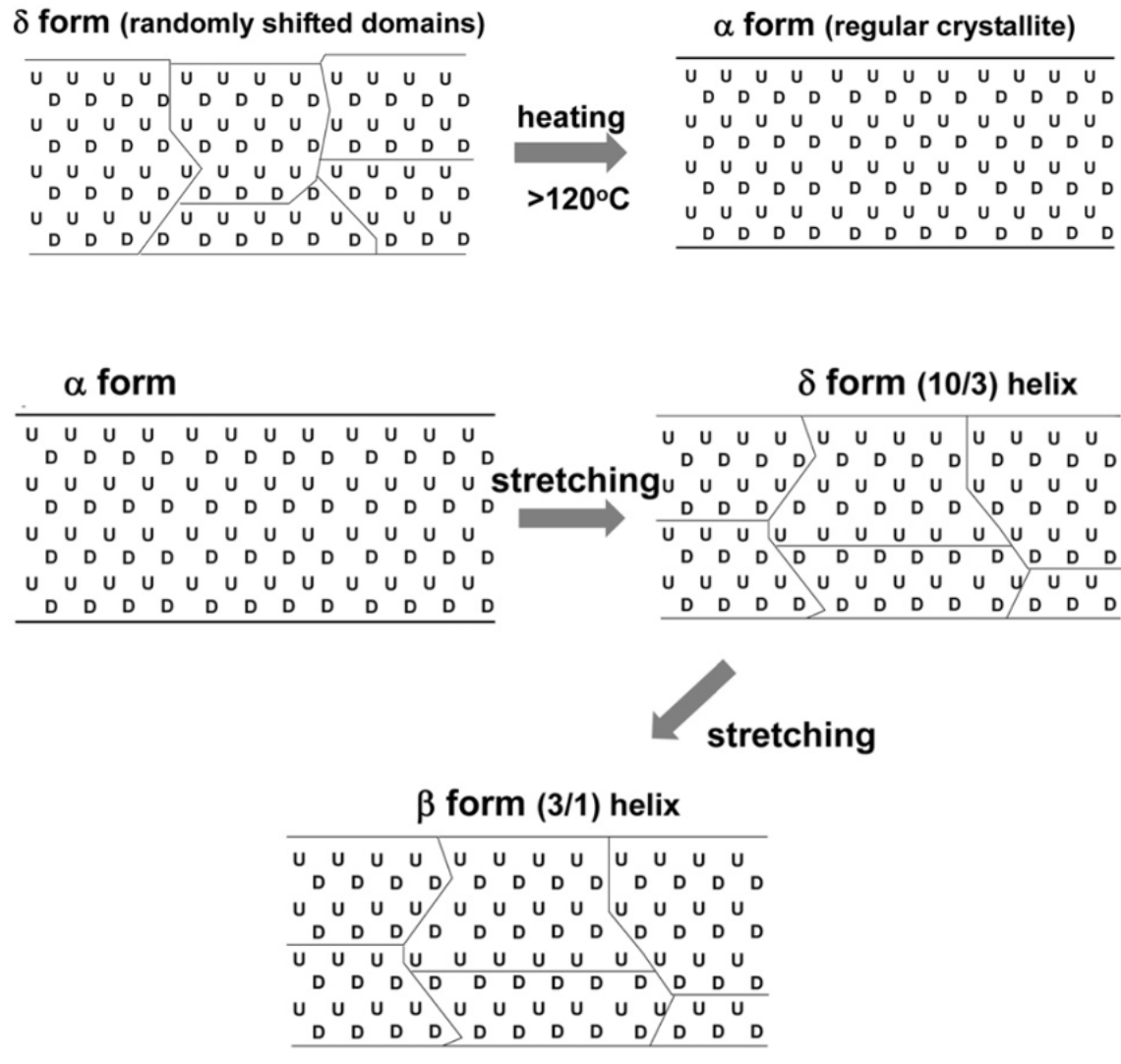


Figure 3. Illustration of the crystalline phase transformations of PLLA after undergoing heating, cooling, and tensile loading.
Source: [12].

With FDM printers, the degree of heating can be controlled by adjusting the extruder nozzle temperature. Common to many FDM printers is a heated print surface, which can be varied in temperature in order to control the rate of cooling of the melted extruded polymer. Variations in either of these parameters can directly affect the crystallinity and associated mechanical properties of the printed part. Research by Liao et al. [13] looked at how crystallinity might be affected by varying the temperature of the print surface in order to control the rate of cooling. Controlling the degree of crystallinity

by annealing the finished part has also been studied. As Hart et al. [14] observed, rapid cooling increases crystalline order and the strength of the finished part, whereas gradual cooling reduces the degree of crystallinity, resulting in a more amorphous and tougher part. Wittbrodt and Pearce [15] isolated a single filament color and examined how variations in the extruder nozzle temperature impacted the final crystallinity of the printed part. Their data is seen in Figure 4.

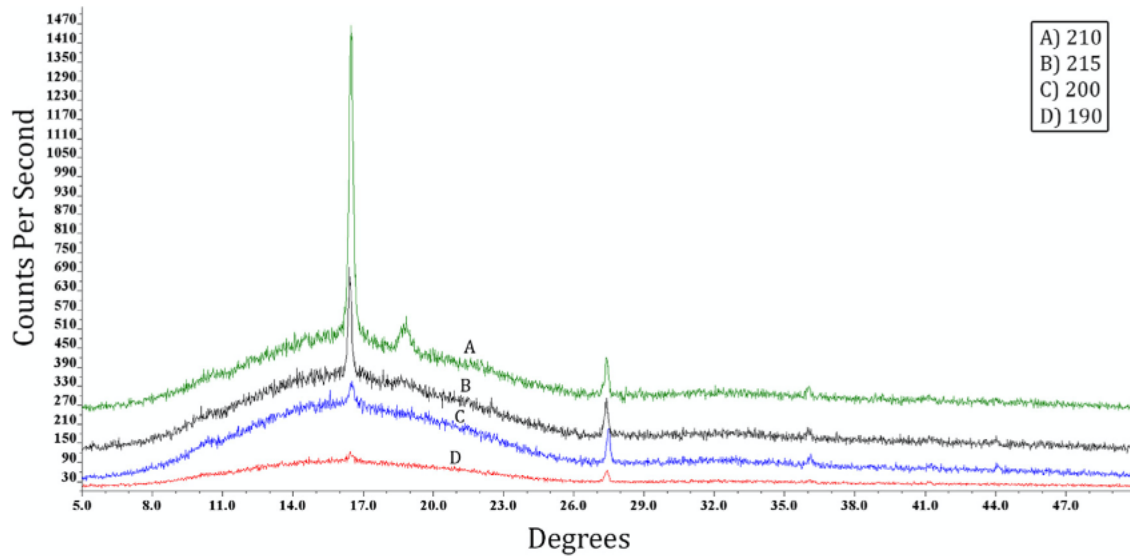


Figure 4. XRD data for white PLA printed with various extruder nozzle temperatures. Source: [15].

4. Filament Pigmentation

Less studied, but important to understanding crystalline effects on mechanical properties in semi-crystalline polymers such as PLA, is the impact of filament color pigmentation. Wittbrodt and Pearce [15] examined the crystallinity of five different PLA filaments, each colored with a unique pigment, all sourced from a single manufacturer. With pigment color being the only variable, XRD data clearly showed variations in the filament crystallinity, as seen in Figure 5 [15]. Manufacturers generally consider their pigmentation recipes to be trade secrets, which makes comparing filament from one manufacturer to another difficult without performing extensive XRD analysis. It is

important to recognize the effects pigmentation has on crystallinity of semi-crystalline polymer filaments as the degree of crystallinity will be affected by heating and cooling processes, which will have a direct impact on the resultant mechanical properties.

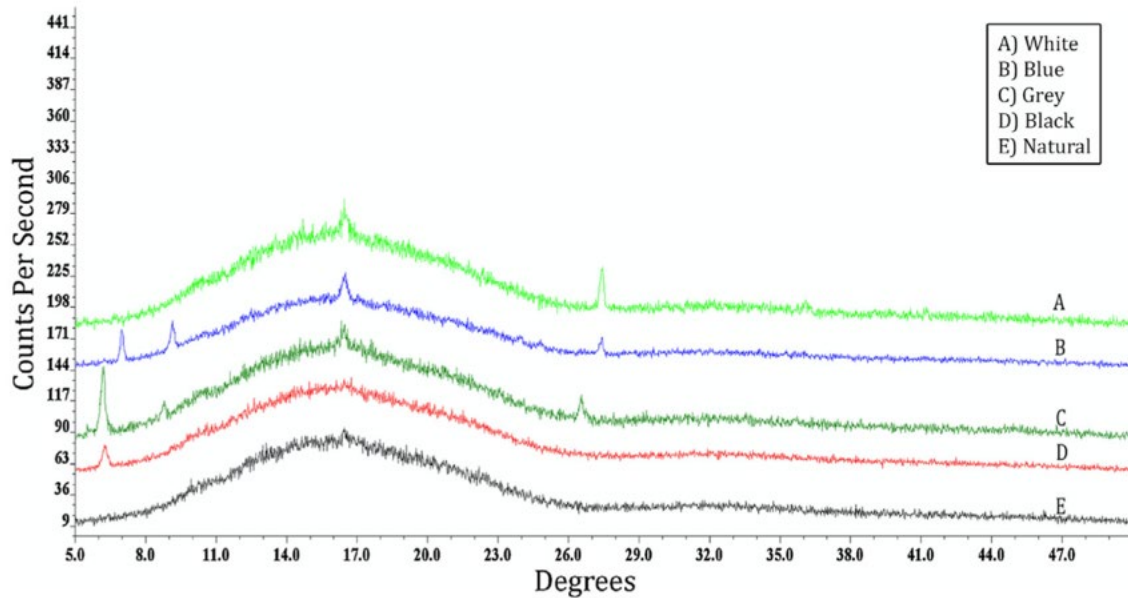


Figure 5. XRD peaks for varying colors of PLA filament.
Source: [15].

5. Limits of Current State of the Art

The majority share of available research has been focused on studying the use of ABS polymers in FDM structural applications. Additionally, many studies have been conducted on polymer matrix composites and not on the raw material itself due to believing the polymer in its raw state would always be mechanically inferior without additives. With the more recent shift in focus to printing with PLA due to its biodegradability and less harmful off-gassing, a fair amount of mechanical research has been done on this polymer. Kiendl and Gao [10] studied how infill orientation angle affected the mechanical properties of FDM PLA, but they did not vary other parameters such as layer thickness or build direction.

Few researchers have studied how the mechanical properties of PETG are affected by FDM printing parameters, and even fewer have studied the effects on PC. Hanon et al. [16] conducted a similar study as Kiendl and Gao, except with PETG, and similarly they did not vary additional parameters. Hill and Haghi [17] were some of the few researchers to study the structural applicability of PC in FDM applications. They too focused solely on the effects of infill orientation angle and no other parameters.

In no other available research was such an extensive study of multiple materials and the mechanical effects of multiple printing parameters discussed as is presented in this thesis.

D. OBJECTIVES

The purpose of this research was to understand how varying FDM printing parameters will affect the mechanical properties of a produced part for use in structural applications. Three FDM parameters, build plane orientation, infill pattern, and layer thickness, were the subject of this thesis.

1. Build Plane Orientation

FDM printers allow three-dimensional (3D) models to be printed in almost any orientation in 3D space. Models can be printed in-line with a primary axis or off-axis, with the use of additional supports. Primarily, parts are produced lying flat in the XYZ plane, or they are printed vertically with the part standing up in the ZXY plane, which are the two orientations studied in this research. Depending on the build orientation, the associated infill material may be aligned either in-line or transverse to the relative stress axis, which may have a direct impact on the associated mechanical properties of the part. It is important to understand how the build orientation affects mechanical performance so end-users can tailor this parameter to be best suited for the structural application.

2. Infill Raster Pattern

With FDM printing, generally the part is produced by first extruding an outline of the external contour with a series of “walls.” After which, unless the part is intended to be hollow, infill is extruded in a pattern determined by the manufacturer in order to add

rigidity and strength to the part. A multitude of infill patterns exist, varying from simple to complex. The density, or spacing, of the infill can vary from widely spaced to completely filled (solid). For this research, four infill patterns were studied in order to characterize how infill affects mechanical properties. These patterns included horizontal lines oriented transverse to the stress axis, vertical lines oriented in-line with the stress axis, and lines alternating plus and minus 45° relative to the stress axis.

3. Layer Thickness

Changing the layer height with FDM allows the manufacturer to control the level of detail, as well as the associated production time, for a part. Thicker layer heights result in faster part production and require less precise tuning of the printer for the print to be successful. This comes at the cost of a rougher surface finish and less observable print detail. Smaller layer heights produce parts with a very fine surface finish, and small details are often resolved, but the print will take much longer to produce. Printing at this level of detail is much less forgiving and requires very precise tuning of the printer. In this research, parts were produced across a range of layer heights, to include: 0.2 mm, 0.16 mm, and 0.1 mm. While this research was not as concerned with surface finish, the intent was to observe if there was a change in mechanical performance based on the variation in layer height.

4. Trends Across Polymers

A final point of this research was to observe mechanical trends for strength and strain versus the printing parameters that were varied in order to identify whether or not a universal printing parameter “recipe” existed that would yield maximum mechanical performance for a specific metric, regardless of material selection.

II. MATERIALS AND METHODS

A. MATERIALS AND 3D PRINTING PARAMETERS

1. Materials

The materials studied in this thesis are listed in Table 1. PLA was of primary interest due to its ubiquity in FDM 3D printing. PETG and PC were included because of their good mechanical properties and increasing use in FDM AM applications. PETG is useful in applications requiring a great degree of toughness, and PC is known for its impact resistance and has many uses in military and transparent glass applications.

Table 1. Material Selection and Associated Manufacturer Specifications

Material	Manufacturer	Color	Diameter	Nozzle Temperature	Print Bed Temperature
PLA	MakerBot	True White	1.75 mm	215-230 °C	60-65 °C
PETG	Push Plastic	Black	1.75 mm	230-250 °C	80-90 °C
PC	Polymaker	True White	2.85 mm	250-270 °C	90-105 °C

2. Printing Parameters

The printing parameters were established using Cura, an open-source slicer software. Slicer software converts a 3D object (i.e., CAD model) into a set of instructions (G-code) the printer can use to make the object. For the tensile specimens created for this research, the default Cura material profiles were used for each respective material type. From there, modifications were made to the default parameters to account for the desired variations in layer thickness and infill pattern. Figure 6 shows a mockup of the studied infill raster patterns and the associated short-hand notation used in this thesis. Figure 7 shows Cura renderings for a snapshot of the printing process for each of the studied infill raster patterns.

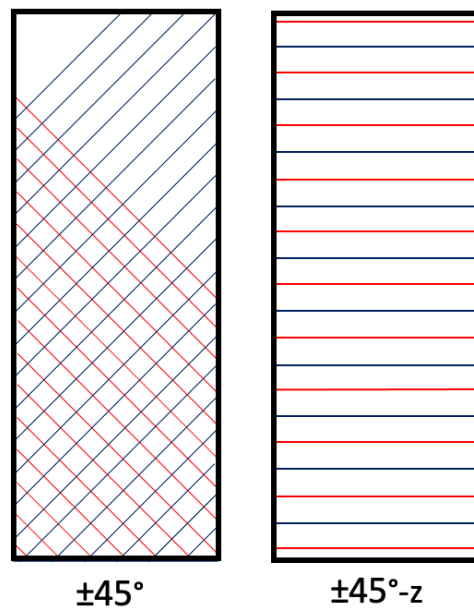
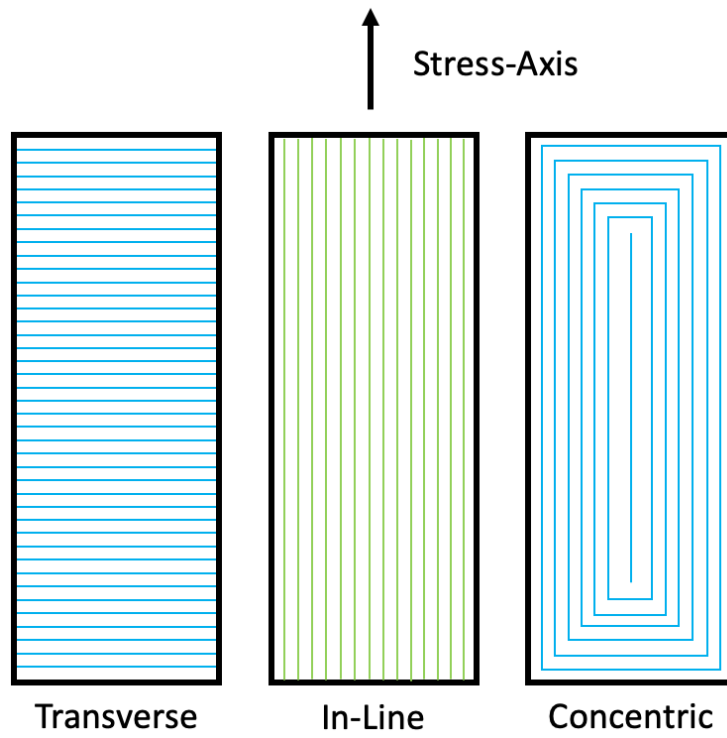


Figure 6. Infill raster patterns with associated short-hand notation

Adjustments were made to the nozzle and bed temperatures as necessary if the default profile parameters were off from the manufacture suggested parameters. For all tensile specimens, regardless of material, layer thickness, or infill pattern, the infill density was set to 100%. This was done in order to obtain the densest sample possible. Additionally, all samples were printed with a 5% overlap between the infill and outer wall based on preliminary trials varying this parameter. All test specimens were printed using a Lulzbot TAZ6 printer (Figure 8) with a 0.5 mm diameter extruder nozzle.

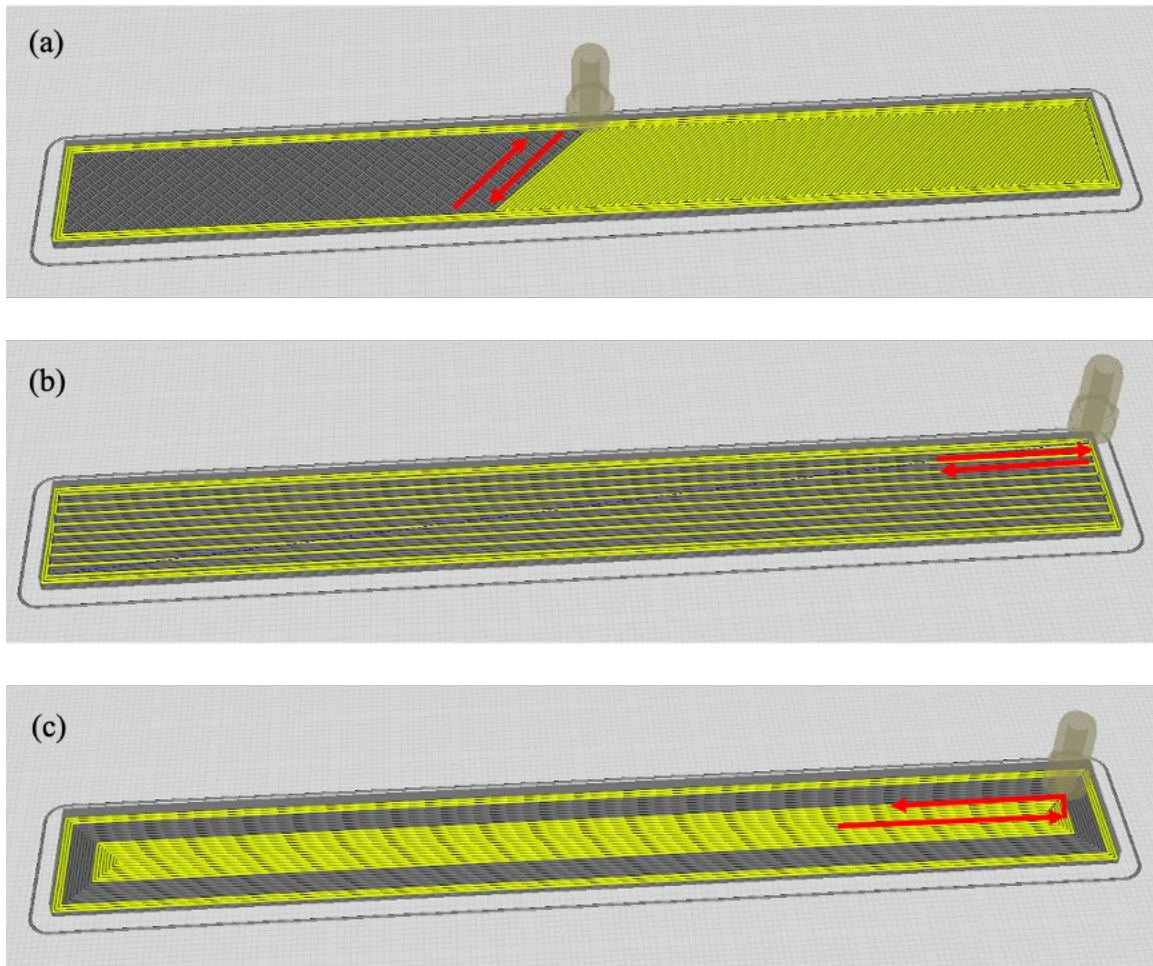


Figure 7. Cura renderings: ± 45 (a), longitudinal lines (b), and concentric (c) (transverse lines not shown)

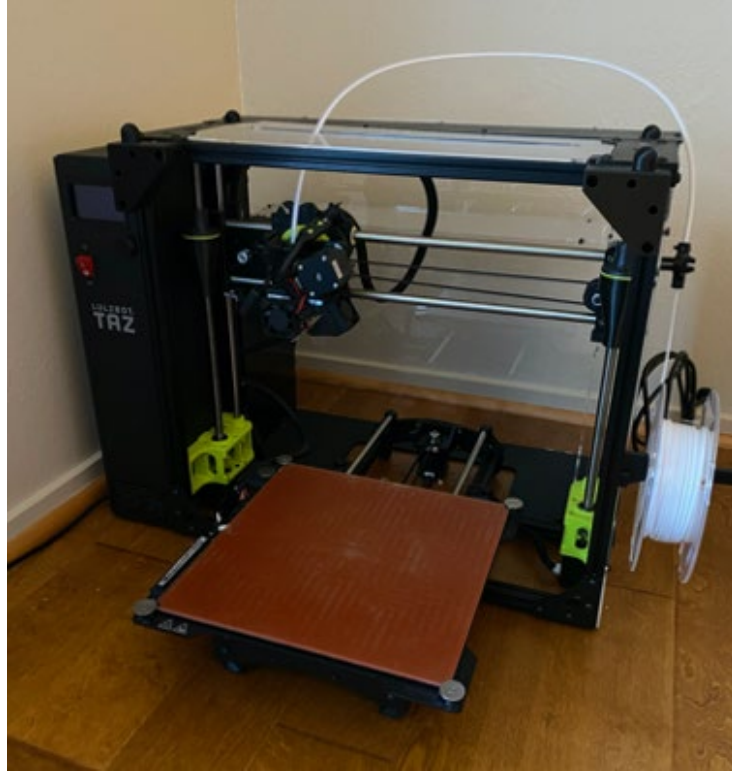


Figure 8. Lulzbot TAZ6 3D printer

B. MECHANICAL TESTING

1. ASTM Standards

Currently, no specific American Society for Testing and Materials (ASTM) standard exists for how to assess mechanical performance of AM polymer objects. ASTM standard D638 outlines standard testing procedures for plastics, but the plastics referred to in this standard are produced with more traditional manufacturing methods and are generally isotropic in nature. ASTM standard D3039 is the standard for tensile testing polymer matrix composites. The broader applicability of this standard is to polymers with anisotropic structure and properties. Research focused on studying the mechanical properties of AM polymers have referred to both standards for reference. A possible downside of standard D368 is the typical “dog-bone” specimen shape. This shape is used to ensure the sample failure takes place within the gage length, outside of any grip surface area. However, the printing of this shape creates many discontinuities in the region where the grip area necks down into the gage length, seen in Figure 9.

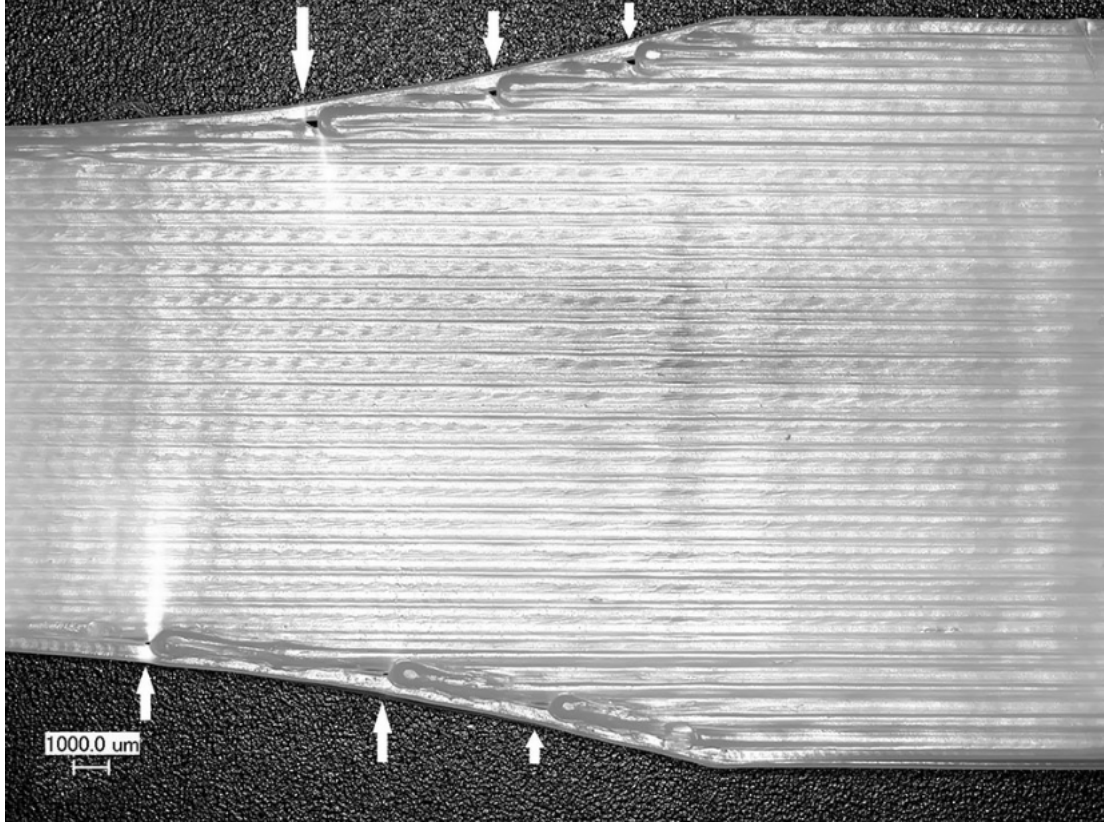


Figure 9. ASTM D638 sample with inherent FDM printing discontinuities and arrows pointing to stress concentration locations. Source: [11].

These discontinuities make it difficult to discern whether failure occurred due to the sample geometry or due to filament discontinuities created as an artifact of the AM processes. For this reason, the D3039 standard was chosen for this research, whose sample geometry, shown in Figure 10, consists of a uniform rectangle, eliminating specimen geometry from being a possible cause of failure. As a result, failure explanations could be isolated to intrinsic material properties and AM defect characterizations. Throughout testing, fracture sites were observed in the gage length as well as near the grips. No discernable change in measured mechanical properties could be attributed to the failure site.



Figure 10. ASTM D3039 sample geometry

2. Tensile Testing Setup

Tensile testing was conducted using an Instron: 5982 Universal Testing System and Instron: 100kN Mechanical Wedge Action Grips, shown in Figure 11. The test specimen dimensions were set to 120 mm (l) x 19 mm (w) x 3.2 mm (t) prior to printing. The actual printed sample dimensions were recorded prior to testing. Dimensional accuracy is a factor to consider with AM, but it was not closely studied in this research. On average, dimensions varied by 7% for PLA, 4% for PETG, and 7% for PC. Each sample was tested to failure using an applied strain rate of 2 mm/min. The maximum recorded force was used in conjunction with the printed sample dimensions to calculate the ultimate strength, and the recorded elongation was used in relation to a standard 50.8 mm gage length to calculate the engineering strain for each sample.



Figure 11. Instron: 5982 Universal Testing System (left) and Instron: 100kN Mechanical Wedge Action Grips (right)

C. CHARACTERIZATION

1. Optical Microscopy

For each test sample, bulk material located in the grip section, away from the fracture location, was cross sectioned and polished. These cross sections would show the internal polymer matrix in its unloaded state. The cross sections were mounted in a resin puck and then polished using a sequence of 240, 400, and 600 grit paper, followed by $6\mu\text{m}$ and $1\mu\text{m}$ diamond suspension. A Nikon: Epiphot 200 optical microscope and associated Nikon imaging software were used to gather cross section images. Images were taken using bright-field contrast.

2. Scanning Electron Microscope

After tensile testing, the fracture surfaces from each sample were removed from the tensile bars for scanning electron microscope (SEM) imaging. For preparation, the removed surfaces were cleaned in an ethanol solution for approximately two minutes using

a Buehler: Ultramet 2005 sonic cleaner. Due to the insulating properties of the polymers and to minimize charging effects, it was necessary to sputter the fracture surfaces prior to imaging. Using a Cressington: 208HR Sputter Coater and a Cressington: mtm20 Thickness Controller (Figure 12), a 4 nm layer of palladium was deposited on top of each fracture surface. The fracture surfaces were imaged using a Zeiss: Neon 40 SEM (Figure 12) with a standard 30 μ m aperture and an electron accelerating voltage of 5 kV. In some instances, it was necessary to reduce the accelerating voltage to 2 kV due to excessive charging. Due to the contour irregularities of the fracture surfaces, it was necessary to vary the working distance between 5 mm and 15 mm in order to obtain the appropriate depth of field to focus the entire image depending on the magnification. The primary detector used for the imaging was the Everhart-Thornley secondary electron (SE2) detector due to its better surface topography resolution, which is useful for the characterization of the fracture sites.

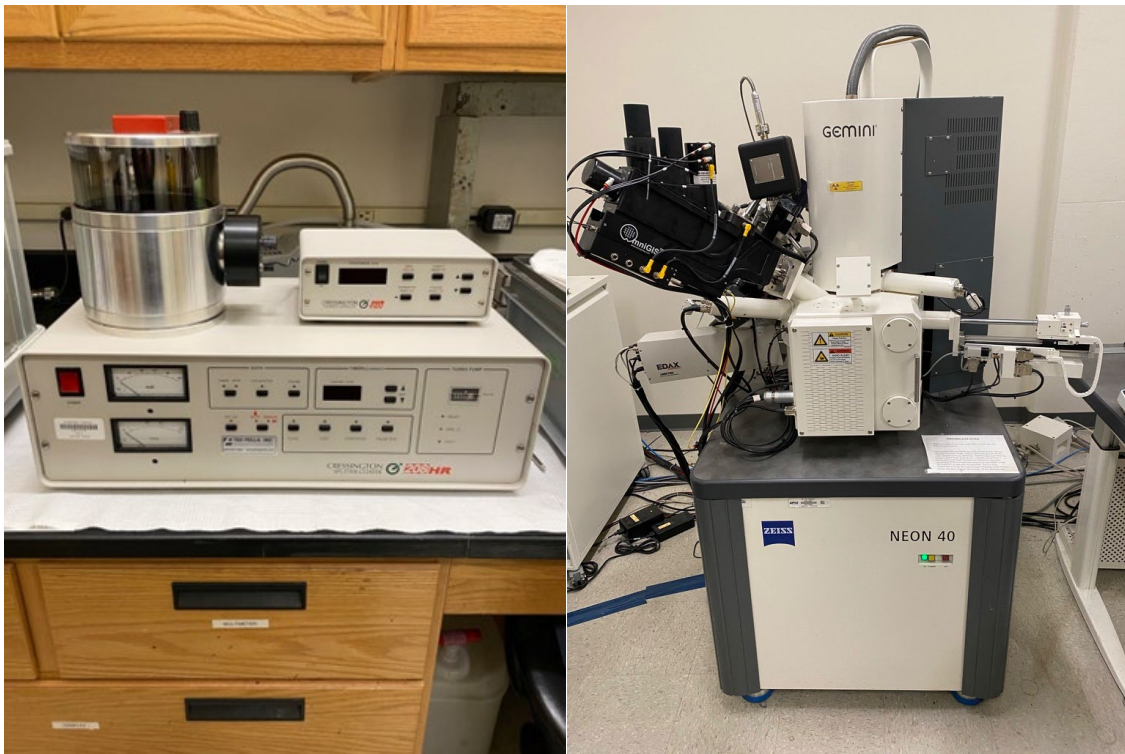


Figure 12. Cressington sputter coater and thickness controller (left) and Zeiss: Neon 40 SEM (right)

3. X-Ray Diffraction

Bulk sections of each sample were removed from the tensile bar geometries after tensile testing in preparation for x-ray diffractometry analysis. These sections were individually mounted on Rigaku 24 mm open trays (Figure 13). The use of clay, which could skew the observed diffraction peaks, was eliminated by shaping the bulk samples such that friction between the material and the tray alone was sufficient to hold the sample in place during testing. A Rigaku Miniflex 600 x-ray diffractometer (XRD), shown in Figure 13, was used for this analysis. The XRD parameters consisted of the standard 40kV/15mA aging and a two-theta scan range of 10° to 90° , at a scan speed of $7^{\circ}/\text{min}$ with a step size of 0.01° . PDF-4+ 2020 RDB, a product of the International Centre for Diffraction Data was used for a XRD database reference. For this research, the following PDF Numbers were referenced: 00-064-1623 (PLA, semi-crystalline), 00-064-1622 (PLA, amorphous), 00-060-1509 (PET, amorphous), and 00-060-1506 (PC, amorphous).



Figure 13. Example of PC sample mounted in tray for XRD analysis (left) and Rigaku Miniflex 600 XRD (right)

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III. RESULTS AND DISCUSSION

A. MICROSTRUCTURAL CHARACTERIZATION (UNDEFORMED)

1. Cross Sections

a. In-Line

The in-line infill raster pattern creates a cross-section that looks like printed beads stacked on top of one another, as seen in Figure 14. The concentric cross-sections are not shown in this report due to them being nearly identical to the in-line cross-sections.

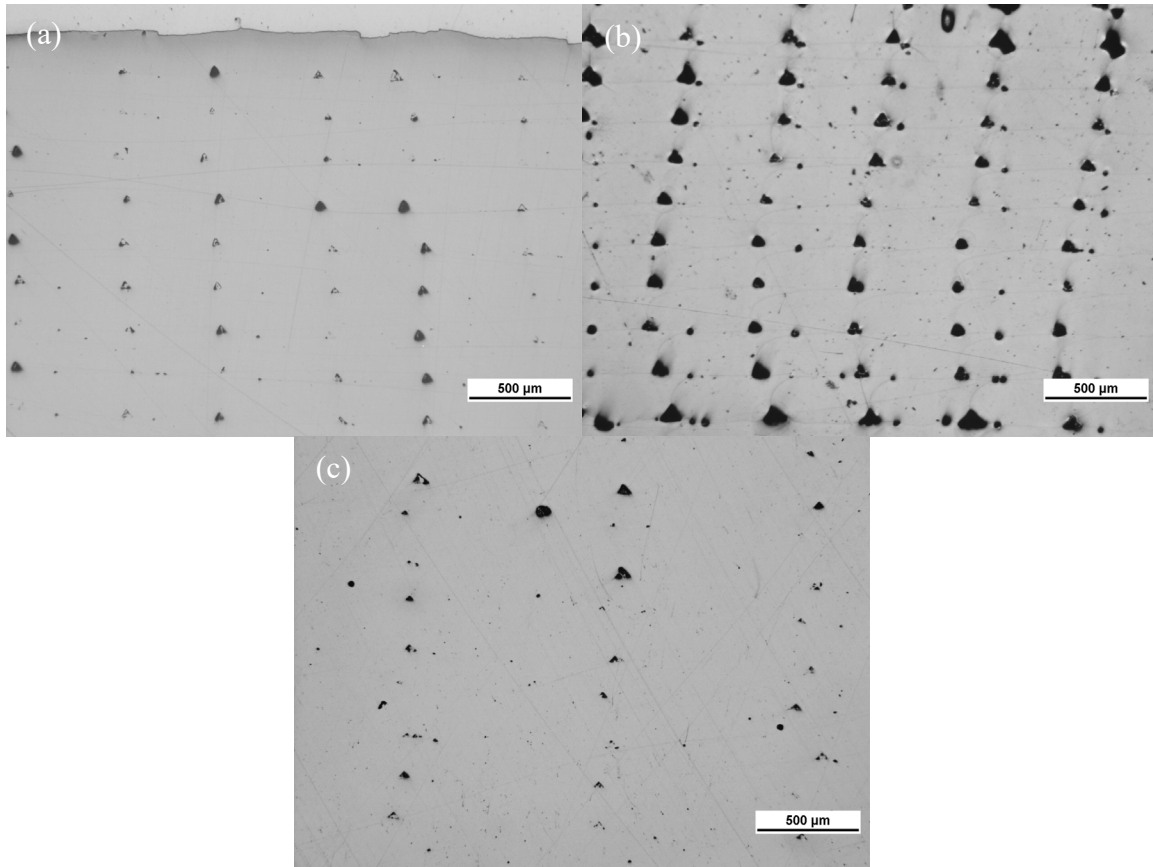


Figure 14. Cross-sections of in-line samples of PLA (a), PETG (b), and PC (c), printed with 0.2 mm layer height

b. Transverse

Cross-sections of the transverse samples show stacked layers, extruded from left to right across the images. The interfacial porosity observed here is not like the diamond shape pores that exist in the in-line or $\pm 45^\circ$ samples. Instead, the porosity observed with the transverse samples are areas where subsequent layers did not properly fuse to the previously extruded layer. While this feature was observed in all materials tested, PLA exhibited the greatest degree of difficulty with interfacial layer fusion. Figure 15 shows examples of this type of porosity in the transverse samples.

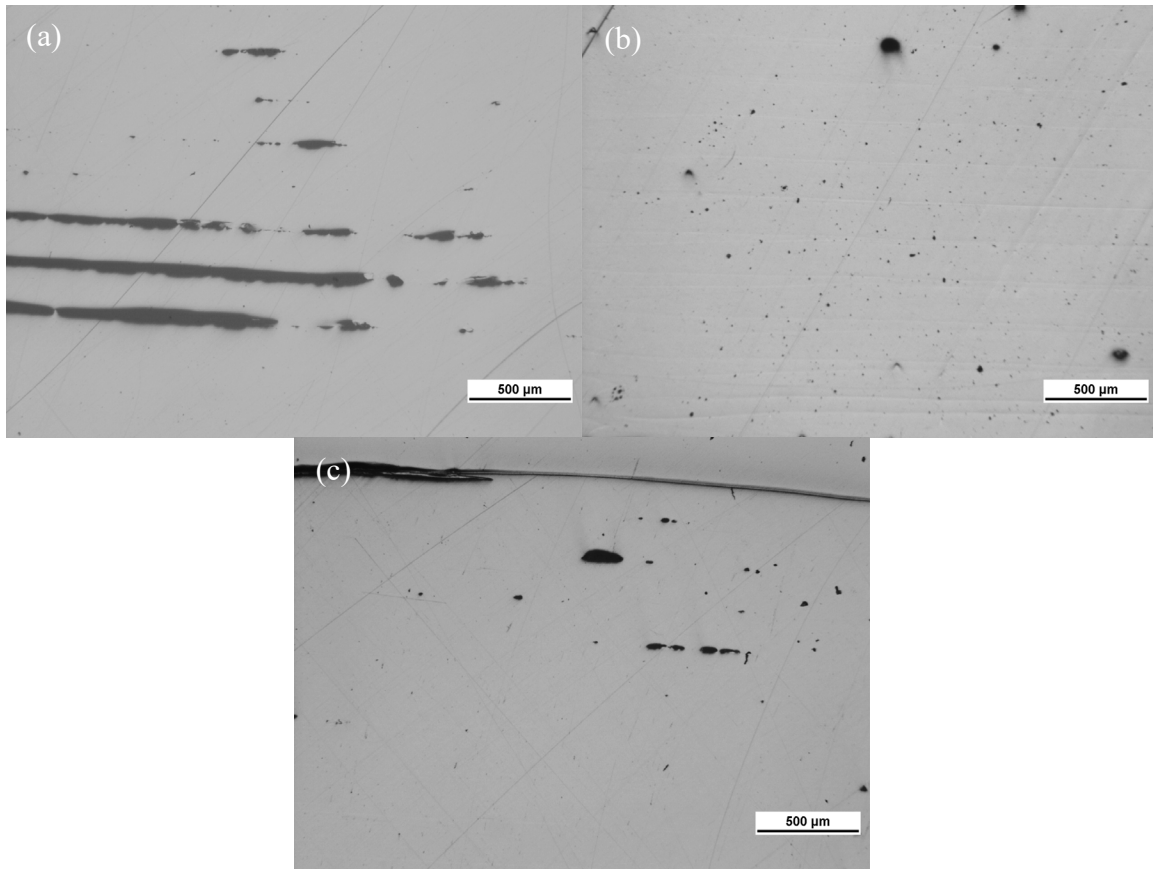


Figure 15. Cross-sections of transverse samples of PLA (a), PETG (b), and PC (c), printed with 0.2 mm layer height

c. $\pm 45^\circ$

When cross-sectioning the $\pm 45^\circ$ samples, the printed beads are not printed directly on top of one another. Instead, in subsequent layers the beads shift back and forth. This is due to the alternating orientation of the printed layers, as well as the cross-sectional cut being 45° incident to the printed fiber. Figure 16 shows the $\pm 45^\circ$ cross-sections for PLA, PETG, and PC, all printed with 0.2 mm layer height. Of note, the PC samples have a significantly smaller interfacial porosity relative to PLA and PETG for the same printed layer height.

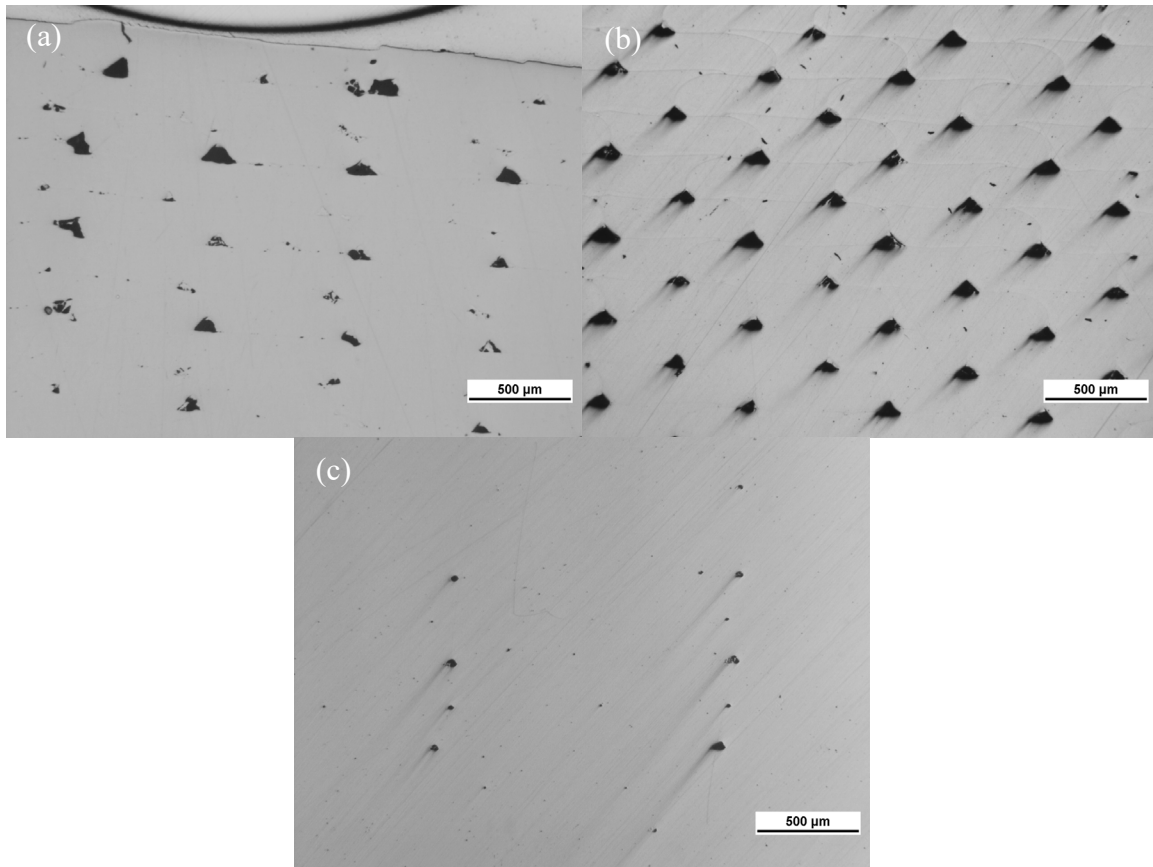


Figure 16. Cross-sections of $\pm 45^\circ$ samples of PLA (a), PETG (b), and PC (c), printed with 0.2 mm layer height

d. $\pm 45^\circ$ -z

$\pm 45^\circ$ -z cross-sections are unique because they occur in between adjacent printed layers. Due to the small cross-sectional dimensions of the samples, the image area predominantly consists of the extruded outer walls. A single, wave-like, extruded bead in the center of the sample is the printer attempting to create the $\pm 45^\circ$ infill. While the infill does alternate directions on subsequent layers, true to the $\pm 45^\circ$ pattern, because the available infill area is so small, the infill comes out almost as a straight line. As a result, large gaps exist between the infill and adjacent walls. Figure 17 shows the porosity of these samples. The PC samples showed the least amount of porosity between the infill and the adjacent walls, but PC also uniquely showed a large amount of trapped air pockets that impacted the interfacial fusion.

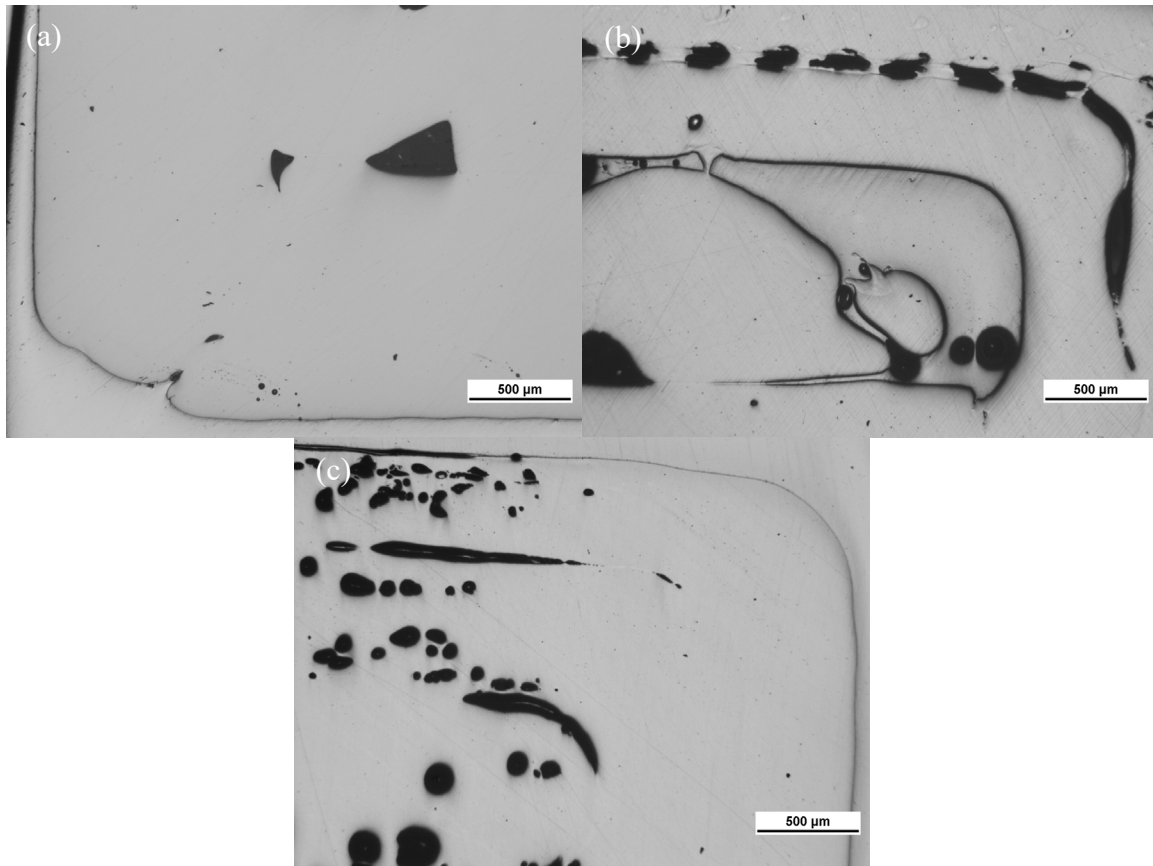


Figure 17. Cross-sections of $\pm 45^\circ$ -z samples of PLA (a), PETG (b), and PC (c), printed with 0.2 mm layer height

2. Phase Analysis

XRD of each polymer in its undeformed state was taken to gain insight whether the polymers tested were amorphous or semi-crystalline. PETG exists in its natural state as an amorphous polymer, which the test data in Figure 18 confirms. Similarly, PC is a predominantly amorphous polymer, which the test data also confirmed. PLA can exist in an amorphous or semi-crystalline state, with varying degrees of crystallinity. Referencing the PDF database, the PLA used for this research is predominantly amorphous with some crystalline peaks and would be considered semi-crystalline. Similar to Wasanasuk et al.'s study of PLLA, the degree of crystallinity in PLA will change as it undergoes heating, extruding, and cooling due to the different PLA crystalline phases that can manifest [12].

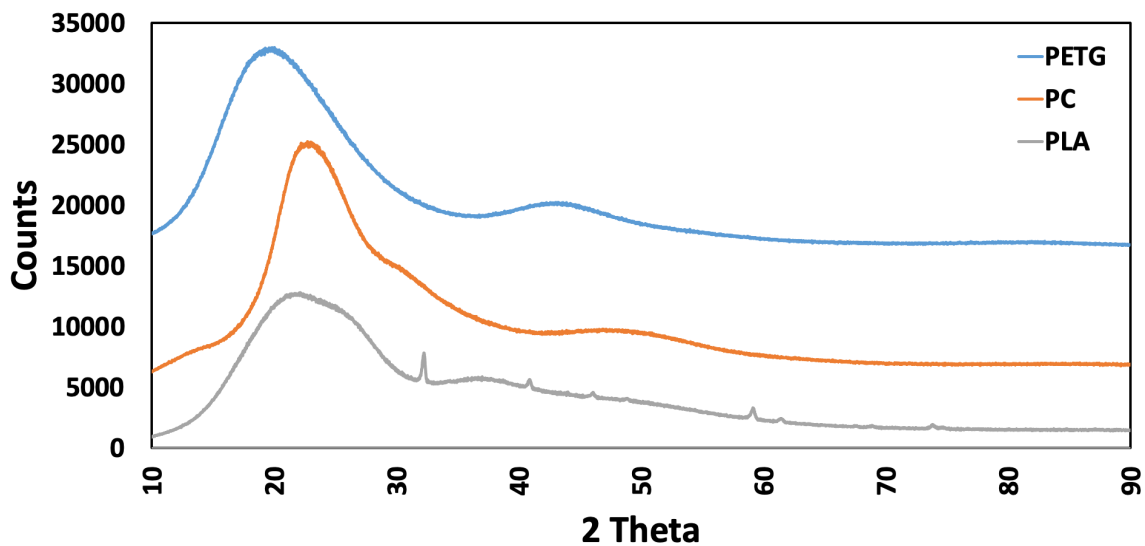


Figure 18. XRD patterns of PETG, PC, and PLA

B. MECHANICAL BEHAVIOR

1. Linear Raster Pattern

a. PLA

The calculated mechanical property data for PLA specimens is listed in Table 2. The plotted data, seen in Figure 19, is representative of individual tests and does not

necessarily account for the statistical uncertainty between samples. Some variations in strain were noted but none of real statistical significance. Despite a noticeable change in densification with the in-line PLA samples seen in Figures 20 and 21, no noticeable change in strength was observed as a result of decreasing the printed layer height from 0.2 mm to 0.1 mm.

Table 2. Tabulated data: PLA printed with line infill raster pattern

Sample Set	Stress (MPa)	Strain (%)	E (MPa)
PLA-LT-0.2	42.4 ± 0.7	6.7 ± 0.5	883.2 ± 32.6
PLA-LT-0.16	48.0 ± 1.6	6.8 ± 0.2	959.5 ± 17.6
PLA-LT-0.1	47.1 ± 1.6	7.4 ± 0.2	901.8 ± 6.8
PLA-LL-0.2	59.5 ± 1.2	12.3 ± 1.6	850.0 ± 26.7
PLA-LL-0.16	60.3 ± 1.3	16.9 ± 7.0	853.8 ± 73.8
PLA-LL-0.1	61.0 ± 3.6	12.9 ± 1.6	976.5 ± 50.0

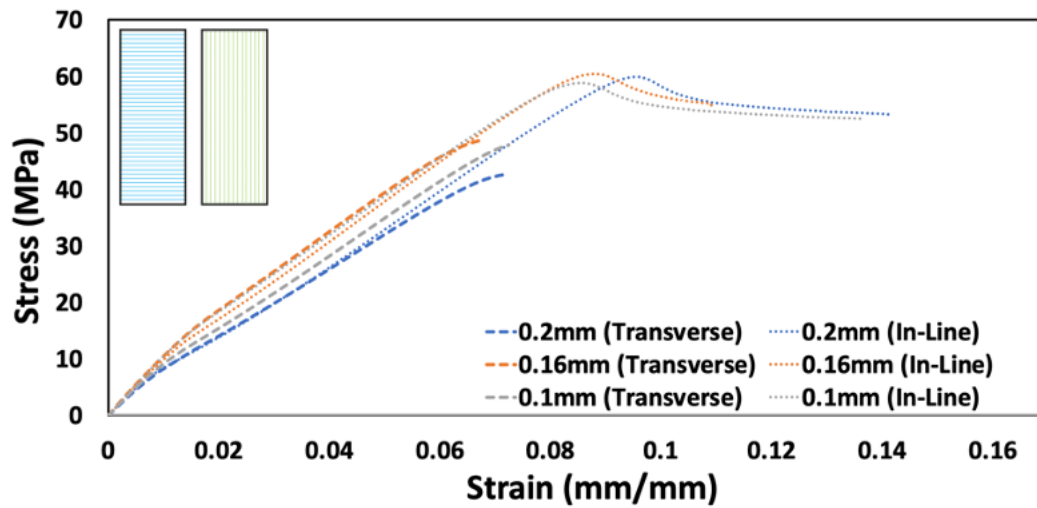


Figure 19. Stress-strain comparison of PLA samples with line infill raster pattern

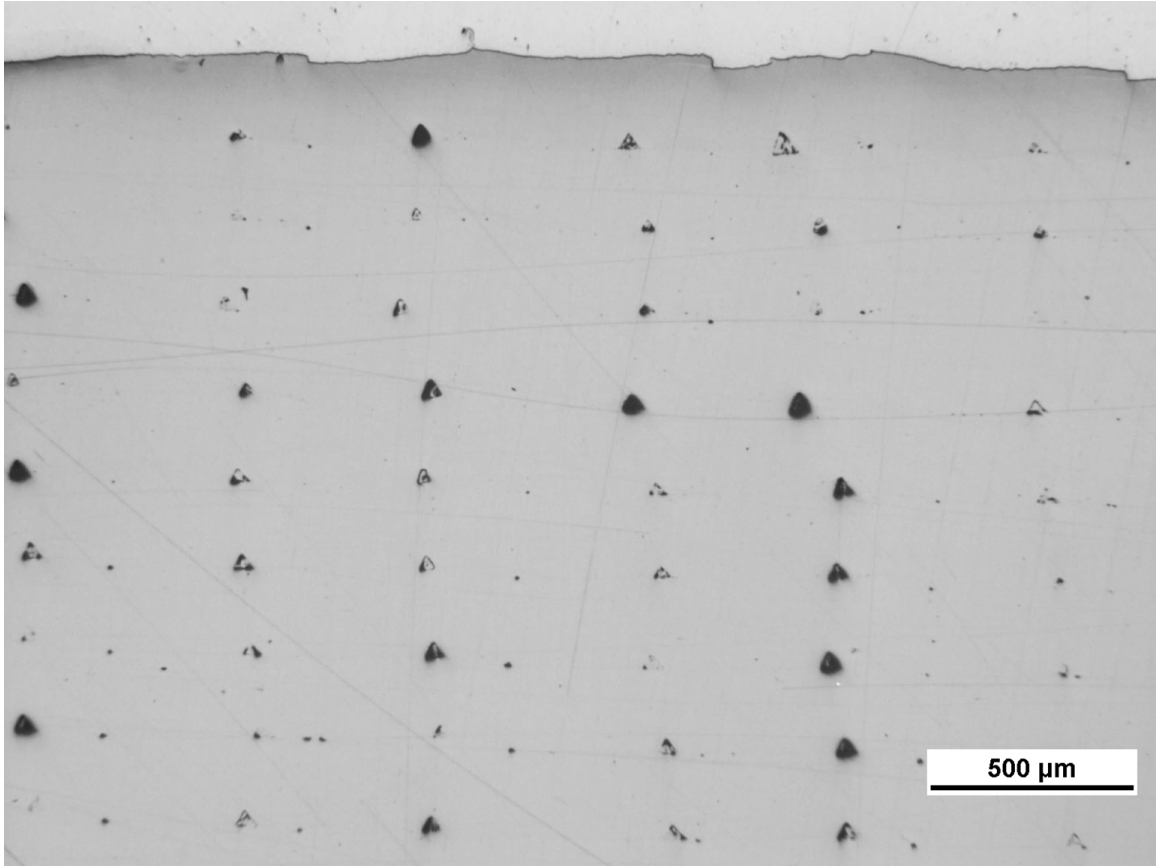


Figure 20. Cross-sectional porosity of in-line PLA printed with 0.2 mm layer height

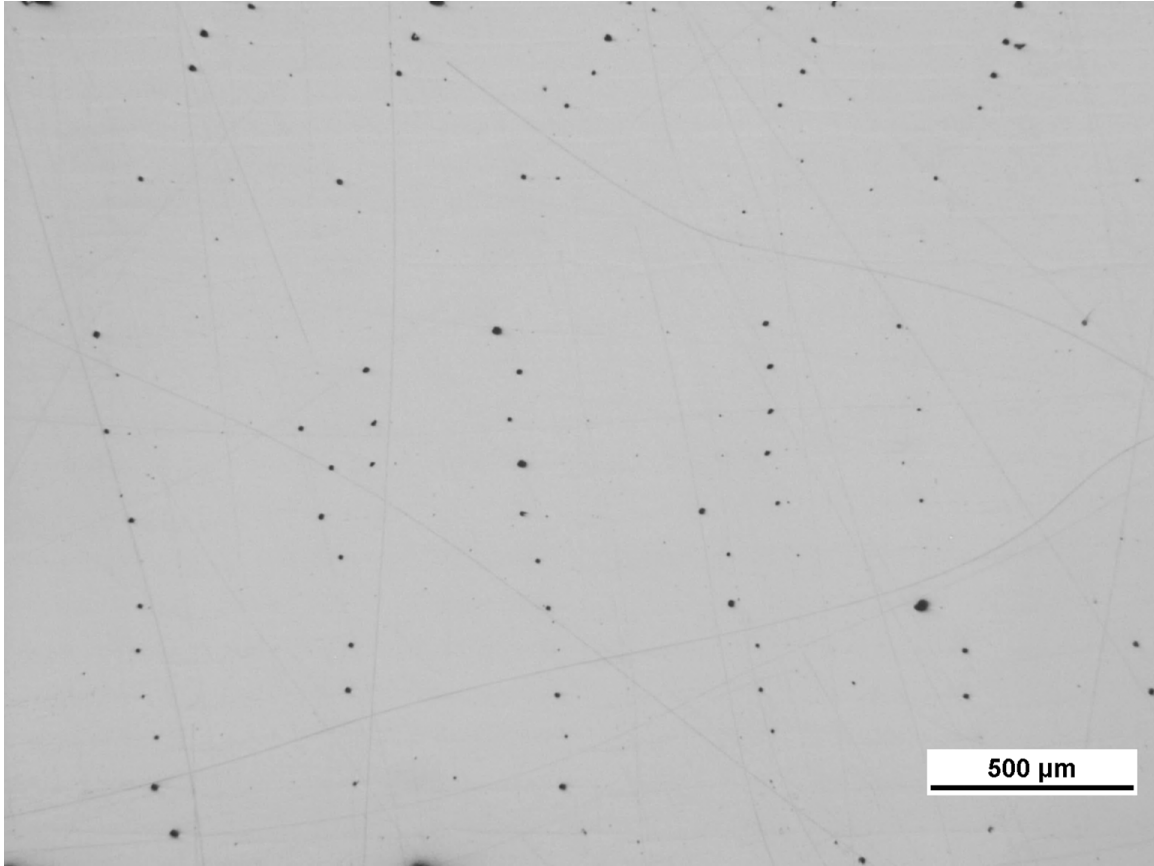


Figure 21. Cross-sectional porosity of in-line PLA printed with 0.1 mm layer height

The transverse PLA samples did see a noticeable change in strength as a result of varying the layer height. For this infill pattern, the reduced layer height resulted in an increased densification of the sample due to a reduction in interfacial porosity (Figures 22 and 23), which resulted in reduced porosity in the outer walls and greater tensile strength. This trend of increasing strength as a result of decreasing the printed layer height aligns with the results seen by Rankouhi et al. in their tests [11].

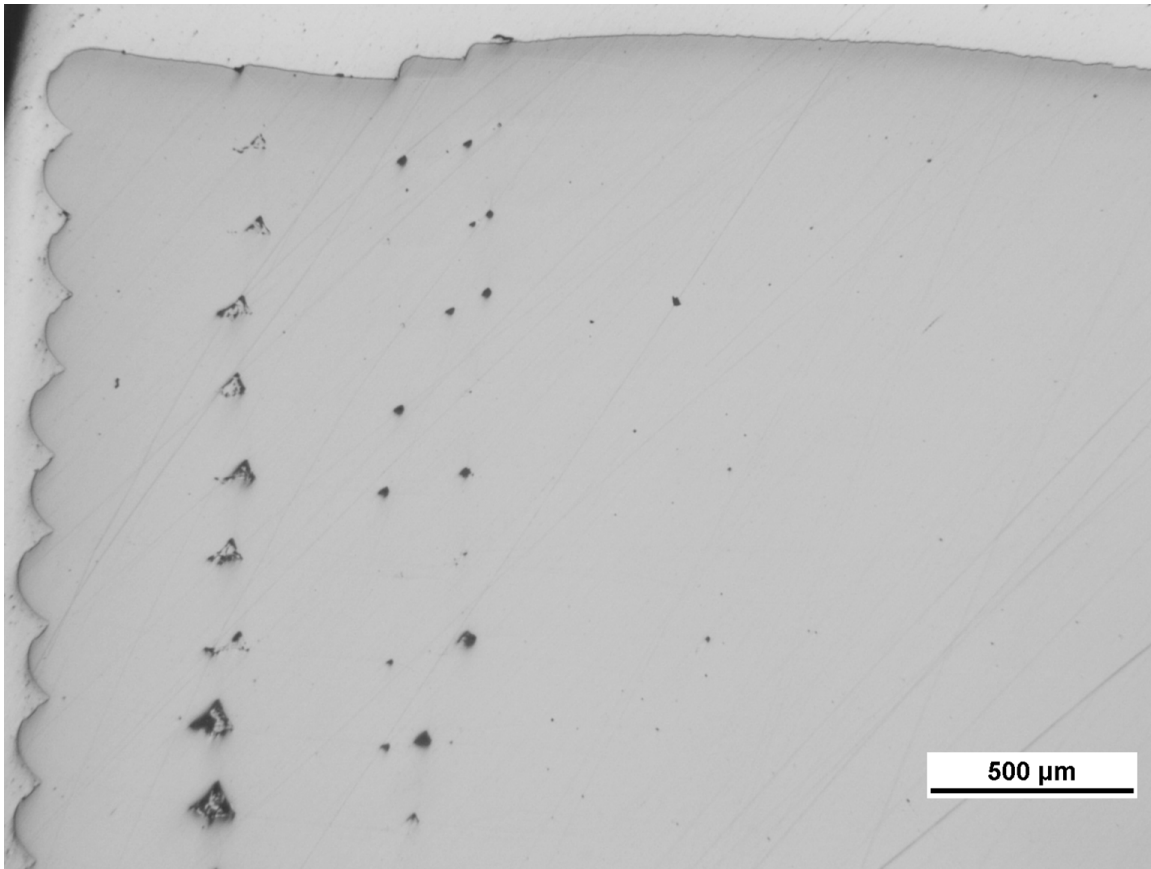


Figure 22. Cross-sectional porosity of transverse PLA printed with 0.2 mm layer height

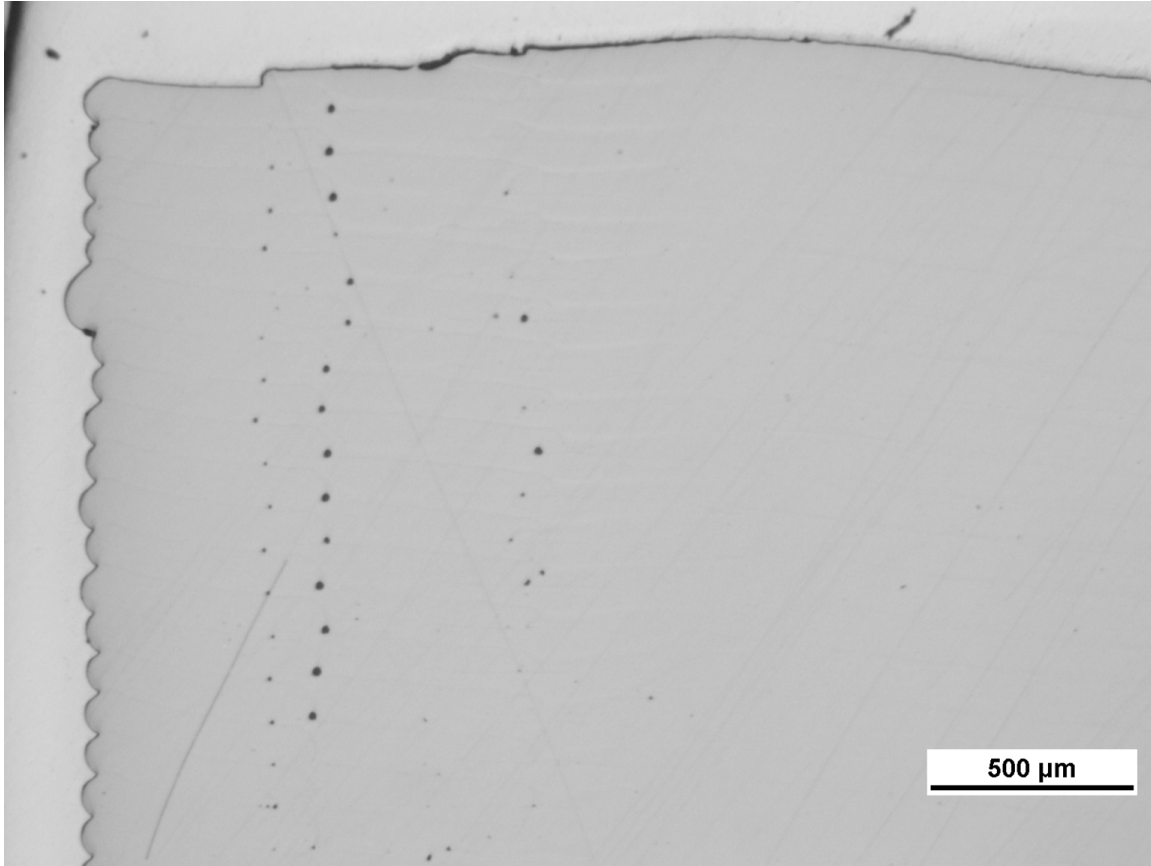


Figure 23. Cross-sectional porosity of transverse PLA printed with 0.1 mm layer height

Unlike the in-line samples, which exhibited a region of necking after the ultimate strength, the transverse samples exhibited no necking after reaching the ultimate strength, regardless of the printed layer height. The entirety of the infill raster pattern in the transverse samples is printed perpendicular to the applied stress axis. Because there are no printed beads in-line with the stress axis, the ultimate strength and resulting failure in these samples was determined by the strength of the interfacial bonding between adjacent layers, rather than the strength of the bulk fibers, which dictated the mechanical performance of the in-line samples. The interfacial bonding strength is much less than the intrinsic material strength, and as a result, the transverse samples lacked a ductile region while tensile testing. Decreasing the layer thickness of the transverse samples from 0.2 mm to 0.16 mm resulted in slightly better strength properties but decreasing the layer height to 0.1 mm created more interfaces and thus more sites for failure to occur at said interfaces. The greatest strength

value occurring in between the extrema of the layer thicknesses tested suggests an ideal layer thickness exists within that range. Reducing the printed layer height to increase mechanical properties is a tradeoff with inducing printer-tuning related defects as a result of printing with high degrees of resolution.

b. PETG

Varying the printed layer height had no apparent effect on the ultimate strength of the PETG samples, regardless of the orientation of the infill lines. The calculated data for both in-line and transverse data sets is listed in Table 3. From these values and the plotted data in Figure 24, it is apparent that varying the orientation of the infill lines relative to the stress axis had no real effect on the ultimate tensile strength. However, the variation in infill direction had a substantial effect on the observed strain. As with PLA, orientation of the infill pattern with relation to the applied stress axis greatly affects the strain properties of the samples. The more printed fibers that aligned with the stress axis, the more the resultant mechanical properties of the final part will be dictated by the intrinsic mechanical properties of the polymer itself. As the printed fiber orientation is altered toward being transverse to the stress axis, interfacial bonding strength starts to impact intrinsic mechanical properties. PETG is a very tough and ductile polymer, which resulted in the observation of significant strain properties in the in-line samples. The in-line samples, regardless of layer height, produced large variations in strain and did not fit a clear trend.

Varying the layer height did not have an effect on the elongation of the transverse samples. The infill pattern of these samples was not aligned with the applied longitudinal stress, instead, the interfacial bonding strength dictated the mechanical properties. The strain seen in the characteristic curves in Figure 24 are not reflective of a consistent trend seen in strain to failure for the in-line pattern.

Table 3. Tabulated data: PETG printed with line infill raster pattern

Sample Set	Stress (MPa)	Strain (%)	E (MPa)
PETG-LT-0.2	43.9 ± 0.7	12.4 ± 1.8	577.7 ± 32.3
PETG-LT-0.16	43.6 ± 3.5	12.3 ± 2.1	629.0 ± 20.4
PETG-LT-0.1	46.3 ± 0.3	14.6 ± 1.3	619.6 ± 28.9
PETG-LL-0.2	44.6 ± 0.3	552.1 ± 73.2	658.7 ± 35.9
PETG-LL-0.16	44.7 ± 0.9	455.9 ± 119.0	667.2 ± 11.6
PETG-LL-0.1	43.6 ± 0.6	275.1 ± 106.8	639.3 ± 7.0

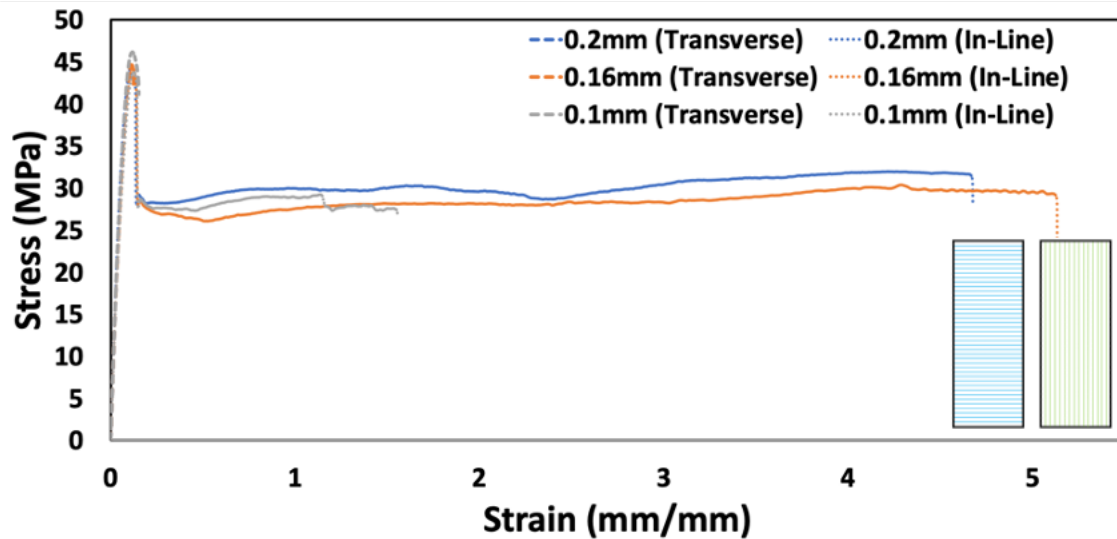


Figure 24. Stress-strain comparison of PETG samples with line infill raster pattern

In both the tests varying layer height and infill pattern orientation, the samples printed with a layer height of 0.1 mm did not correlate with expected trends. Optical microscopy of these particular samples indicated samples that were highly densified relative to the samples printed at 0.2 mm or 0.16 mm layer heights. The optical imagery seen in Figure 25 and Figure 26 shows extruded fibers in the 0.1 mm samples having a unique “hook” shape defect, which is an artifact of over-extruded filament that builds up

on top of adjacent extruded fibers. This over-extrusion is caused by improperly tuned vertical height of the extruder nozzle, and as a result, the extruder nozzle was too close to the print surface. As the level of associated detail increases with a print, there is greater opportunity for defects to arise because more precise printer tuning is required to sustain high resolution features throughout the entire build. In these samples, the defects that manifested as artifacts of the printer tuning dominated the intrinsic properties of the PETG fiber. The SEM imagery in Figure 27 highlights the presence of the “hook” defects in the PETG-LL-0.1 samples.

With the in-line samples, the “hook” defects reduced the ductility in the sample by inhibiting the interfacial movement of adjacent fibers, resulting in samples that failed more brittle and exhibited relatively less strength and significantly less strain properties. With the transverse samples, the mechanical performance is determined by the interfacial bonding strength of the adjacent layers stacked on top of one another. Due to the “hook” defects creating an over-densification effect, more extruded material was in contact, and the observed ultimate strength was greater.

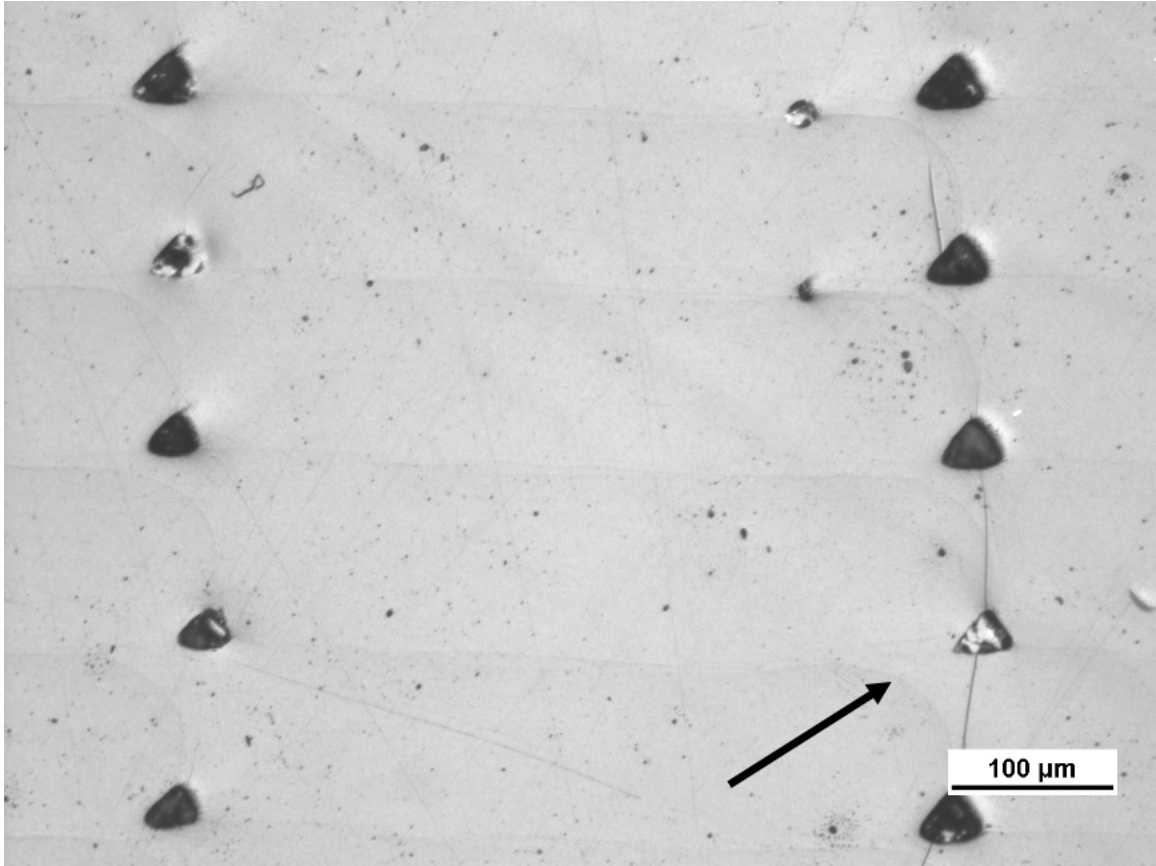


Figure 25. “Hook” defects in PETG sample printed with 0.1 mm layer height and in-line infill raster pattern

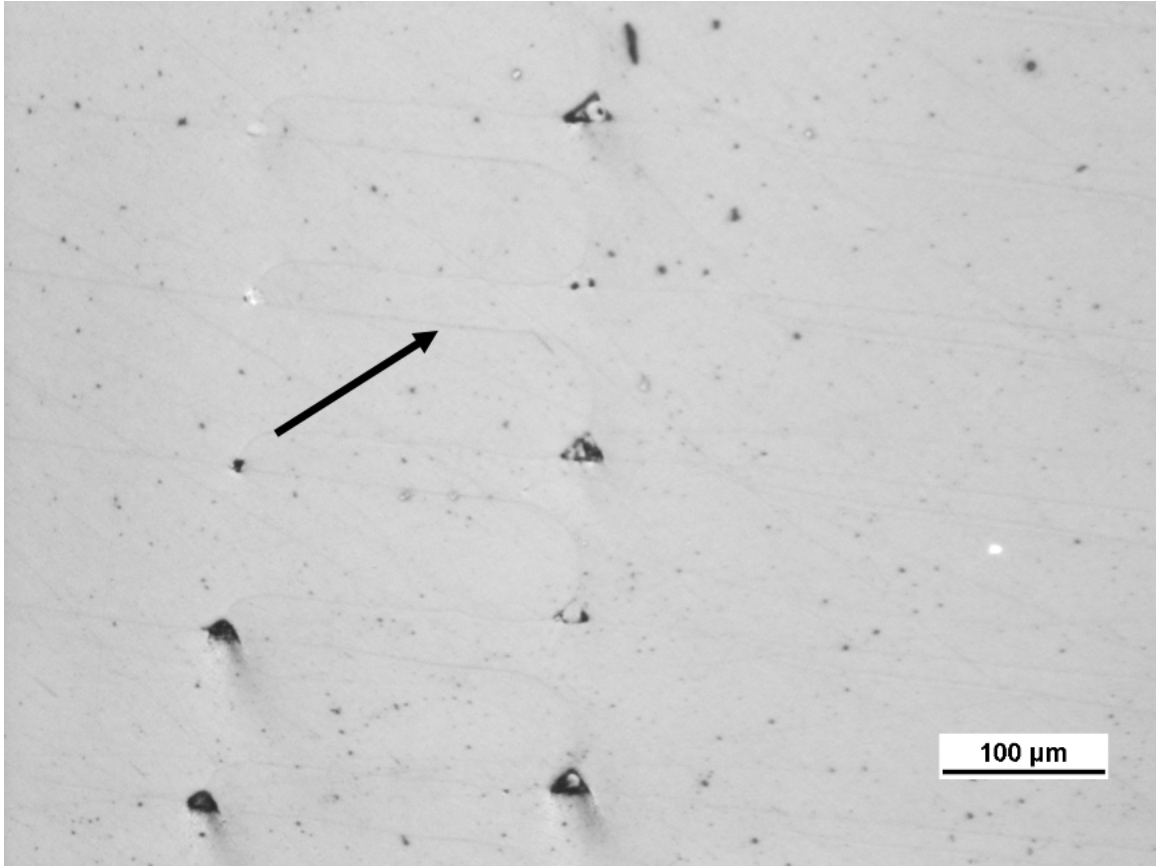


Figure 26. “Hook” defects in PETG samples printed with 0.1 mm layer height and transverse infill raster pattern

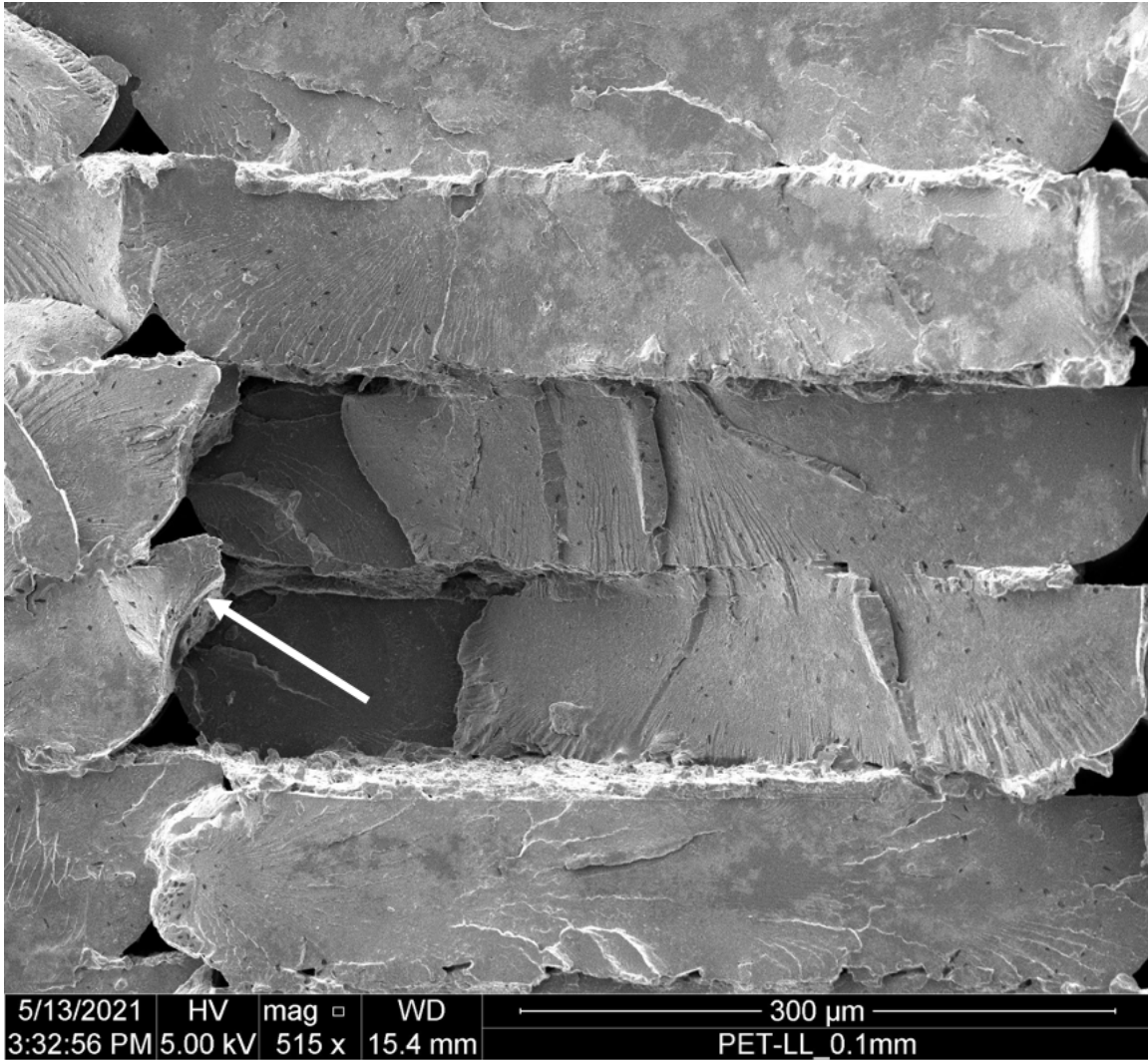


Figure 27. Over-extrusion “hook” defects in PETG-LL-0.1

c. PC

Based on the data shown in Table 4, the in-line PC samples showed a slight increase in ultimate strength as layer height decreased. Differences in strain performance among these in-line specimens due to variations in layer height were statistically insignificant. Figure 28 and Figure 29 show the porosity of the samples decreasing as the printed layer height was reduced from 0.2 mm to 0.1 mm. The increased cross-sectional density is the reason why the samples printed with a smaller layer height exhibited greater strength properties.

Table 4. Tabulate data: PC printed with line infill raster pattern

Sample Set	Stress (MPa)	Strain (%)	E (MPa)
PC-LT-0.2	54.4 ± 1.2	13.8 ± 2.7	703.2 ± 13.8
PC-LT-0.16	55.3 ± 1.6	14.0 ± 1.4	693.7 ± 18.7
PC-LT-0.1	50.3 ± 2.0	11.0 ± 0.8	662.9 ± 22.1
PC-LL-0.2	58.6 ± 1.1	14.6 ± 0.5	680.6 ± 31.8
PC-LL-0.16	60.7 ± 1.6	14.9 ± 1.1	735.0 ± 7.2
PC-LL-0.1	63.3 ± 2.1	15.1 ± 0.2	766.1 ± 24.3

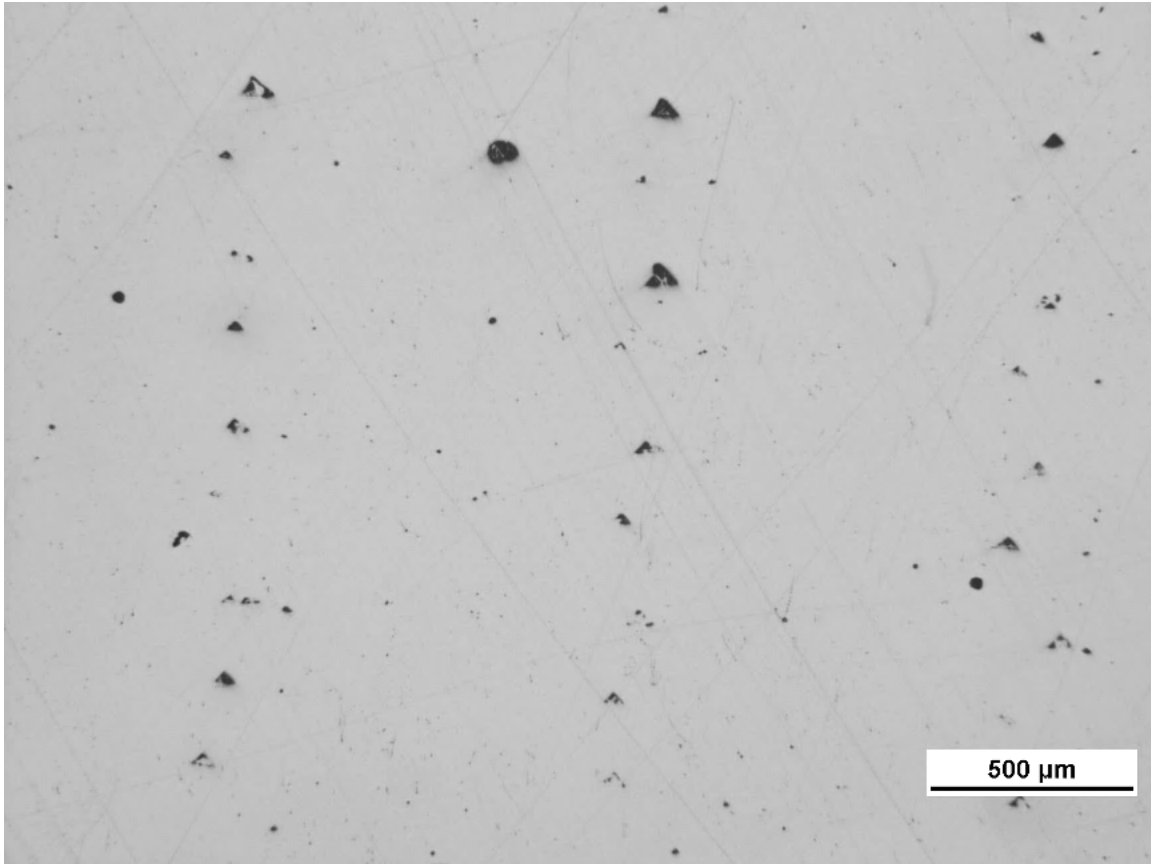


Figure 28. Cross-sectional porosity of in-line PC printed with 0.2 mm layer height

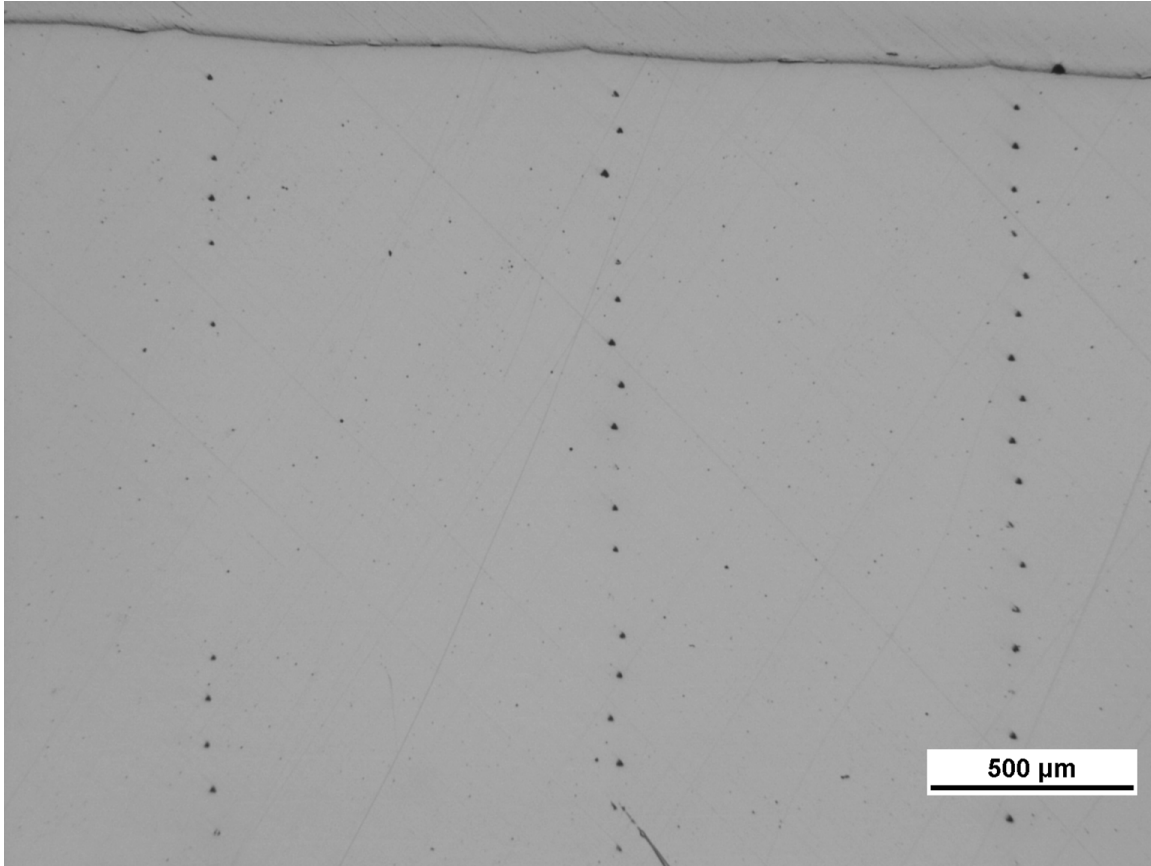


Figure 29. Cross-sectional porosity of in-line PC printed with 0.1 mm layer height

For the transverse samples, no statistically significant change in ultimate strength or strain was observed between samples printed with a layer height of 0.2 mm and those printed with a layer height of 0.16 mm. For these specimens, the samples printed with a layer height of 0.1 mm diverged from expected trends. Printing with very fine resolution leads to opportunities for printer tuning related defects to manifest in the printed sample. Precise printer tuning is required in order to obtain ideal layer adhesion between subsequent printed beads. As seen in Figure 30, when the printer tuning is even slightly off at such fine resolution, layer adhesion defects can occur.

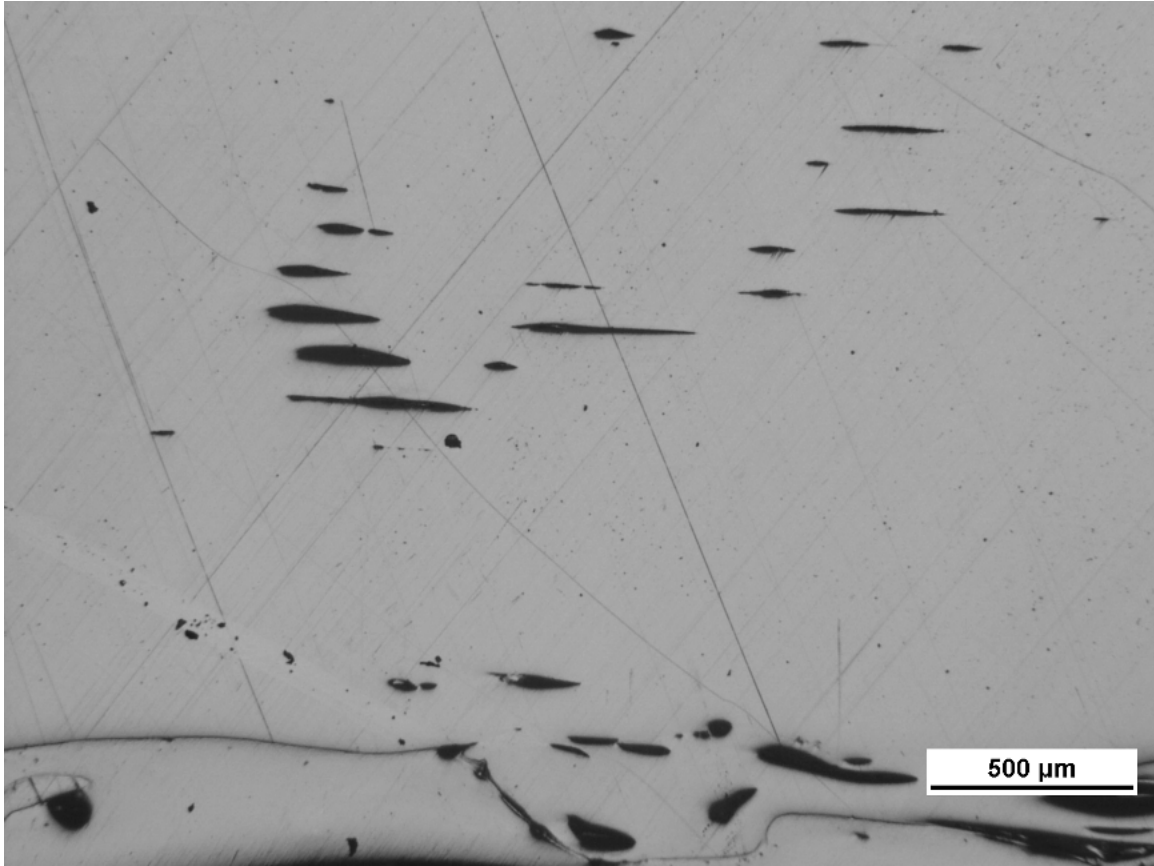


Figure 30. Transverse layer adhesion defects in PC-LT-0.1

Based on the data plotted in Figure 31, there is very similar mechanical behavior between the samples, regardless of infill pattern orientation and layer thickness, which indicates PC has very strong interfacial bonding. PC's interfacial bonding is strong enough such that the ultimate strength and strain metrics of the transverse samples approach that of the in-line samples. Nevertheless, having the printed fibers aligned with the tensile stress axis results in both higher strength and ductility as compared to those with the transverse line pattern.

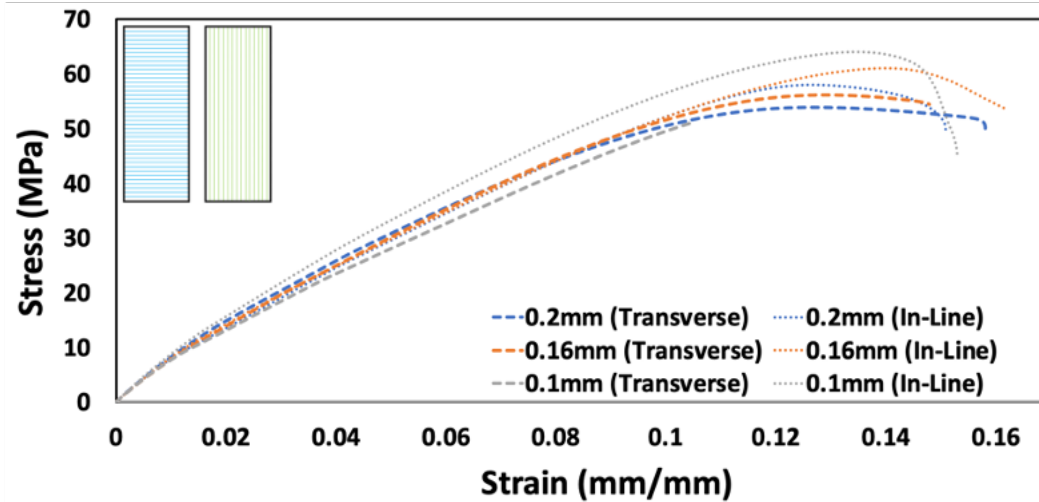


Figure 31. Stress-strain comparison of PC samples with line infill raster pattern

2. Concentric Raster Pattern

a. PLA

The mechanical behavior of the concentric infill pattern, shown in Figure 32, was very similar to the behavior of the in-line samples. This was expected due to the gage length of the concentric pattern consisting entirely of printed fibers oriented in-line with the stress axis. The data for these samples, listed in Table 5, shows the ultimate strength did not change as a result of varying the printed layer height, and their strength values were similar to those observed from the in-line samples.

Additionally, the strain values of the concentric samples did not vary significantly with variation in the printed layer height. Again, the strain values of the concentric samples were similar to the values of the in-line samples. Deviating from the in-line pattern, the concentric samples exhibited a slight shift in Young's Modulus from one layer height to another. The stiffest specimens were those printed with 0.1 mm layers. The concentric infill raster pattern is not a unidirectional infill pattern like the in-line raster pattern. Instead, the concentric infill pattern starts with a single fiber that is extruded down the center of the sample, and the remaining infill is printed spiraling outward from the center. This “coiling” pattern creates the addition of transverse sections at the ends of the samples, outside of the

gage length. Under load, these transverse sections inhibit the interfacial sliding motion of the in-line fibers within the gage length. This restriction of motion causes the printed samples to change in stiffness as the printed layer height is adjusted. With the smaller layer heights, more layers make up the printed part, which results in more transversely printed areas, affecting the in-line translational motion of the fibers in the gage length and the associated strain and stiffness properties. Additional studies would need to be conducted to understand the effects of printed layer height on the mechanical stiffness of the printed part.

Table 5. Tabulated data: PLA printed with concentric infill raster pattern

Sample Set	Stress (MPa)	Strain (%)	E (MPa)
PLA-C-0.2	58.7 ± 0.8	11.3 ± 0.8	814.4 ± 25.8
PLA-C-0.16	57.6 ± 1.1	13.5 ± 2.6	791.3 ± 98.0
PLA-C-0.1	58.5 ± 1.0	14.8 ± 4.3	906.9 ± 43.7

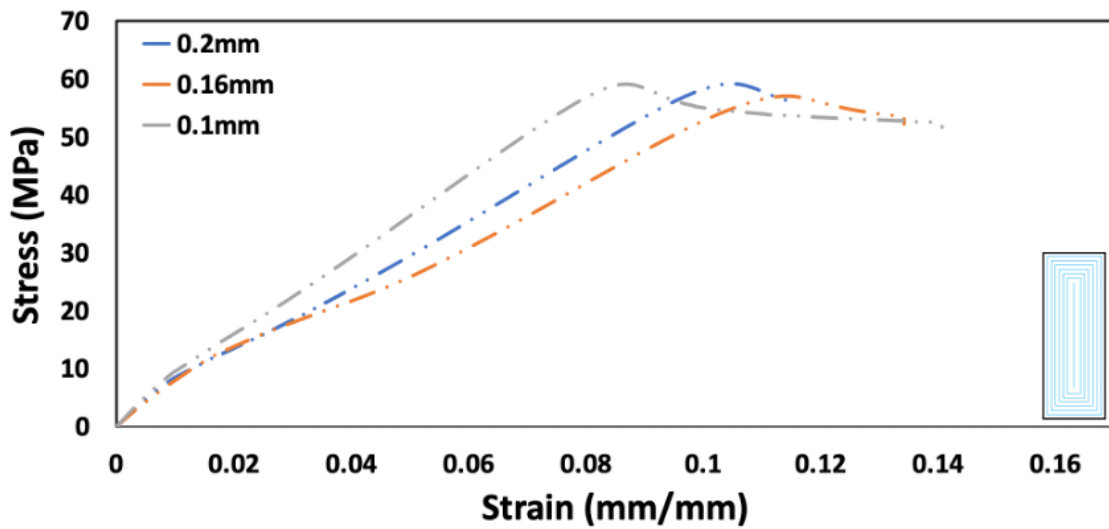


Figure 32. Stress-strain comparison of PLA samples with concentric infill raster pattern

b. PETG

PETG samples printed with concentric infill exhibited similar mechanical behavior and performance as the in-line samples, as seen by the data listed in Table 6 and Figure 33. The ultimate strength of the concentric samples remained uniform despite the variation in printed layer height. These strength values were very close to the strength values seen with the in-line samples. Strain values among the concentric samples still exhibited considerable variations and did not fit a clear trend. The inherent toughness of PETG mitigated any effects the concentric infill raster pattern may have had on the modulus properties.

Table 6. Tabulated data: PETG printed with concentric infill raster pattern

Sample Set	Stress (MPa)	Strain (%)	E (MPa)
PETG-C-0.2	45.0 ± 0.8	378.5 ± 95.9	664.9 ± 9.5
PETG-C-0.16	46.1 ± 1.1	427.1 ± 187.8	629.5 ± 15.7
PETG-C-0.1	46.2 ± 0.7	399.0 ± 57.1	660.4 ± 10.1

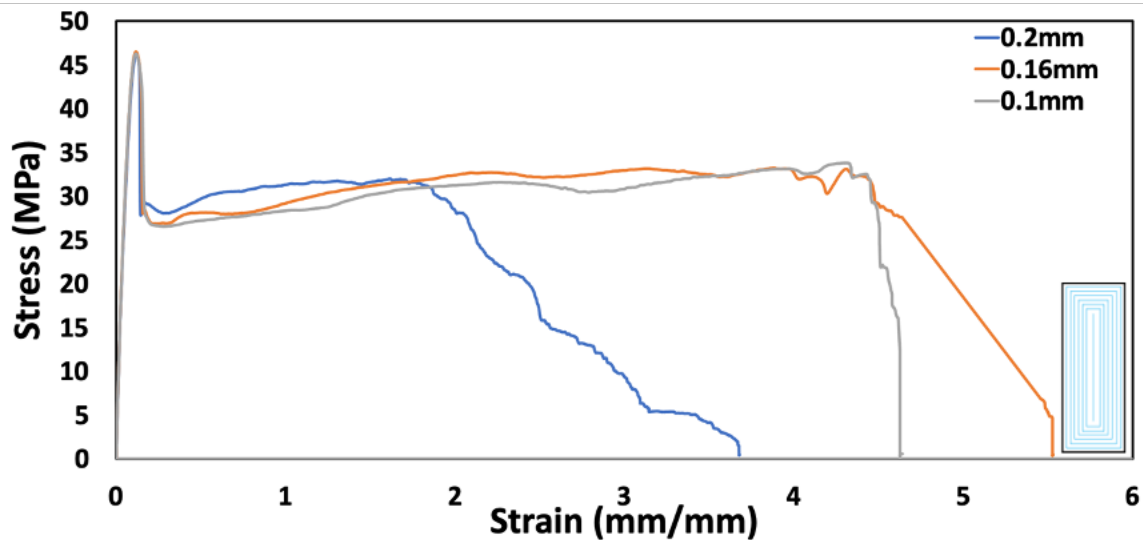


Figure 33. Stress-strain comparison of PETG samples with concentric infill raster pattern

c. PC

Similar to trend observed with PLA and PETG, the concentric PC samples behaved and performed nearly identical to the in-line PC samples. As with the in-line samples, the ultimate strength of the concentric samples increased slightly as layer height decreased, as seen from the data in Table 7. Based on the data, and the plot shown in Figure 34, the strain performance of the concentric samples remained largely unchanged as the layer height changed, which is the same trend observed with the in-line samples. In PC, no statistically observed shift in modulus occurred, which is attributed to the superior intrinsic bonding strength of PC.

Table 7. Tabulated data: PC printed with concentric infill raster pattern

Sample Set	Stress (MPa)	Strain (%)	E (MPa)
PC-C-0.2	60.0 ± 1.1	15.9 ± 1.6	676.1 ± 7.2
PC-C-0.16	61.3 ± 1.5	15.2 ± 0.6	707.4 ± 34.6
PC-C-0.1	63.0 ± 1.4	14.9 ± 0.2	701.7 ± 32.6

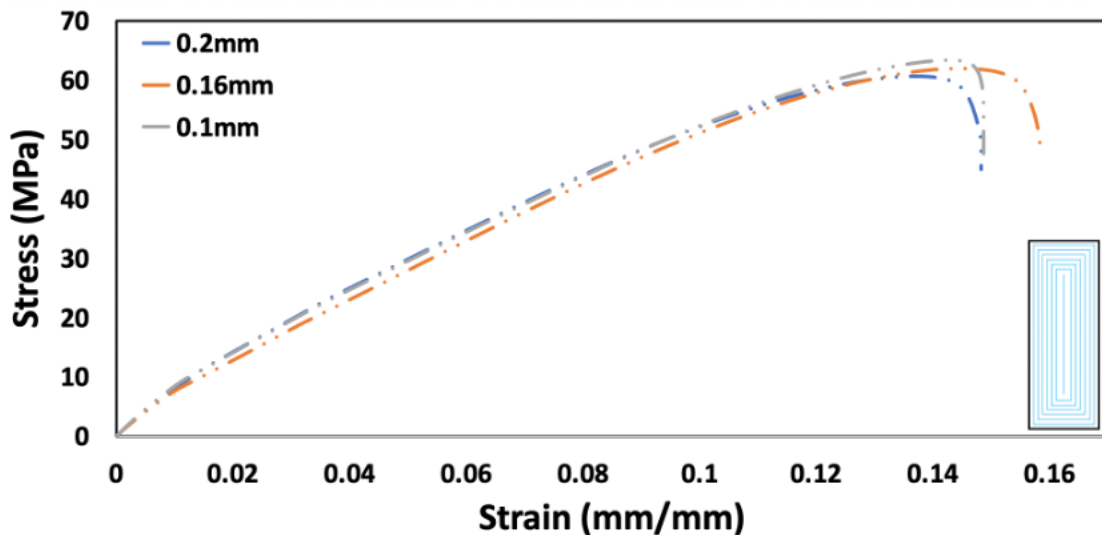


Figure 34. Stress-strain comparison of PC samples with concentric infill raster pattern

3. $\pm 45^\circ$ Raster Pattern

a. *PLA*

Seen from the data in Table 8, printing with an alternating $\pm 45^\circ$ infill raster pattern with PLA showed a moderate increase in ultimate strength as the printed layer height was decreased from 0.2 mm to 0.1 mm. This increase in strength was attributed to a reduction in interfacial porosity that occurred as the layer height was reduced, creating a denser, stronger sample, as seen in Figure 35. Also noted from the data, and the plot in Figure 36, is the maximum strain remained relatively consistent despite the increase in strength.

Table 8. Tabulated data: PLA printed with $\pm 45^\circ$ infill raster pattern

Sample Set	Stress (MPa)	Strain (%)	E (MPa)
PLA-45-0.2	51.7 ± 0.9	10.8 ± 0.6	1004.4 ± 56.6
PLA-45-0.16	52.9 ± 0.3	12.2 ± 1.0	1011.1 ± 19.0
PLA-45-0.1	56.1 ± 2.2	10.4 ± 0.5	1092.7 ± 109.8
PLA-45z-0.2	44.5 ± 3.1	7.1 ± 0.9	830.6 ± 42.5
PLA-45z-0.16	51.1 ± 1.3	7.3 ± 0.3	911.0 ± 34.5
PLA-45z-0.1	44.0 ± 3.7	5.3 ± 1.1	936.0 ± 68.8

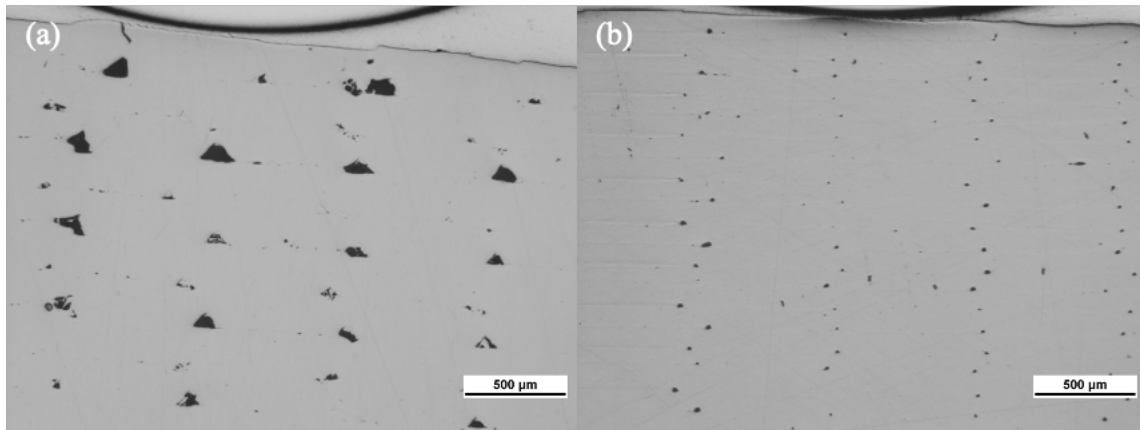


Figure 35. Cross-sectional porosity of $\pm 45^\circ$ PLA printed with 0.2 mm layer height (a) and 0.1 mm layer height (b)

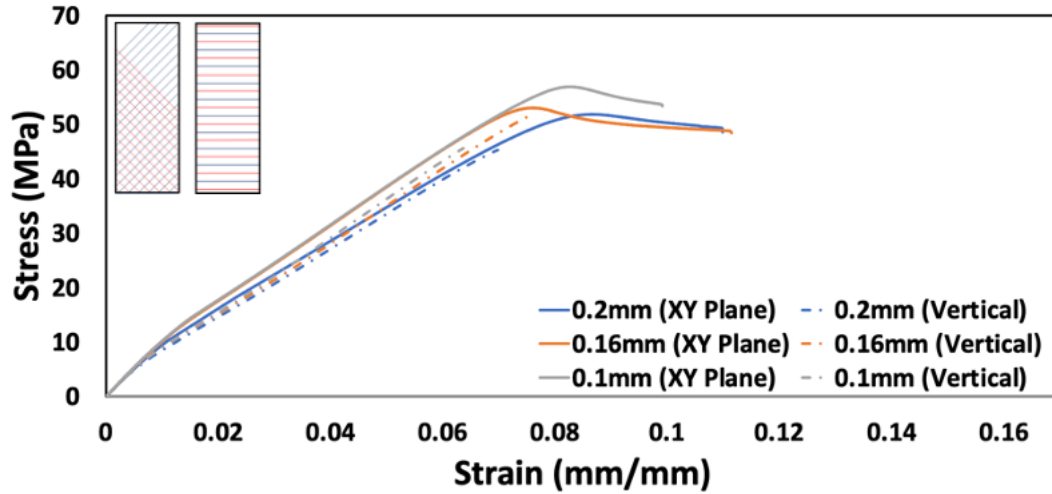


Figure 36. Stress-strain comparison of PLA samples with $\pm 45^\circ$ infill raster pattern

The SEM imagery in Figure 37 shows the PLA samples printed with 0.2 mm and 0.1 mm layer heights are both highly densified. Additionally, both samples exhibited primarily brittle failure characteristics, as seen by the predominantly coplanar shearing that is present in both samples. The similarities in microstructure and failure characteristics explain why the PLA samples exhibited very similar strain performance regardless of printed layer height.

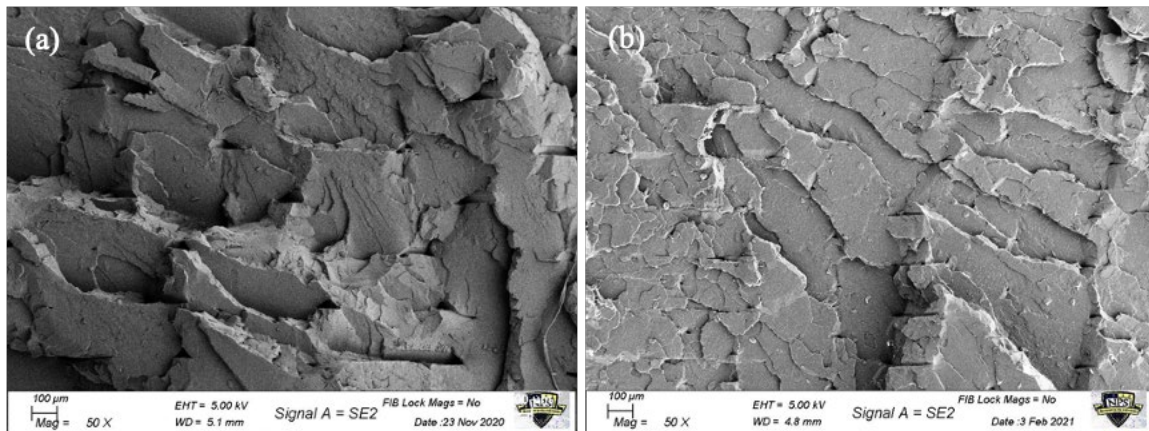


Figure 37. Fracture imagery of PLA-45-0.2 (a) and PLA-45-0.1 (b)

The $\pm 45^\circ$ samples printed vertically ($\pm 45^\circ$ -z) had considerably lower strength than those samples printed flat in the XYZ plane. Additionally, the vertical samples exhibited no ductile region prior to failure, exhibiting purely brittle failure mechanisms. The explanation for this behavior is similar to that of the samples printed with transverse lines infill raster pattern. The vertically printed samples consisted of hundreds of layers printed on top of one another. These layers end up being oriented perpendicular to the stress axis, relying solely upon interfacial layer adhesion properties to determine the resulting mechanical properties. SEM imagery seen in Figure 38 clearly shows how these samples fail in between printed layers.

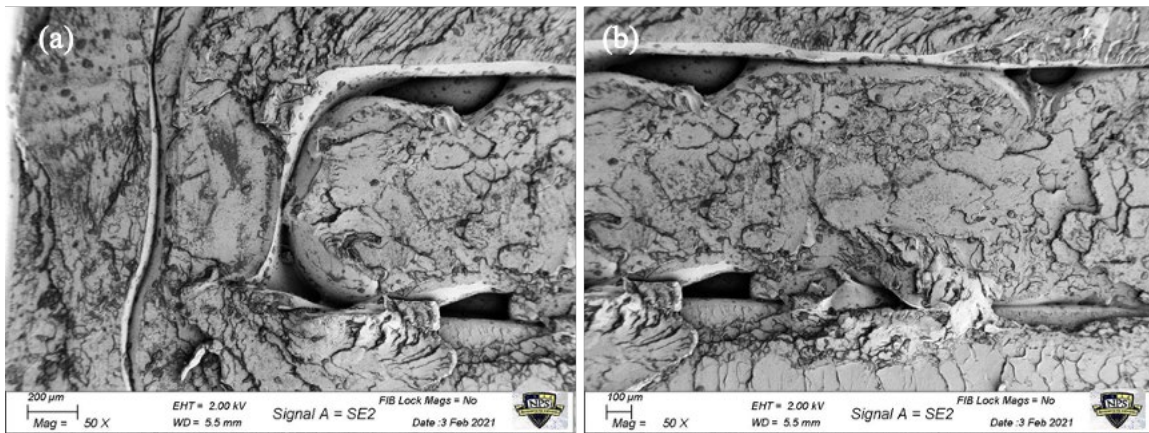


Figure 38. Fracture imagery of PLA-45z-0.2 (a) and PLA-45z-0.1 (b)

b. PETG

PETG exhibited similar mechanical behavior trends as PLA when printing using a $\pm 45^\circ$ infill raster pattern. The data in Table 9 shows a slight increase in ultimate strength as the printed layer height decreases from 0.2 mm to 0.1 mm. The maximum strain also remained relatively consistent despite the increase in the strength. Seen from the plot in Figure 39, the vertically printed samples did not exhibit a ductile region prior to failure and had considerably less strain performance for the same reasons that explained the strain performance behavior in PLA.

Table 9. Tabulated data: PETG printed with $\pm 45^\circ$ infill raster pattern

Sample Set	Stress (MPa)	Strain (%)	E (MPa)
PETG-45-0.2	38.6 ± 1.7	13.5 ± 1.4	497.2 ± 6.4
PETG-45-0.16	42.9 ± 2.6	15.0 ± 0.7	578.7 ± 5.4
PETG-45-0.1	43.0 ± 0.8	12.7 ± 0.3	656.6 ± 23.2
PETG-45z-0.2	35.2 ± 1.3	9.7 ± 1.9	586.8 ± 25.2
PETG-45z-0.16	35.3 ± 3.9	10.2 ± 2.3	577.9 ± 47.5
PETG-45z-0.1	38.3 ± 4.8	10.0 ± 3.6	587.3 ± 18.7

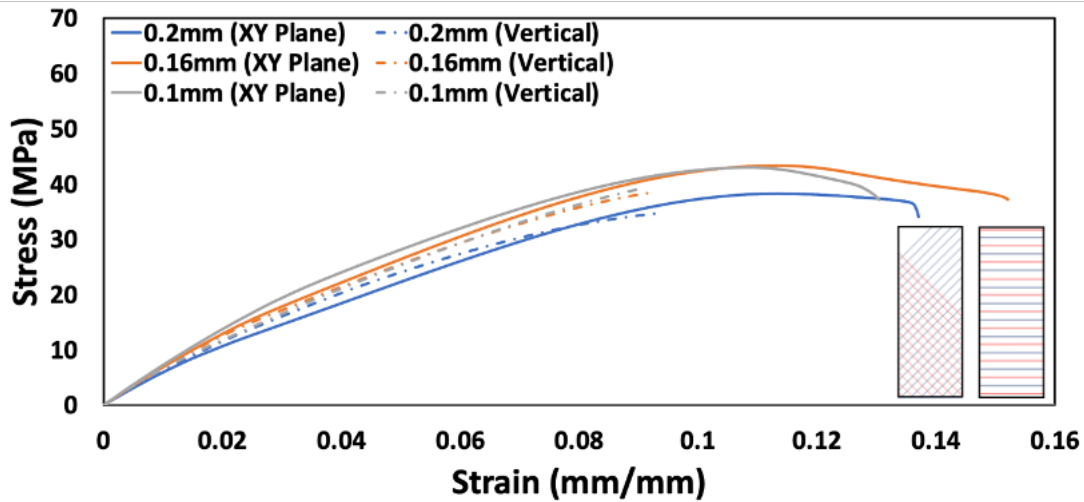


Figure 39. Stress-strain comparison of PETG samples with $\pm 45^\circ$ infill raster pattern

c. PC

When printed in the XYZ plane, the $\pm 45^\circ$ PC samples exhibited nearly equal ultimate strength and final strain values across different layer thicknesses, as seen from the tabulated data in Table 10 and the plot in Figure 40. This trend was unique to PC, and it is attributed to PC's superior interfacial bonding, which negated any of the effects that varying the printed layer height may have had on the mechanical performance.

Table 10. Tabulated data: PC printed with $\pm 45^\circ$ infill raster pattern

Sample Set	Stress (MPa)	Strain (%)	E (MPa)
PC-45-0.2	55.5 ± 1.1	14.4 ± 2.3	657.5 ± 10.7
PC-45-0.16	57.0 ± 0.6	15.0 ± 1.7	647.5 ± 11.8
PC-45-0.1	56.0 ± 1.6	14.9 ± 0.8	636.0 ± 13.7
PC-45z-0.2	34.9 ± 3.5	7.5 ± 0.7	661.0 ± 34.6
PC-45z-0.16	35.4 ± 2.7	6.9 ± 0.9	698.2 ± 40.0
PC-45z-0.1	26.0 ± 2.6	4.6 ± 0.4	783.5 ± 25.1

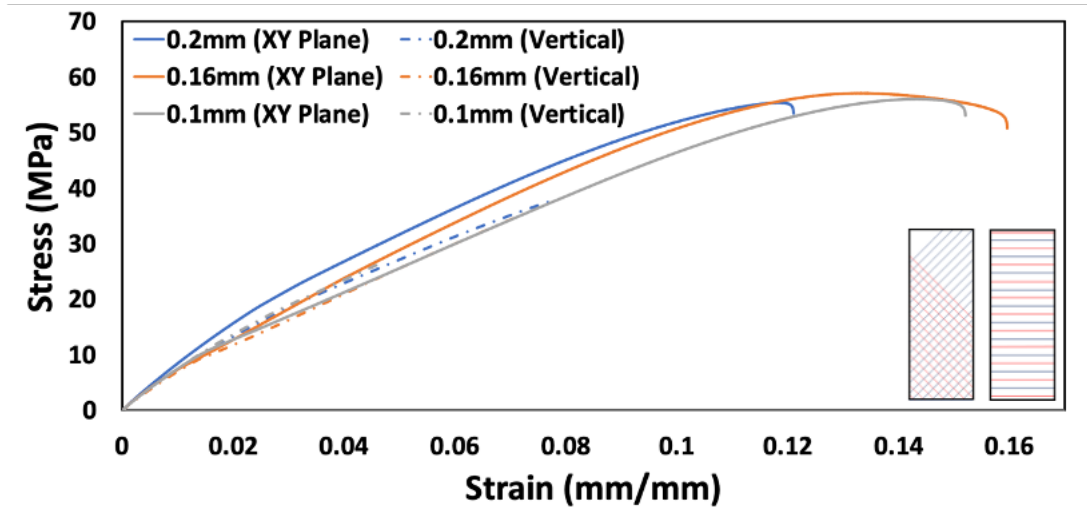


Figure 40. Stress-strain comparison of PC samples with $\pm 45^\circ$ infill raster pattern

The $\pm 45^\circ$ -z PC samples exhibited significantly lower mechanical properties than those printed in the XYZ plane. Just as with PLA and PETG, this build direction causes the mechanical performance to be solely based on the interfacial bonding strength of adjacent printed layers. The vertically printed samples, consisting of a 0.1 mm layer height, did not follow the expected trend of exhibiting similar mechanical performance as the vertically printed samples using a 0.2 mm or 0.16 mm layer height. Because the mechanical properties of these samples are based on the interfacial bonding strength, it was expected that ultimate strength and final strains be uniform, regardless of the printed layer height.

SEM imagery in Figure 41 shows a large quantity of porous defects present in the 0.2 mm sample, indicative of air bubbles, which most likely manifested as a result of a discrepancy with the feed rate of the filament into the hot end of the extruder nozzle. The 0.1 mm sample exhibits this porosity but to a much lesser extent. Not shown, the 0.16 mm samples also exhibited these porous defects in great quantity. Despite the greater degree of defects, the 0.2 mm and 0.16 mm samples still mechanically outperformed the 0.1 mm samples. Reducing the layer height increases the mechanical property dependency on interfacial bonding by increasing the number of layers in the finished sample. The lack of porous defects in the 0.1 mm SEM imagery indicates the effect of interfacial bonding on mechanical properties is greater, to an extent, than the effect of the porosity defects.

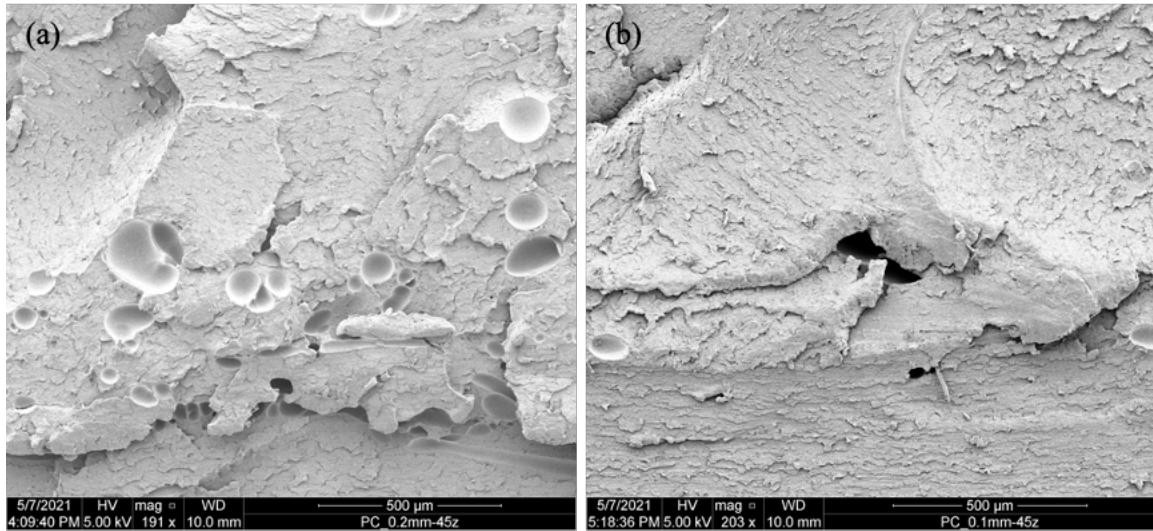


Figure 41. SEM imagery of PC-45z-0.2 (a) and PC-45z-0.1 (b)

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IV. CONCLUSIONS AND FUTURE DIRECTIONS

A. CONCLUSIONS

This research demonstrated how various 3D printing processing parameters have an impact on the mechanical properties of the finished part. Ultimate strength and overall toughness are significantly impacted by the orientation of the printed fibers, which make up the infill raster pattern. In all materials tested, samples printed with either in-line or $\pm 45^\circ$ infill raster pattern exhibited significantly greater degrees of toughness over the samples printed with infill raster patterns oriented perpendicular to the stress axis. With infill raster patterns oriented perpendicular to the stress axis, mechanical properties are solely reliant on the interfacial bonding strength of adjacent layers. When designing a part for structural use by means of FDM AM, special attention should be given to the applicable stress axis so the infill can be properly oriented in order to impart the desired mechanical properties.

Additionally, this research observed the effects of various printed layer heights on the resultant mechanical properties of the finished part. In general, the reduction in printed layer height resulted in a sample that was highly densified and exhibited greater strength properties as a result. The downside to printing with very fine layer heights, such as 0.1 mm, is the printer tuning must be highly precise in order to not induce printing related defects. At such fine resolutions, any deviation from the ideal printing temperature, flow rate, nozzle-offset, etc., will have a greater impact on the structure and resulting mechanical properties of the finished part. When considering the printed layer height during the design phase, the trade space between mechanical properties and printer tuning precision must be evaluated.

The intrinsic material properties of the polymer must be considered when designing a structural component using FDM AM. Printer settings that yield better strength or strain characteristics in one polymer may not necessarily do the same in another polymer. This impact was predominantly apparent in the PETG-LT samples, which exhibited strength values in the vicinity of the PETG-LL samples. In the other materials tested, that variation in infill raster pattern orientation created a significant disparity in observed strength.

Additionally, in several instances where PLA and PETG samples saw increased strength due to a reduction in printed layer height, the same effect was not observed in the PC samples, where PC's superior intrinsic bonding largely mitigated mechanical effects of the layer height reduction. While the mechanical properties of a printed part can be significantly impacted by varying the printing parameters, the degree of impact these printing parameters have is determined by the intrinsic material properties.

B. FUTURE WORK

- Print specimens using larger layer heights and across a broader range, such as 0.2 mm, 0.3 mm, and 0.4 mm. Larger layer heights will mitigate effects of poor printer tuning that have a greater potential to manifest using smaller layer heights such as 0.1 mm, and the broader range may make trends in data more apparent.
- Consider printing samples using just infill and no walls. Isolating the infill in mechanical testing would provide for a more accurate comparison of the mechanical performance of each infill raster pattern.
- Given an infill raster pattern geometry, samples could be printed with varying numbers of outer walls to determine an ideal wall count.
- In PLA, the rate of cooling directly impacts the degree of crystallinity in the finished part, which subsequently effects the mechanical performance. Given filament manufacturers provide broad temperature ranges for each specification, a study which sought to find the ideal extruder nozzle and print bed temperatures would be beneficial.
- It is known AM produced parts exhibit various degrees of residual stress due to the thermal cycling of the extruded filament. There are very few published studies focusing on the mechanical and geometry effects of post process annealing, especially with PLA and PC.

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