

# Impact of Printing Parameters on Mechanical Properties of 3D Printed Structures Using Fused Deposition Modeling

Daniel Hui

Southridge School, 2656 160 St, Surrey, BC V3Z 0B7, Canada; daniel.hui081@gmail.com

**ABSTRACT:** Fused Deposition Modeling (FDM) is one of the most widely adopted Additive Manufacturing (AM) techniques due to its low cost, compatibility with a broad range of materials, design flexibility, and rapid prototyping capabilities. Key printing parameters—such as nozzle diameter, infill pattern and density, print speed, layer thickness, and print orientation—significantly influence the mechanical performance of FDM-printed components. This study investigates the effects of solid infill density, layer thickness, and print orientation on the mechanical properties of parts fabricated using polylactic acid (PLA) and thermoplastic polyurethane (TPU), two of the most used FDM materials. Results indicate that increasing the infill density with an aligned rectilinear pattern from 15% to 100% improves the ultimate tensile strength (UTS) of PLA samples from  $36.88 \pm 0.37$  MPa to  $55.71 \pm 0.14$  MPa, representing a ~51% increase and conversely, altering the infill orientation from  $0^\circ$  (aligned with the loading direction) to  $90^\circ$  (perpendicular) results in a 45.7% decrease in UTS under identical infill conditions. Additionally, increasing the layer height from 150  $\mu\text{m}$  to 300  $\mu\text{m}$  leads to a 22% reduction in UTS. Comparative analysis reveals that while TPU exhibits significantly less UTS than PLA, it achieves an approximately 36-fold increase in ultimate tensile strain, underscoring its superior ductility. These findings offer valuable insights into how FDM printing parameters influence the mechanical performance of printed parts, guiding material and process selection for application-specific requirements.

**KEYWORDS:** 3D Printing, Fused Deposition Modeling, Mechanical Properties, Polylactic Acid, Thermoplastic Polyurethane.

## ■ Introduction

Additive manufacturing (AM) is a concept where the construction of 3D objects occurs through a layer-by-layer deposition process. The process involves a multitude of steps, from digitally designing the model – typically a CAD model – to printing it using a 3D printer with specific parameters, which display significant effects for researchers and industries alike to test and develop technology. Among various additive manufacturing methods, Fused Deposition Modeling (FDM) is one of the most adopted techniques.<sup>1</sup> Unlike other printing methods, such as Selective Laser Sintering (SLS), which uses lasers and powder, FDM extrudes melted thermoplastics through a heated nozzle to create the part by depositing layers. Over the past two decades, FDM has become highly accessible and affordable; hence, its usage has grown extensively for educational purposes, hobbyists, and most especially, for industrial prototyping. FDM is used in industries for functional prototype fabrication, product design testing, and even low-volume manufacturing due to its relatively inexpensive costs compared to traditional methods of manufacturing.<sup>1,2</sup> The FDM method has capabilities to make durable parts with quick turnarounds, which has also given it a niche in areas like aerospace, automotive, and consumer products. Low-cost by nature, the technology, along with affordable materials, makes it one of the most economical options in the additive manufacturing spectrum.<sup>3–5</sup> The design process begins in the CAD modeling system, a digital version of the 3D design of the object. This digital model forms the basic structure of the final product, containing all the details that need to be printed. Once the CAD model is prepared, it is then converted into the STL file

format. The STL file converts this three-dimensional design into a format readable by the 3D printer, breaking down complex shapes into a mesh of triangles representing the object's surfaces. Then, the STL is brought into a slicer program, which is one of the critical steps in 3D printing. The slicing software examines the 3D model and slices it into multiple layers or "slices," thereby creating a toolpath for the printer nozzle to follow.<sup>6</sup> It allows the optimization of many printing parameters, such as layer height, speed of printing, infill density, and structures of supports, etc. Those parameters are critical, as they directly influence the mechanical properties, surface finish, and overall quality of the printed parts. These parameters should be optimized in the way best suited for the project, whether in terms of strength, flexibility, or aesthetic appearance.<sup>7</sup> FDM technology offers versatility in terms of material selection, which makes most kinds of thermoplastics available for use when the need arises. The most common materials used include Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Thermoplastic Polyurethane (TPU), Thermoplastic Elastomer (TPE), Polycarbonate (PC), and many other thermoplastics. PLA is the most commonly used material in FDM due to its ease of printing, low cost, and biodegradability, making it suitable for many applications.<sup>8–13</sup> On the other hand, ABS is much stronger and heat-resistant; therefore, it would be better to use it in functional parts where higher strength-to-weight ratios are needed. TPU and TPE bring flexibility to the equation, offering rubber-like properties that are perfect for producing parts with elasticity and impact resistance, such as helmet pads for impact absorption, shoe midsoles, and phone cases.<sup>2,14</sup> Therefore, to create a flexible model, the ductil-

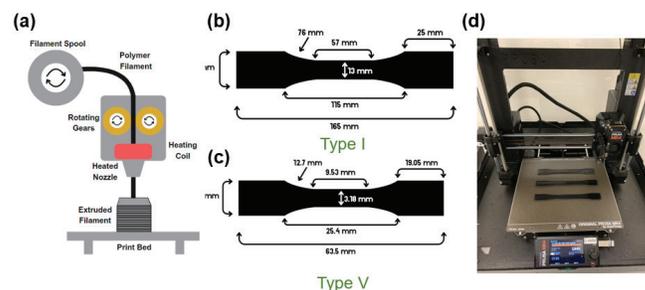
ity of TPU would be favored; on the other hand, PLA is more suitable as a stiffer material that can withstand tensile load without extreme deformation.<sup>2,14</sup> While each material has its unique properties, they all play a significant role in expanding the capabilities of FDM technology for diverse applications. Additionally, the incorporation of materials like nanoparticles enables the tuning of mechanical properties for a wide range of engineering and innovative applications. For example, the mechanical properties of PLA are altered with the use of inorganic nanoparticles, such as an increase in tensile strength and ductility, by the developed interfacial adhesion formed by said nanoparticles.<sup>15</sup> Instead of adding additional material, another method of altering mechanical properties is through changing printing parameters.

The purpose of this paper is to find the mechanical properties of 3D-printed parts, which depend on several critical factors in relation to the final performance of these components. More precisely, it focuses on the analysis of various factors affecting structural performance, such as infill orientations, material variation between PLA and TPU, pull rate, layer thickness, infill ratio, impact strength, flexibility, and durability of printed objects. Understanding the influence of infill orientation is crucial, as it determines the internal structure of the printed object, hence affecting the strength of the component in withstanding forces applied and distributing the same force uniformly. Mechanical strength may differ significantly with changing orientations, making this a critical refinement variable to achieve an optimal balance between strength and material efficiency. Polylactic Acid and Thermoplastic Polyurethane are two of the most common materials in fused deposition modeling printing. PLA is known for its rigidity, ease of processing for printing, and eco-friendliness, whereas TPU offers much better flexibility and elasticity, thus being especially suitable for applications requiring resistance to impacts or components that can be deformed.<sup>9,16</sup> The paper aims to highlight how differences in these materials result in different mechanical properties of the printed parts and their suitability for specific applications. Pull rate is the speed at which the sample endures tensile force during testing, which significantly affects the sample's strain rate. Variations in pull rates will give the sample different times to respond to the applied stress. Layer thickness (i.e., height) is another critical factor, given the influence of this parameter on the level of detail, surface finish, and mechanical properties of the 3D printed object. While thicker layers tend to decrease print time, they may sacrifice the strength and precision of the part; thinner layers provide better detail and smoother surfaces at the cost of longer printing durations.<sup>17</sup> The present study aims to identify an optimal layer thickness to balance the mentioned trade-offs. Finally, the infill ratio—the percentage of the interior volume of the part that is solid—directly affects the weight, strength, and material consumption of the print. Increasing the infill ratios generally increases the strength and durability of the part while also increasing the material requirements and length of printing time.<sup>7,8,17</sup> This study investigates how major 3D printing parameters influence the mechanical properties of PLA and TPU parts, establishing a direct link between pro-

cessing parameters and resulting performance. By exploring the process–microstructure–properties relationship, the findings provide valuable insight for manufacturers to optimize 3D printing settings—enhancing part strength and durability while minimizing material waste. This contributes to more efficient, high-performance, and sustainable manufacturing practices.

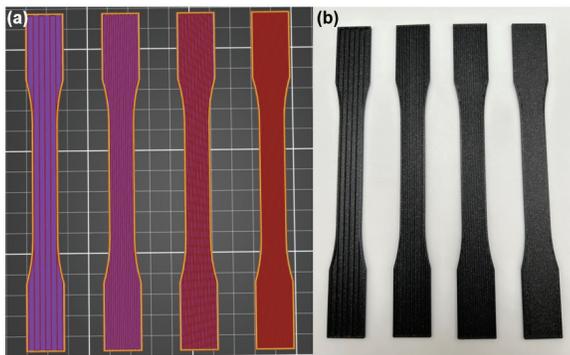
## ■ Methods

The polylactic acid filament used in this study was sourced directly from Hatchbox, featuring a diameter of 1.75 mm and a recommended nozzle temperature range of 180–210 °C. Thermoplastic polyurethane filament was purchased from E-SUN (eTPU-95A) with a 1.75 mm diameter and recommended print temperature of 220–250 °C. All samples were printed using a Prusa MK4 3D printer equipped with a 400 µm nozzle and a heated print bed set to 65 °C, as shown in **Figure 1(a)**. Tensile specimens were designed in SolidWorks following ASTM D638 Type 1 and Type 5 standards, with a nominal thickness of  $3.2 \pm 0.4$  mm. Their dimensions are illustrated in **Figures 1(b)** and **1(c)**. The print speed was maintained at 20 mm/s, and printed Type 1 samples with varying infill densities are shown in **Figure 1(d)**.



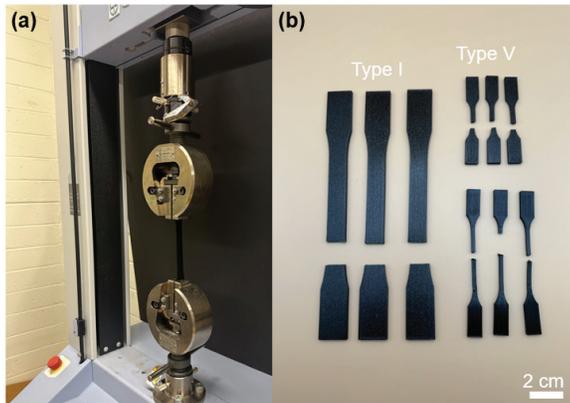
**Figure 1:** Schematic illustration of (a) fused deposition modeling (FDM) printing, (b, c) standard samples according to ASTM-D638 Type 1 and 5, the overall thickness of both samples (d), and (e) printed samples using TPU. The Prusa MK4 printer was used in this study to print all Type 1 and Type 5 samples. Printed samples include both PLA and TPU.

In FDM printing, solid infill refers to the internal structure of a print, typically rendered using various patterns such as gyroid, cubic, or rectilinear. These patterns and their densities significantly influence both the mechanical properties and the overall print quality. In this study, aligned rectilinear infill patterns with varying solid infill density were used to assess the effect of infill density on the mechanical properties of FDM printed structures using PLA and TPU. G-code files were generated using PrusaSlicer, and **Figure 2(a)** displays a schematic of Type 1 samples with infill densities of 15%, 45%, 75%, and 100%. Filled samples (100%) had no internal voids, whereas 15% infill samples exhibited partial filling. Mid-print views of the different densities are provided in **Figure 2(b)**.



**Figure 2:** 3D printed samples with solid infill ratios of 15%, 45%, 75%, and 100%, (a) schematic of slicing, (b) printed samples showing various infill densities. The sample on the left was printed with 15% infill, while the sample on the right features 100% infill. Prusa Slicer software was used for slicing CAD files and generating G-codes.

To characterize the mechanical properties of printed Type 1 and 5 samples using both PLA and TPU, we used a Shimadzu AGS-X universal testing machine with a 10 kN load cell, according to ASTM D638, as shown in **Figure 3(a)**. All tests were conducted under a pull rate (i.e., strain rate) of 12 mm/min. Multiple samples were tested under each condition to ensure result consistency, with a calculated measurement uncertainty of approximately 2%, primarily due to cross-sectional area variation and load cell sensitivity. **Figure 3(b)** shows failed specimens from post-tensile testing. It is important to note that the reported stress–displacement data are based on the separation between the grips, not true strain.



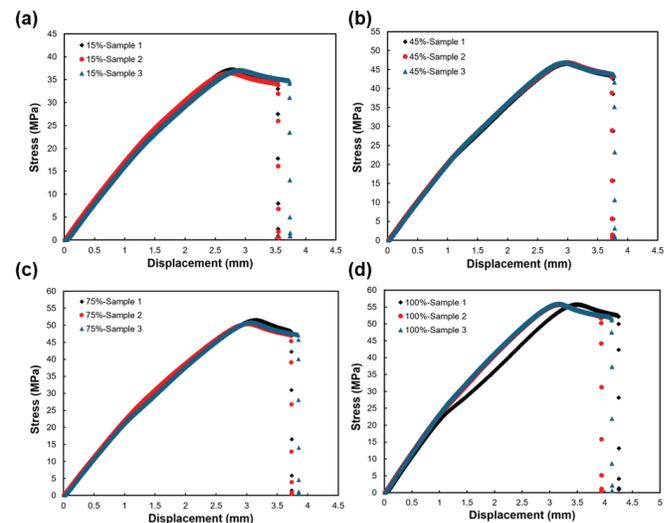
**Figure 3:** (a) Shimadzu AGS-X tensile machine with 10 kN load cell, (b) 3D printed Type 1 and 5 samples after testing. All samples were tested under a 12 mm/min pull rate, where TPU samples showed much larger elongation compared to PLA due to the low stiffness of TPU.

## ■ Results and Discussion

**Figure 4** presents the mechanical performance of 3D-printed PLA tensile specimens featuring aligned rectilinear infill patterns at varying densities—15%, 45%, 75%, and 100%. Each condition was tested with three samples at a pulling rate of 12 mm/min. In most thermoplastics, the higher pull rate leads to an increase in ultimate tensile strength since the lamella has less time to deform and undergo molecular rearrangement. In contrast, lower pull rates could result in lower UTS due to polymer chain deformation. On the other hand, PLA exhibits more brittle behavior with lower elongation at

higher pull rates, while lower pull rates allow greater plastic deformation and higher ductility. At 15% infill, the specimens demonstrated an average ultimate tensile strength (UTS) of  $36.88 \pm 0.37$  MPa and an ultimate displacement of  $2.80 \pm 0.06$  mm, indicating limited load-bearing capacity due to the low internal material density, as shown in **Figure 4(a)**. As the infill density increased to 45%, the UTS improved to  $46.71 \pm 0.13$  MPa, with a slight rise in displacement to  $2.98 \pm 0.04$  mm, reflecting enhanced internal support and resistance to tensile loads, as shown in **Figure 4(b)**.

Further increasing the infill to 75% resulted in a significant jump in UTS to  $50.86 \pm 0.59$  MPa and displacement to  $3.08 \pm 0.08$  mm, demonstrating a closer approach to fully dense conditions and improved ductility. Finally, the 100% infill samples achieved the highest UTS of  $55.71 \pm 0.14$  MPa and the greatest displacement of  $3.30 \pm 0.17$  mm, confirming that fully solid specimens exhibit superior tensile strength and deformation tolerance. These findings align with previous studies on the influence of infill density on mechanical performance in 3D-printed polymers.<sup>9</sup>



**Figure 4:** Impact of solid infill density ratio on mechanical properties of 3D printed samples with aligned rectilinear and (a) 15%, (b) 45%, (c) 75%, and (d) 100% solid infill densities. Increasing the infill density leads to enhanced ultimate tensile strength. Printed samples with 15% and 45% infill densities showed a 26.6% difference in ultimate tensile strength (UTS). Increasing the infill to 75% resulted in an additional 8.9% improvement in UTS, while a further increase to 100% infill yielded a total UTS gain of 9.5%.

As illustrated in **Figure 4**, the increase in ultimate tensile strength with higher infill densities is primarily attributed to the enhanced load-bearing capacity of the printed specimens. A higher infill ratio introduces a greater volume of material along the tensile axis, which distributes mechanical loads more uniformly across the structure. This improved stress distribution minimizes localized stress concentrations, especially in the gauge section, and significantly reduces the likelihood of early crack initiation. Conversely, samples with lower infill percentages contain more voids and structural discontinuities that act as stress concentrators, creating a higher possibility of failure under load. Moreover, increased infill density promotes improved bonding between adjacent extruded layers. The greater overlap and tighter contact between print paths strengthen

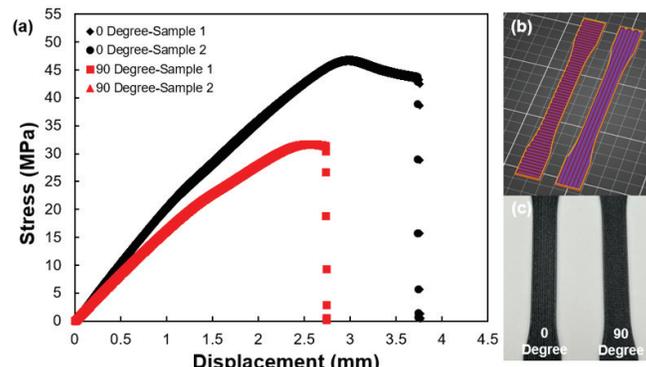
interfacial adhesion, a critical factor for the mechanical performance of FDM-printed components. Enhanced interlayer cohesion increases resistance to delamination and contributes to a more uniform and continuous material network, allowing the printed structure to withstand external forces better. This robust layer-to-layer integrity ensures that the applied tensile stress is transferred efficiently throughout the entire volume of the specimen, improving its structural resilience.

Additionally, the observed increase in displacement at failure (i.e., strain) with rising infill density reflects enhanced ductility of the printed samples. Denser infill leads to a more continuous and cohesive polymer matrix that can undergo greater plastic deformation before fracturing. This increased energy absorption capacity results from a combination of better interlayer bonding and a reduction in internal flaws, which delays the onset of crack propagation. Altogether, these findings emphasize the critical role of infill density in determining both the strength and toughness of 3D-printed components with thermoplastics, making it one of the key parameters in optimizing mechanical performance for structural applications.

Another critical parameter influencing the mechanical performance of 3D-printed structures is print orientation, which refers to the direction of printed layers. Print orientation and interlayer bonding lead to different mechanical properties. In this study, we investigated the mechanical impact of two orientations—horizontal (0°) and vertical (90°)—on samples printed with aligned rectilinear infill at 45% density, as shown in **Figure 5(a)**. Two specimens per orientation were tested under identical conditions. The horizontally printed samples (0°) exhibited a significantly higher ultimate tensile strength (UTS) of  $46.7 \pm 0.13$  MPa, compared to  $32.05 \pm 0.5$  MPa for the vertically printed samples (90°), reflecting a strength reduction of nearly 31%. Moreover, the 0° samples showed superior ductility, with an ultimate displacement of  $2.98 \pm 0.04$  mm, approximately 19% greater than that of the 90° samples. This difference is primarily attributed to the orientation of the printed layers relative to the tensile loading direction. At 0°, the layers are aligned with the applied stress, promoting efficient load transfer along continuous filament paths. In contrast, the 90° orientation subjects the weaker interlayer bonds to direct tensile forces, increasing susceptibility to delamination and early failure. **Figures 5(b)** and **5(c)** provide a cross-sectional comparison highlighting these structural differences.

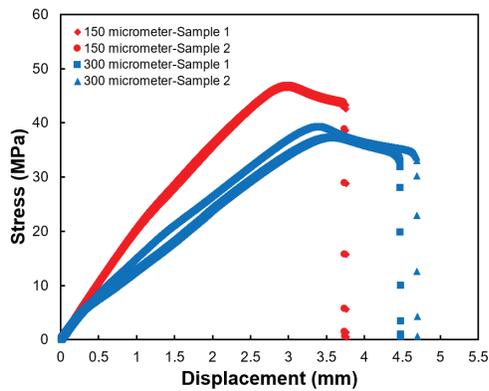
In the 90-degree print orientation, the extruded filament paths align parallel to the direction of the applied tensile load. This alignment allows the tensile stress to be carried directly along the continuous strands of polymer, leveraging the intrinsic strength of the material within each filament. Consequently, this configuration enhances load-bearing capacity and tensile strength. In contrast, the 0-degree orientation positions the printed layers perpendicular to the applied load. In this case, the tensile force must be transferred across the interlayer interfaces, which are formed primarily through thermal fusion during printing. These interfacial bonds are typically weaker due to limited polymer chain diffusion and insufficient adhesion, making them more susceptible to delamination under stress. As a result, samples printed in the 0-degree orientation

exhibit significantly lower UTS compared to those printed at 90 degrees. In this orientation, failure tends to initiate and propagate along the layer boundaries, highlighting the anisotropic nature of FDM-printed parts. Overall, when tensile forces are applied along the weaker interlayer direction, mechanical performance is dominated by the quality of interlayer adhesion, leading to reduced strength and durability relative to orientations where stress is carried through continuous filament paths.



**Figure 5:** (a) Impact of print orientation on mechanical properties of printed PLA samples, (b, c) 3D printed samples with 0-degree and 90-degree infill orientations with 45% infill density. The horizontally printed samples (0°) exhibited a significantly higher ultimate tensile strength of  $46.7 \pm 0.13$  MPa, compared to  $32.05 \pm 0.5$  MPa for the vertically printed samples (90°), reflecting a reduction in strength of nearly 31%. Moreover, the 0° samples showed greater ductility, with an ultimate displacement of  $2.98 \pm 0.04$  mm, about 19% higher than that of the 90° samples.

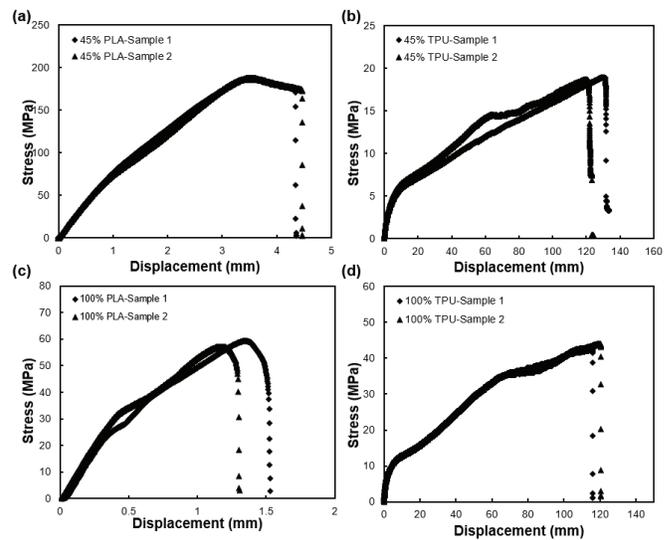
Additionally, we investigate the impact of layer height on the mechanical properties of printed samples. Type 1 samples using PLA were printed with 150  $\mu\text{m}$  and 300  $\mu\text{m}$  layer heights under the same infill shape, density, and orientation of aligned rectilinear, 45%, and 0 degrees, respectively. **Figure 6** shows the mechanical properties of the tested samples under a 12 mm/min pull rate. The obtained results indicated that the samples with 150  $\mu\text{m}$  yield an UTS of  $46.71 \pm 0.13$  MPa, where 300  $\mu\text{m}$  layer height results in an ultimate tensile strength of  $38.28 \pm 1.5$  MPa, which is 22% lower compared to 150  $\mu\text{m}$  samples. This is due to the weaker interlayer bonding because of the smaller surface area for bonding between layers. Moreover, as layer height increases, the cooling time between layers is lengthened, leading to ineffective thermal fusion between deposited layers. Furthermore, the displacement of 150  $\mu\text{m}$  samples at failure was  $3.76 \pm 0.02$  mm compared to  $4.58 \pm 0.16$  mm for printed PLA samples with 300  $\mu\text{m}$  layer height. This is attributed to delayed crack propagation, which occurs by absorbing more energy with larger layer heights. In addition, thicker layers behave more like bulk materials, enabling individual layers to deform further before breaking.<sup>18</sup>



**Figure 6:** Mechanical properties of printed samples with 150  $\mu\text{m}$  and 300  $\mu\text{m}$  layer height using PLA. This result indicates that samples printed with a 150  $\mu\text{m}$  layer height achieved a UTS of  $46.71 \pm 0.13$  MPa, whereas those printed at 300  $\mu\text{m}$  exhibited a lower UTS of  $38.28 \pm 1.5$  MPa, representing a 22% decrease compared to the 150  $\mu\text{m}$  samples.

Material selection between polylactic acid and thermoplastic polyurethane is critical in FDM 3D printing, as it directly affects the mechanical performance and suitability of printed parts for different applications. PLA is a stiff, brittle, and easy-to-print biopolymer that offers high tensile strength and dimensional accuracy, making it ideal for rigid components and prototypes. In contrast, TPU is a flexible, elastic material with excellent impact resistance and high elongation at break, allowing it to absorb energy and deform without breaking. While PLA provides better structural rigidity, TPU excels in applications requiring flexibility and durability under dynamic loading. Therefore, choosing between PLA and TPU depends on the intended function of the printed part and the needed balance between strength, stiffness, and flexibility.

**Figure 7** depicts the mechanical properties of printed Type 5 samples according to ASTM D638 with PLA and TPU samples under solid infill densities of 45% and 100%. All samples were printed with a layer height of 150  $\mu\text{m}$ . The reason for printing Type 5 samples is that they have a shorter length (63.5 mm) compared to Type 1 samples, which have a length of 165 mm. Type 1 TPU samples were not tested due to the excessive elongation properties that surpassed the travel distance of our Shimadzu AGS-X tensile machine. As shown in **Figure 7(a)**, Type 5 PLA samples with 45% infill have an ultimate tensile strength and ultimate displacement at failure of  $185.5 \pm 2.2$  MPa and  $4.27 \pm 0.24$  mm, respectively. In contrast, Type 5 TPU samples showed a UTS of  $18.81 \pm 0.16$  MPa, which is almost 10-fold less compared to the PLA samples. Furthermore, we found that TPU samples demonstrated significantly higher elongation at break of  $127.6 \pm 6.05$  mm compared to  $4.27 \pm 0.24$  mm for PLA, as shown in **Figure 7(b)**. As the solid infill density increased to 100%, the UTS and displacement at breakage of PLA samples decreased to  $58.24 \pm 1.5$  MPa and  $1.41 \pm 0.16$  mm, respectively, as presented in **Figure 7(c)**. This is attributed to the anisotropic nature that makes samples more rigid with limited ability to deform, leading to early failure. However, TPU samples with 100% infill showed higher UTS compared to 45% with almost the same elongation. **Figure 7(d)** illustrates the result for tensile testing of TPU samples with 100% infill density.



**Figure 7:** Mechanical properties of Type 5 PLA and TPU samples with 45% and 100% solid infill densities. PLA samples with 45% infill exhibited high strength ( $185.5 \pm 2.2$  MPa) but low elongation ( $4.27 \pm 0.24$  mm), while TPU samples showed much lower strength ( $18.81 \pm 0.16$  MPa) but significantly higher elongation ( $127.6 \pm 6.05$  mm). Increasing PLA infill to 100% reduced both its strength and ductility due to increased rigidity and anisotropy. In contrast, TPU samples with 100% infill achieved higher strength than their 45% counterparts while maintaining similar elongation.

A comparison between **Figure 7(b)** and **7(d)** demonstrates a significant enhancement in ultimate tensile strength (UTS) as the solid infill density increases from 45% to 100%, with UTS values rising from  $18.81 \pm 0.16$  MPa to  $45.28 \pm 0.2$  MPa. This substantial improvement can be attributed to the increased material volume and structural integrity associated with higher infill densities. Similar to the trends observed in PLA samples, higher infill density reduces the presence of internal voids and gaps, which typically act as stress concentrators and crack initiation sites. Moreover, greater infill promotes enhanced overlap between adjacent extruded filaments and layers, resulting in stronger interfacial bonding and improved layer fusion during the printing process. This improved continuity within the printed structure allows for more efficient stress transfer and distribution under tensile loading, thereby increasing the overall load-bearing capacity and mechanical performance of the printed parts.

This study contributes to a deeper understanding of the critical relationship between processing parameters, resulting microstructures, and mechanical properties in fused deposition modeling of thermoplastic materials. By systematically examining the effects of infill density, layer height, and print orientation in both PLA and TPU, this work offers valuable insights for optimizing FDM printing strategies tailored to specific mechanical performance requirements. The findings have broad implications for advancing the use of FDM in applications ranging from consumer products to functional prototypes and flexible electronics.

## Conclusion

In conclusion, this study systematically investigated the influence of key fused deposition modeling printing parameters—such as solid infill density, layer height, and print

orientation—on the mechanical properties of 3D printed components, using both PLA and TPU materials. The results demonstrate that increased infill density and optimized layer height significantly enhance ultimate tensile strength (UTS) and stiffness, particularly in PLA samples, due to improved interlayer bonding and reduced internal voids. Our results showed that the ultimate tensile strength (UTS) increased significantly from  $36.88 \pm 0.37$  MPa to  $55.7 \pm 0.14$  MPa as the infill ratio was raised from 15% to 100%. The horizontally printed samples ( $0^\circ$ ) exhibited a significantly higher ultimate tensile strength (UTS) of  $46.7 \pm 0.13$  MPa, compared to  $32.05 \pm 0.5$  MPa for the vertically printed ones ( $90^\circ$ ), reflecting a strength reduction of nearly 31.4%. In addition, printed PLA samples with  $150 \mu\text{m}$  resulted in a UTS of  $46.71 \pm 0.13$  MPa, while those printed at  $300 \mu\text{m}$  exhibited a lower UTS of  $38.28 \pm 1.5$  MPa—approximately 22% less. This reduction is primarily attributed to weaker interlayer bonding, as thicker layers provide less surface area for adhesion between layers. Interestingly, despite the lower strength, samples with a  $300 \mu\text{m}$  layer height showed greater displacement at failure ( $4.58 \pm 0.16$  mm) compared to the  $150 \mu\text{m}$  samples ( $3.76 \pm 0.02$  mm), indicating increased ductility and deformation before fracture. Comparing the mechanical properties of PLA and TPU samples (Type 5) under the same printing parameters showed that PLA samples at 45% infill exhibited a high ultimate tensile strength (UTS) of  $185.5 \pm 2.2$  MPa with low elongation ( $4.27 \pm 0.24$  mm) compared to TPU samples with  $18.81 \pm 0.16$  MPa UTS while showing significantly higher elongation ( $127.6 \pm 6.05$  mm). Increasing PLA infill to 100% reduced both UTS ( $58.24 \pm 1.5$  MPa) and elongation ( $1.41 \pm 0.16$  mm), likely due to increased rigidity and anisotropy causing early failure. Conversely, TPU samples with 100% infill exhibited higher UTS than those with 45% infill, while maintaining similar elongation, which demonstrates TPU's ductile nature. This work highlights the critical role of material selection and process optimization in tailoring the mechanical behavior of FDM-printed parts for diverse functional applications.

### ■ Acknowledgments

I would like to express my sincere gratitude to Professor Mortaza Saeidi for his invaluable support and insightful guidance throughout the course of this work.

### ■ References

- Jandyal, A.; Chaturvedi, I.; Wazir, I.; Raina, A.; Ul Haq, M. I. 3D Printing – A Review of Processes, Materials and Applications in Industry 4.0. *Sustainable Operations and Computers* **2022**, *3*, 33–42. <https://doi.org/10.1016/j.susoc.2021.09.004>.
- Prabhakar, M. M.; Saravanan, A. K.; Lenin, A. H.; Leno, I. J.; Mayandi, K.; Ramalingam, P. S. A Short Review on 3D Printing Methods, Process Parameters and Materials. In *Materials Today: Proceedings*; Elsevier Ltd, 2020; Vol. 45, pp 6108–6114. <https://doi.org/10.1016/j.matpr.2020.10.225>.
- Shahrubudin, N.; Lee, T. C.; Ramlan, R. An Overview on 3D Printing Technology: Technological, Materials, and Applications. In *Procedia Manufacturing*; Elsevier B.V., 2019; Vol. 35, pp 1286–1296. <https://doi.org/10.1016/j.promfg.2019.06.089>.
- Guo, N.; Leu, M. C. Additive Manufacturing: Technology, Applications and Research Needs. *Frontiers of Mechanical Engineering* **2013**, *8* (3), 215–243. <https://doi.org/10.1007/S11465-013-0248-8>.
- Turner, B. N.; Gold, S. A. A Review of Melt Extrusion Additive Manufacturing Processes: II. Materials, Dimensional Accuracy, and Surface Roughness. *Rapid Prototyp J* **2015**, *21* (3), 250–261. <https://doi.org/10.1108/RPJ-02-2013-0017/FULL/XML>.
- Gokhare, V. G.; Raut, D. N.; Shinde, D. K. *A Review Paper on 3D-Printing Aspects and Various Processes Used in the 3D-Printing*. [www.ijert.org](http://www.ijert.org).
- Birosz, M. T.; Ledenyák, D.; Andó, M. Effect of FDM Infill Patterns on Mechanical Properties. *Polym Test* **2022**, *113*. <https://doi.org/10.1016/j.polymertesting.2022.107654>.
- Turaka, S.; Jagannati, V.; Pappula, B.; Makgato, S. Impact of Infill Density on Morphology and Mechanical Properties of 3D Printed ABS/CF-ABS Composites Using Design of Experiments. *Heliyon* **2024**, *10* (9). <https://doi.org/10.1016/j.heliyon.2024.e29920>.
- Xu, T.; Shen, W.; Lin, X.; Xie, Y. M. Mechanical Properties of Additively Manufactured Thermoplastic Polyurethane (TPU) Material Affected by Various Processing Parameters. *Polymers (Basel)* **2020**, *12* (12), 1–16. <https://doi.org/10.3390/polym12123010>.
- Tirado-Garcia, I.; Garcia-Gonzalez, D.; Garzon-Hernandez, S.; Rusinek, A.; Robles, G.; Martinez-Tarifa, J. M.; Arias, A. Conductive 3D Printed PLA Composites: On the Interplay of Mechanical, Electrical and Thermal Behaviours. *Compos Struct* **2021**, *265*. <https://doi.org/10.1016/J.COMPSTRUCT.2021.113744>.
- Madhavan Nampoothiri, K.; Nair, N. R.; John, R. P. An Overview of the Recent Developments in Polylactide (PLA) Research. *Biore-sour Technol* **2010**, *101* (22), 8493–8501. <https://doi.org/10.1016/J.BIORTECH.2010.05.092>.
- Hamad, K.; Kaseem, M.; Yang, H. W.; Deri, F.; Ko, Y. G. Properties and Medical Applications of Polylactic Acid: A Review. *Express Polym Lett* **2015**, *9* (5), 435–455. <https://doi.org/10.3144/EXPRESSPOLYMLET.2015.42>.
- Murariu, M.; Dubois, P. PLA Composites: From Production to Properties. *Adv Drug Deliv Rev* **2016**, *107*, 17–46. <https://doi.org/10.1016/J.ADDR.2016.04.003>.
- Kristiawan, R. B.; Imaduddin, F.; Ariawan, D.; Ubaidillah; Arifin, Z. A Review on the Fused Deposition Modeling (FDM) 3D Printing: Filament Processing, Materials, and Printing Parameters. *Open Engineering*. De Gruyter Open Ltd January 1, 2021, pp 639–649. <https://doi.org/10.1515/eng-2021-0063>.
- Mulla, M. Z.; Rahman, M. R. T.; Marcos, B.; Tiwari, B.; Pathania, S. Poly Lactic Acid (PLA) Nanocomposites: Effect of Inorganic Nanoparticles Reinforcement on Its Performance and Food Packaging Applications. *Molecules* **2021**, *26* (7), 1967. <https://doi.org/10.3390/molecules26071967>.
- Decuir, F.; Phelan, K.; Hollins, B. C. Mechanical Strength of 3-D Printed Filaments. *Proceedings - 32nd Southern Biomedical Engineering Conference, SBEC 2016* **2016**, 47–48. <https://doi.org/10.1109/SBEC.2016.101>.
- Qamar Tanveer, M.; Mishra, G.; Mishra, S.; Sharma, R. Effect of Infill Pattern and Infill Density on Mechanical Behaviour of FDM 3D Printed Parts- a Current Review. *Mater Today Proc* **2022**, *62*, 100–108. <https://doi.org/10.1016/j.matpr.2022.02.310>.
- Shergill, K.; Chen, Y.; Bull, S. An Investigation into the Layer Thickness Effect on the Mechanical Properties of Additively Manufactured Polymers: PLA and ABS. *International Journal of Advanced Manufacturing Technology* **2023**, *126* (7–8), 3651–3665. <https://doi.org/10.1007/S00170-023-11270-Y/TABLES/11>.

## ■ Author

Daniel Hui, a rising senior at Southridge School in British Columbia, Canada, is deeply passionate about engineering. With a strong foundation in math and science, he plans to pursue Mechanical Engineering at university. Daniel is driven by innovation, hands-on problem-solving, and a passion for sustainable design and technology, with potential future contributions in these areas.