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Investigation of Tensile and Impact Properties of 3D-Printed Parts with Varying Nozzle Diameters and Infill Densities

Md. Shahporan Rimon, Sajal Chandra Banik*

Department of Mechanical Engineering, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh

ABSTRACT

This study investigates the effects of nozzle diameter and infill density on the mechanical behavior of PLA+ parts, focusing on tensile and impact properties. I used a Bambu Lab A1 3D printer to manufacture the specimens at infill densities of 50% and 100%, with all other printing parameters fixed. The influence of nozzle diameter on structural integrity and load-bearing capacity was tested at four sizes: 0.2 mm, 0.4 mm, 0.6 mm, and 0.8 mm. The study's results show that tensile properties and impact energy are highly correlated to both nozzle diameter and infill density. The larger the nozzle diameter, the higher the tensile stress and impact energy. Consistently enhancing the mechanical strength of a material is the increasing infill density of the polymer part. Based on the results, we can obtain some valuable insight into setting the FDM printing parameters that achieve a balance in accuracy, strength and toughness of the PLA+ parts for engineering and practical applications.

Keywords: 3D Printing, PLA+, Nozzle Diameter, Infill Density, Mechanical Properties.

1. Introduction

3D printing, also known as additive manufacturing, is a process for creating three-dimensional objects from a digital model by depositing material, typically layer by layer [1]. This technology has changed many industries, including manufacturing and healthcare, helping to make complex parts accurately and to specifications. There are many types of 3D printing. But most popular is Fused Deposition Modelling (FDM). In FDM, an apparatus pushes melted plastic through a nozzle. This happens layer by layer [2]. FDM is receiving much attention because it's cheaper to produce with a good flexibility in designing and capable of fabricating complex isotropic geometries without the use of molds and tooling [3]. Among the various thermoplastics used in FDM, polylactic acid (PLA) and its modified version PLA+ are a favored choice due to their biodegradability along with easy printability and mechanical properties [4]. The strength and performance of the FDM 3D printed parts highly depend on variations in settings used while printing which are layer height, print direction, print speed, infill %, nozzle size, etc [5]. The bonding between layers, presence of voids and quality deposition of the materials affect mechanical properties such as tensile strength and impact resistance and dimensional accuracy [6], [7], [8]. Even though lots of studies have looked into the effects of each of the parameters, not many have researched the combined effect of nozzle diameter and infill density, especially for PLA+. Recent investigations have shown that increasing nozzle diameter can improve tensile strength and impact energy up to an optimal range, beyond which performance declines due to reduced interlayer adhesion [9], [10], [11], [12]. Also, increasing the infill density can significantly improve its tensile strength and impact energy by filling the voids and improving strength [7], [8]. Sudin et al. [9]reported that larger nozzle of 0.6 mm with high infill (100%) produced the tensile strength 6-12% better than that with smaller nozzles. Extra experimentation are needed to learn how our parameters effect the PLA+ materials i.e. tensile properties and their impact energy.

This study looks at the tensile properties and impact energy of PLA+ parts made with a nozzle diameter of 0.2 mm, 0.4 mm, 0.6 mm, and 0.8 mm at 50% and 100% infill density that was manufactured on a Bambu Lab A1 3D printer. In this study, finer nozzle filament will be made with the expectation that the tensile property, impact energy, and density will increase and finally give us better manufacturing guidelines. The tensile tests were done as per the standards of ASTM D638 Type I and impact tests on ASTM E23. The findings will serve as useful guidance to determine the optimal nozzle size and infill density of FDM-printed PLA+ parts for mechanical performance in engineering applications.

2. Methodology

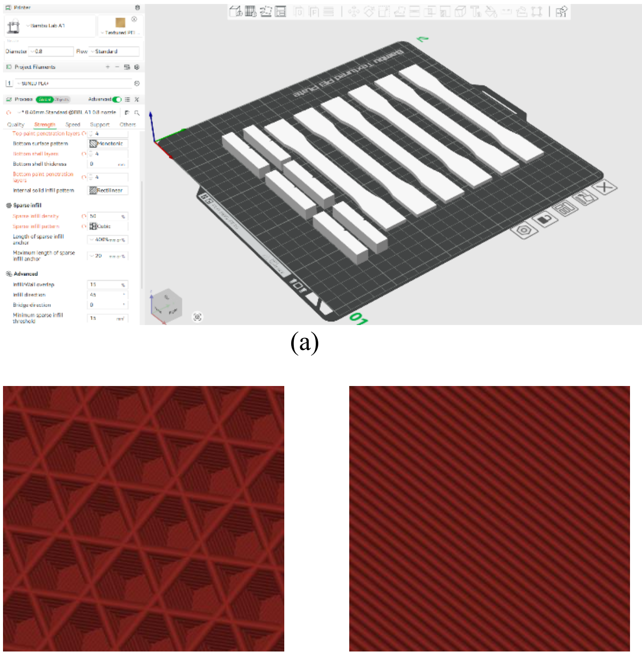
2.1 Materials

In this study, the filament used was Sunlu PLA+ (1.75 mm diameter). This filament is easy to process, has good mechanical properties and is biodegradable. PLA+ was selected instead of standard PLA due to its enhanced mechanical properties and improved printability. All filaments were taken from the same batch to maintain uniform material properties. Interchangeable metal nozzles were used to produce different extrusion orifice sizes, with stainless-steel nozzles employed for the smaller diameters (0.20 and 0.40 mm) and hardened-steel nozzles for the larger diameters (0.60 and 0.80 mm). For the nozzles with diameters of 0.2 mm and 0.4 mm, Stainless steel was used. Hardened steel was used for the 0.6 mm and 0.8 mm nozzle sizes which had greater extrusion rates and reduce wear. These nozzles are shown in **Figure 1**.

Fig. 1 Four nozzle diameters (0.2 mm, 0.4 mm, 0.6 mm, and 0.8 mm)

2.2 3D Printing Process

Specimens were printed on a Bambu Lab A1 FFF 3D printer that has an interchangeable nozzle system. Four nozzle sizes—0.2, 0.4, 0.6, and 0.8 mm—were used to prepare the samples. All specimens were produced from 1.75 mm PLA+ taken from a single production batch to ensure material consistency. Four nozzle diameters (0.20, 0.40, 0.60 and 0.80 mm) were used, each paired with a scaled layer height (0.10, 0.20, 0.30 and 0.40 mm, respectively). Tensile and impact samples were prepared according to ASTM D638 Type I and ASTM E23, respectively. Slicing and G-code generation were performed with Bambu Studio software **(Figure 2a)** with two infill densities: 100% **(Figure 2b)** and 50% **(Figure 2c)**.



(a)

(b) (c)

Fig. 2 (a) The Bambu Studio software used to set printing parameters (b) 50% infill density (c) 100% infill density.

Tensile (ASTM D638 Type I), and Charpy impact (ASTM E23) specimens were printed flat (0°) so layer planes were parallel to the build plate. The printing parameters were kept constant for all prints except for the nozzle diameter and infill densities. The printing parameters were kept constant for all prints except for the nozzle diameter. Table 1 shows the printing parameters.

Table 1 Printing parameters used in the study

Parameter	**Value**
Nozzle diameters	0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm
Filament	PLA+
Infill density	50% and 100%
Nozzle temperature	220 °C
Bed temperature	65 °C
Filament diameter	1.75 mm
Initial layer speed	50 mm/s
Inner wall speed	300 mm/s
Infill speed	250 mm/s
Travel speed	550mm/s
Outer wall speed	200 mm/s
Sparse infill pattern	Cubic
Wall loops	2
Top surface pattern	Monotonic
Top shell layers	4
Bottom surface pattern	Monotonic
Bottom shell layers	4
Print orientation	0° (flat)
Layer heights	0.1 mm, 0.2 mm, 0.3 mm, and 0.4 mm

The generated G-code files were transferred to the printer for fabrication.

2.3 Specimen Preparation

After generating G-code, the parts were printed on a Bambu Lab A1 using PLA+ filament. Tensile test specimens were fabricated according to the ASTM D638 Type I standard, while impact test specimens were prepared following the ASTM E23 Charpy notched specifications. Each nozzle size group contained five tensile and five impact specimens to ensure statistical reliability, as shown in **Figure 3**.

Fig. 3 Samples fabricated on the Bambu Lab A1

For each nozzle diameter and infill density, five tensile specimens, and five impact specimens were printed. Therefore, for each infill level (50% and 100%), a total of 40 tensile specimens and 40 impact specimens were fabricated.

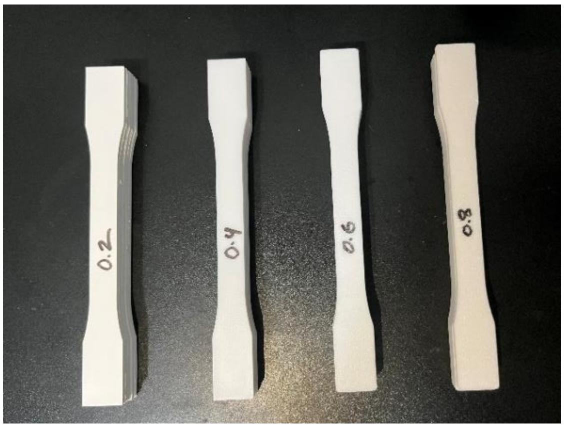
2.4 Tensile Testing

Tensile tests were conducted on specimens designed according to ASTM D638 Type I standards, as shown in **Figure 4(a)**. The experiments were performed using a Shimadzu UH-F1000kNX C1 Universal Testing Machine, shown in **Figure 4(b)**, to measure maximum force, stress, strain, and displacement.

All tests were performed at room temperature (≈23 °C). For each nozzle diameter, five specimens were tested and the measured tensile properties were averaged. Table 2 presents the tensile test parameters.

Table 2 Tensile test set up and parameter

Parameter	Value
Full length	165 mm
Grip section width	19 mm
Parallel section width	13 mm
Gauge length	50 mm
Parallel length	57 mm
Typical thickness	3.2 mm
Distance between grips	115 mm
Speed	5mm/min



(a)

(b)

Fig. 4 (a) Fabricated the tensile samples of 3D-printed parts according to ASTM D638 Type I (b) Experimental tensile test set-up.

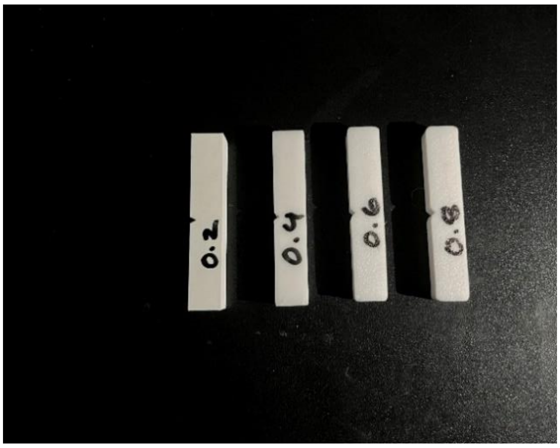
Five specimens were tested for each nozzle diameter. Results are reported as mean ± standard deviation.

2.5 Impact Testing

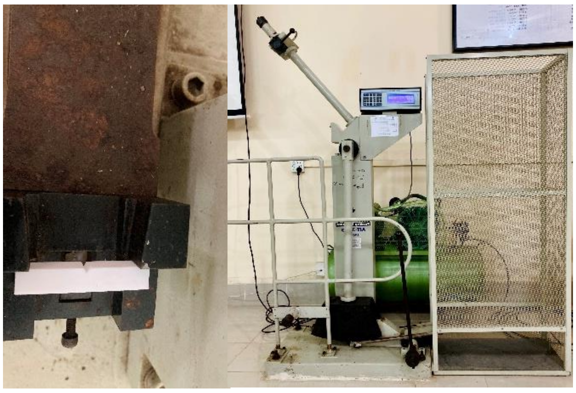
Impact tests were performed on specimens in accordance with ASTM E23 standards, **Figure 5(a)**. The impact tests shown in **Figure 5(b)** were performed using the Universal pendulum impact tester (AIT 300 D), to measure energy for fracture. The tester uses a 24 kg pendulum with an 80 cm arm length, operated at a maximum swing angle of 140°. The absorbed energy during fracture was calculated in joules and average value of five samples for each nozzle size. Table 3 presents the impact test parameters.

Table 3 Impact test setup and parameter

Parameter	Value
Specimen size	55 mm × 10 mm × 10 mm
Notch type	Charpy V-notch
Notch depth	2.0 mm
Notch angle	45°
Notch root radius	0.25 mm
Support span	40 mm
Pendulum mass	24 kg
Arm length	800 mm
Release angle	140°



(a)



(b)

Fig. 5 (a) Fabricated the impact samples of 3D-printed parts according to ASTM E23 (b) Experimental Impact test set-up.

For each nozzle diameter, five replicate specimens were tested. Data are reported as mean ± standard deviation.

3. Result and Discussion

3.1 Tensile Properties at 50% Infill

The average tensile test results for PLA+ specimens printed with 50% infill are shown in **Figure 6**. The 0.8 mm nozzle achieved the highest tensile stress (41.1082 N/mm²), with strength increasing as nozzle diameter increased. The maximum force, strain, and displacement all followed the same pattern. At 50% infill, increasing the nozzle diameter from 0.20 to 0.80 mm steadily improved all measured properties. The maximum force rose from 1.3247 kN to 1.9506 kN, maximum stress from 34.34 N/mm² to 41.11 N/mm², strain from 5.094% to 5.838%, and displacement from 2.902 mm to 3.757 mm. These results suggest larger nozzles lay down thicker filament lines, which reduce internal voids and improve bonding between roads and layers, allowing the parts to carry higher loads and deform more before breaking.

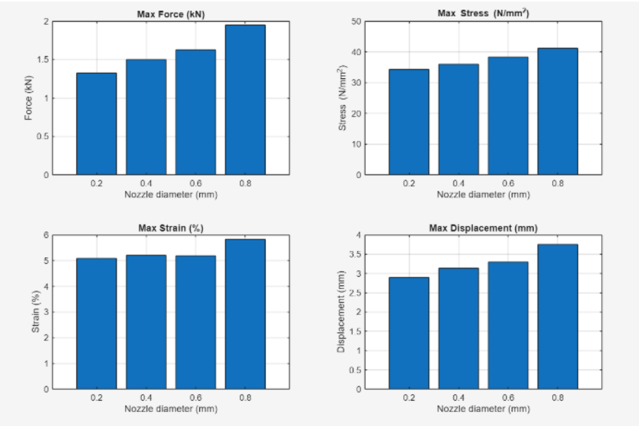


Fig. 6 The Effect of four different nozzle sizes on maximum force, stress, strain, and displacement at 50%.

The tensile properties increased with increasing nozzle diameter, with the 0.8 mm nozzle achieving the highest strength (41.1082 N/mm²) due to improved interlayer adhesion and reduced void content.

3.2 Tensile Properties at 100% Infill

For 100% infill, the average tensile performance improved across all nozzle sizes. The 0.6 mm nozzle achieved the highest strength (45.8714 N/mm²), while the 0.8 mm nozzle improved from 41.1082 N/mm² (50% infill) to 43.5673 N/mm². At 100% infill, increasing the nozzle size to 0.60 mm gives the best results: maximum force goes from 1.540 kN to 2.016 kN, maximum stress from 39.001 to 45.871 N/mm², strain from 5.900% to 7.193%, and displacement from 5.199 mm to 7.039 mm. For the 0.80 mm nozzle, the measured values show a slight decrease compared with the 0.60 mm nozzle. Increasing the infill density from 50% to 100% consistently improves the tensile properties across all nozzle diameters, indicating that higher infill enhances load transfer and overall tensile performance. The better performance comes from removing internal gaps and improving load transfer in the denser parts. Tensile properties are shown in **Figure 7**.

A tensile strength of 45.87 N/mm² was measured for the 0.6 mm nozzle. The 0.6 mm nozzle likely performed best because, with 0.2 mm layers, its extrusion width gives good overlap and holds heat longer. The thicker, well-fused filament lines fill gaps and make stronger bonds between layers while keeping extrusion stable. As a result, parts printed on the Bambu Lab A1 show less internal porosity and more consistent tensile and impact strength.

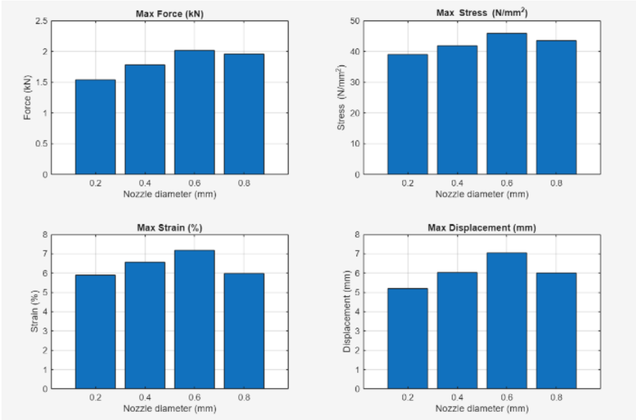


Fig. 7 The Effect of four different nozzle sizes on maximum force, stress, strain, and displacement at 100%.

3.3 Comparing Tensile Strength Across Infill Densities

Maximum tensile stress increased with infill density for all nozzle diameters. Tensile stress rises with nozzle diameter and infill: samples printed at 100% infill are stronger than those at 50%. For the 50% infill condition, maximum tensile stress rose as nozzle diameter increased; the 0.8 mm nozzle produced the highest stress values at each of these infill levels. For specimens printed at 100% infill, the maximum stress was achieved with the 0.6 mm nozzle, with the 0.8 mm nozzle showing comparable performance, whereas the 0.2 mm and 0.4 mm nozzles exhibited lower stress values. Compares tensile stress at 50% and 100% infill for different nozzle diameters shown in **Figure 8**.

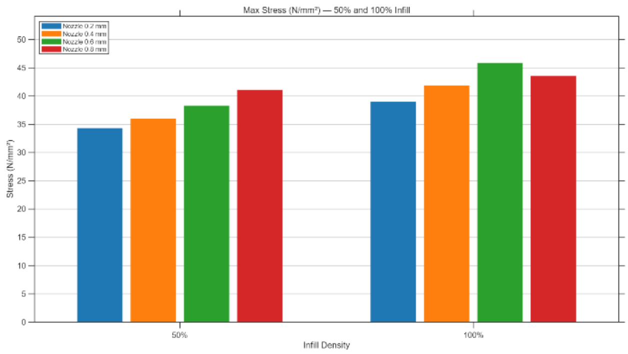


Fig. 8 Comparison of maximum tensile stress

These results indicate larger nozzles and full infill improve PLA+ tensile performance.

3.4 Impact Resistance

Impact energy increased steadily with higher infill density for all nozzle sizes tested (0.2, 0.4, 0.6, and 0.8 mm). Larger nozzle diameters were linked to greater absorbed impact energy, and increasing the infill density also raised the energy absorption. At 50% infill, the absorbed impact energy increases from 1.0 J for the 0.2 mm nozzle to 1.4 J for the 0.8 mm nozzle. The 0.4 mm and 0.6 mm nozzles show intermediate values of 1.1 J and 1.25 J, respectively. At 100% infill the same trend is stronger: impact energy rises from 1.3 J (0.2 mm) to 2.0 J (0.8 mm). Notably, the 0.6 mm nozzle records a high value of 1.95 J, nearly matching the largest nozzle. The 0.8 mm nozzle showed the highest impact energy absorption (2.0 J at 100% infill). Compares impact energy at 50% and 100% infill for different nozzle diameters shown in **Figure 9**.

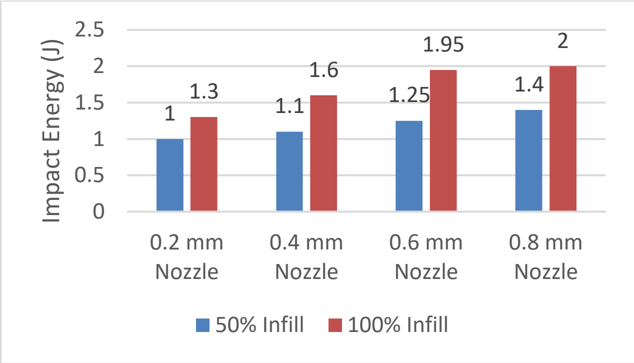


Fig. 9 Comparison of impact energy

The bar chart shows that impact energy increases monotonically with infill density for all nozzle diameters. Specimens printed at 100% infill consistently exhibited higher impact energy than those printed at 50% infill, attributable to reduced internal porosity and improved load transfer. Larger nozzle diameters further increased energy absorption through stronger inter-bead bonding. Thicker extrusion beads enhanced interlayer adhesion and slowed crack propagation during impact. Consequently, absorbed energy increased with infill density for all nozzle sizes because the denser structure is more resistant to fracture; thus, nozzle diameter and infill density jointly govern impact resistance.

4. Conclusion

The objective of this study was to experimentally investigate the effects of nozzle diameter and infill density on the tensile properties and impact energy of 3D printed PLA+ specimens. The investigation involved an analysis of four nozzle diameters (0.2 mm, 0.4 mm, 0.6 mm, and 0.8 mm) and two infill density (50% and 100%). Larger nozzles produced thicker, hotter extrusions that fused more completely, leaving few internal gaps. As a result, tensile strength and impact resistance increased. Smaller nozzles created thinner strands that cooled quickly and formed weaker joints. This results in lower strength and toughness. For 100% infill, the highest tensile strength of 45.87 N/mm² was obtained using the 0.6 mm nozzle.

- For both infill levels, the tensile properties and impact energy increased as the nozzle diameter became larger. The thicker extruded lines from bigger nozzles formed fewer layer joints, which helped the material absorb more energy and slowed down crack propagation.
- Increasing infill density from 50% to 100% improved the tensile and impact performance of all nozzle sizes.
- The 0.2 mm nozzle is ideal for intricate small models that need good printing precision, but which takes longer to print. The 0.4 mm nozzle is the one used most often for general purpose printing. It represents an ideal balance between speed and quality. Nozzles that are 0.6 to 0.8 mm in diameter allows printing to be faster either will improving tensile strength and impact resistance.
- Selecting an appropriate nozzle diameter requires consideration of the target mechanical properties, the intended application, and additional factors such as material consumption and surface quality.

Overall, the results indicate that nozzle diameter and infill density should be looked together to achieve the desired mechanical performance of the final component. In future studies, the effect of these parameters in combination with printing orientation, layer height, and post-processing could be studied to improve mechanical properties more. In the future we could look at nozzle size and infill density on the tensile properties and impact energy of other materials that are commonly used in FFF 3D printing (e.g. TPU, Nylon, PC, AB, PLA carbon, PLA wood, PETG, PVA).

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