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Infill pattern and density effects on the tensile properties of 3D printed PLA material

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Abstract. Additive manufacturing such as 3D printing is considered as a highly convenient manufacturing process since it enables to create any 3D objects. It is known that different materials, printing techniques, and printing parameters are affecting the mechanical properties of the printed objects. However, studies on the mechanical properties of the 3D printed structure are still limited. In this work, investigation of the relationship between two printing parameters, i.e. infill pattern and infill density were conducted on the Polylactic Acid (PLA) material. Three infill densities, 25%, 50%, and 75%, and three infill patterns, grid, tri-hexagon, and concentric, were chosen. The tensile test, ASTM D638, was employed to obtain the material properties based on these two printing parameters. An open-source 3D printing slicer software, Cura, was used to manufacture the tensile specimens. The Young's modulus, yield strength, and ultimate strength were recorded and examined. The results showed that the tensile properties increase as infill density increases. Of the three-printing pattern, the concentric has the highest values of tensile properties regardless of the infill densities. This finding can be used as a reference for creating a finite element model (FEM) as well as predicting the optimum tensile properties with respect to the printing parameters.

1. Introduction

Three-Dimensional (3D) Printing is one of the additive manufacturing methods. It performs rapid prototyping (RP) using a Computer-Aided Design (CAD). It is a manufacturing method that builds 3D objects by printing, i.e. melting and solidifying, the material layer by layer. The system consists of a frame, stepper motors, extruder with hot-end nozzle, a computer, and a microcontroller. The microcontroller, such as Arduino utilizing an open-source software [1], controls the movement of the extruder through stepper motors in X, Y, Z directions. Nowadays, the technology of 3D printing is becoming more affordable [2] and considered as highly promising for the future manufacturing industries [3] and higher education purposes [4].

The materials commonly used in non-metallic 3D printing are thermoplastics such as Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) [5]. Based on literatures, PLA is mostly used because of its affordability, availability, and its weightlessness. Additionally, the mechanical properties of the 3D printed PLA are higher than that of the ABS [6].

Considering limited research and experiment data in the literature on the mechanical properties of the 3D printed PLA material, this study focused on the relationship between two printing parameters,



infill density and infill pattern. Tensile tests based on ASTM D638 were conducted to obtain the material properties based on these printing parameters. An open-source 3D printing slicer software, Cura, was used to vary the printing parameters. The tensile properties, i.e. Young's modulus, yield strength, and ultimate strength were presented and discussed.

2. Research methodology

2.1. Specimen fabrication

Three infill densities, 25%, 50%, and 75%, and three infill patterns, grid, tri-hexagon, and concentric, were chosen. Hence, nine combinations of the printing parameters were set. Following the ASTM standard, five test specimens were manufactured for each combination, totaling of forty-five manufactured specimens to be tested.

The specimens were printed using Anycubic i3 Mega extruder. The material, 1.75 mm PLA filament, with printing melting temperature around 190°C - 230°C. The specimen printing temperature was set at 210°C. The dimension of the specimens was according to ASTM D638-Type I standard, shown in figure 1 below. The software used for controlling the printing parameters was the open-source slicer software, Cura.

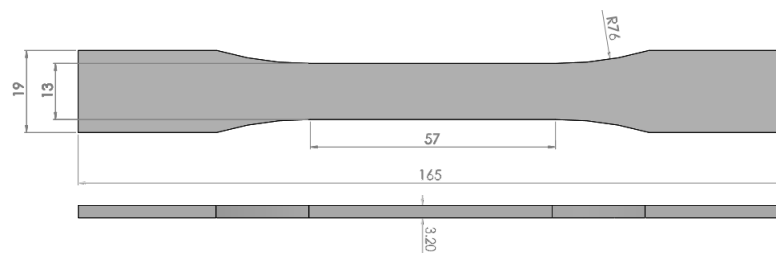


Figure 1. The dimension of ASTM D638 – type I test specimen in mm.

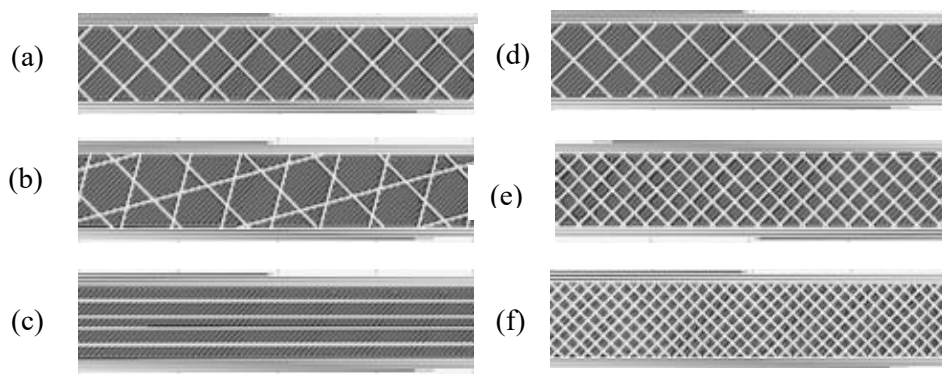


Figure 2. Infill patterns: (a) grid, (b) tri-hexagonal, and (c) concentric. Grid pattern infill densities: (d) 25%, (e) 50%, and (f) 75%.

The three infill patterns shown in figure 2 are (a) grid, (b) tri-hexagonal, and (c) concentric. The grid pattern prints the object layer in 90 degrees crossing paths, where the paths make 45 degrees angle with respect to the axial axis of the specimen. The tri-hexagonal pattern prints the object layer in three different path directions, differed by 120 degrees rotation from one path to another. The lowest path angle with respect to the specimen axial axis is 30 degrees. The concentric pattern prints in the direction of the specimen axial axis. Subfigures (d), (e), and (f), in figure 2 represent the grid pattern increasing infill density of 25%, 50%, and 75%, respectively. The printing parameters are listed in table 1.

Table 1. Printing parameter constants of test specimens.

Parameters	Values
Layer Height	0.1 mm
Horizontal Shell: a solid layer top and bottom	3 layers
Wall Thickness	1.2 mm
Top/Bottom Thickness	0.6 mm
Printing Temperature	210° C
Build Plate Temperature	70° C
Printing Speed	50 mm/s

2.2. Tensile test

The ASTM D638 “Standard Test Methods for Tensile Properties of Plastics” [7] was applied to test the specimens. The tensile tests were conducted using the Universal Testing Machine, Test Resource 313. The crosshead testing rate (i.e. constant speed tensile test) was set at 5 mm/min. The output of the tensile tests was recorded as the uniaxial tensile load versus the elongation (changes in length), which were then transformed into engineering stress and strain curves. The engineering stress was calculated by dividing the load with the initial cross-sectional area of the specimen.

In this experiment, it was found that the engineering strain obtained from the machine was less accurate. Therefore, strain gauges were used to obtain a more accurate one [8]. A strain gauge was attached to the center of the specimen to measure the axial deformation, as illustrated in figure 3. The strain measurements were recorded using the National Instruments data acquisition system, NI-9265, along with the LabView software.

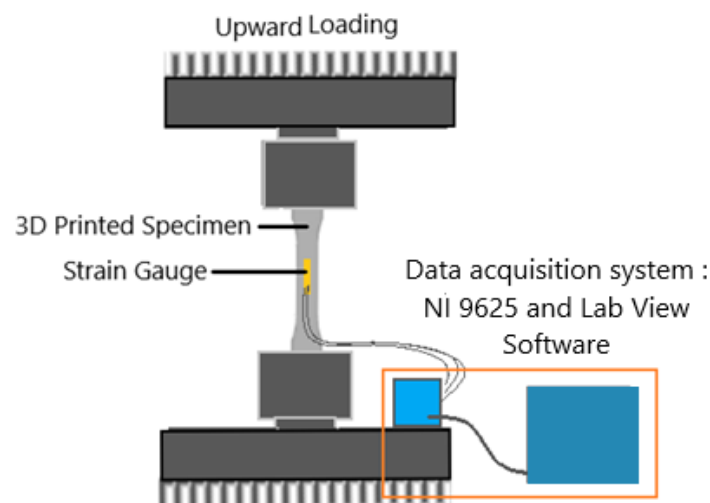


Figure 3. The strain gauge attached to the specimen in the tensile machine and connected to the data acquisition system.

The tensile properties, such as Young’s modulus, yield strength, and ultimate strength were then calculated. The yield strength was obtained by constructing a tangent line from the offset strain of 0.2%; the extended tangent line that intersects the stress-strain curve is the approximation for yield point. The Young’s modulus was obtained by evaluating the value of stress with respect to strain, $\frac{\Delta\sigma}{\Delta\epsilon}$ [10, 11] which represents the gradient of the stress-strain curve at the elastic region [12]. The ultimate strength was obtained by taking the highest peak of the curve.

3. Results and discussion

The test results of the nine combinations are summarized in table 2 and plotted in figure 4. The values shown are Young's modulus, yield strength, and ultimate strength which were extracted from the average measurement values of each combination of the five specimens tested according to the ASTM standard.

Table 2. Tensile properties of the PLA Specimens.

	Infill Pattern	Infill Density	Young's Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)
1	Grid	25 %	2.76 \pm 0.38	28.1 \pm 0.23	29.7 \pm 1.29
2	Grid	50 %	2.8 \pm 0.12	29.6 \pm 0.78	31.5 \pm 2.17
3	Grid	75 %	3.28 \pm 0.17	33.3 \pm 1.33	35.4 \pm 0.46
4	Tri-hexagonal	25 %	2.61 \pm 0.21	25.5 \pm 2.13	27.8 \pm 0.94
5	Tri-hexagonal	50 %	2.72 \pm 0.14	27.6 \pm 1.11	30.6 \pm 1.23
6	Tri-hexagonal	75%	3.01 \pm 0.21	35.9 \pm 0.59	37.3 \pm 1.11
7	Concentric	25 %	3.14 \pm 0.19	33.7 \pm 2.12	32.6 \pm 0.71
8	Concentric	50 %	3.27 \pm 0.11	40.3 \pm 0.26	44.3 \pm 2.94
9	Concentric	75%	3.897 \pm 0.37	40.98 \pm 0.84	42.2 \pm 2.47

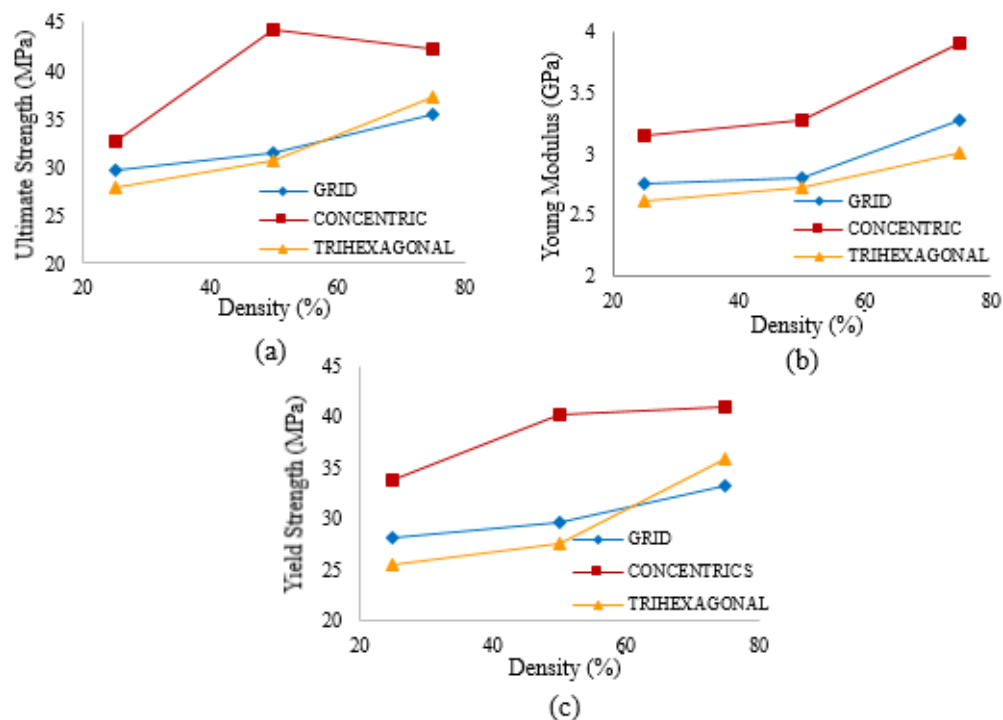


Figure 4. The tensile properties values with respect to the various infill densities and infill patterns: (a) Young's modulus, and (b) yield strength, (c) ultimate strength.

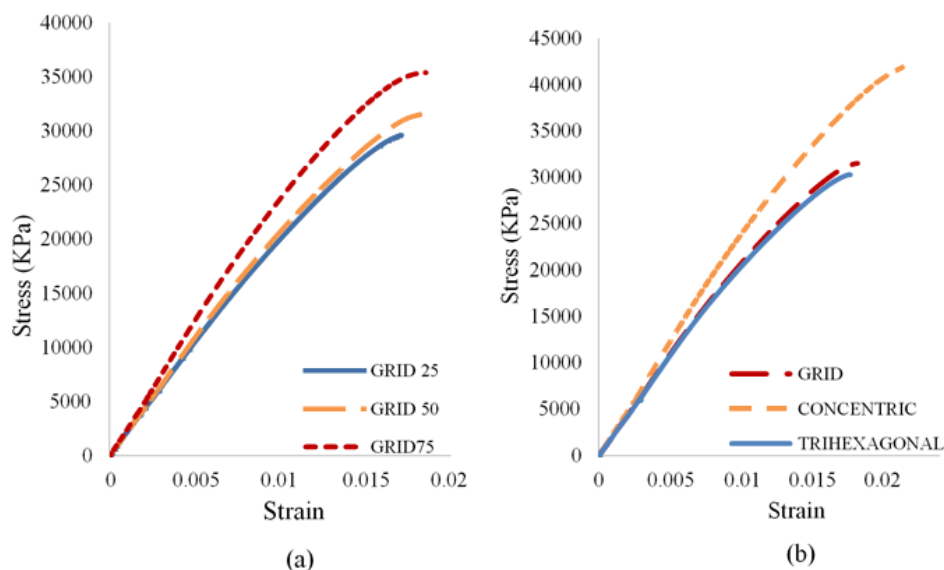


Figure 5. Stress-strain plots: (a) grid pattern with varied infill densities, (b) 50% infill density with varied infill patterns.

In general, the trend shows that the tensile properties are increasing as the infill density increases, except for the concentric pattern with 75% infill density, where the value of ultimate strength is decreasing from 44.3 MPa to 42.2 MPa. This trend is depicted in Figure 5(a), showing the grid with increasing infill densities of 25%, 50%, and 75%. Similar finding shows that higher infill density implies higher resistance to applied stress internally [9].

In addition, infill patterns have an effect on tensile properties. In Figure 5(b), for the infill density of 50%, the Young's modulus of the grid pattern is similar to the tri-hexagonal pattern with an incrementally higher value. The concentric definitely has a much higher value than the other two. It can be hypothesized that the maximum values of the tensile properties are achieved by having the pattern path in the same direction as the tensile load direction.

Based on the result, the highest tensile properties corresponded to concentric pattern with 75% of infill density, where it has 42.2 MPa of ultimate strength, 3.89 GPa of Young's modulus, and 40.98 MPa of yield strength. In addition, grid pattern with 100% infill density was tested and it was recorded that the Young's modulus and yield strength were 3.6 GPa and 48.2 MPa, respectively. For 100% infill density, the effect of infill pattern on mechanical properties is negligible [13].

4. Conclusion

The tensile properties of 3D printed PLA material with a combination of two printing parameters, infill density and infill pattern, were measured by tensile test experiment. In general, the results showed that increasing the infill density increases the tensile properties for the three infill patterns. Moreover, the infill patterns affect the tensile properties. Concentric infill pattern demonstrated the highest tensile properties compared with the other two while the grid and tri-hexagonal pattern are at similar levels. The results can be used as reference data for creating finite element model (FEM) and predicting the optimum tensile properties with respect to the selection of the printing parameters. Comprehensive investigation on the effect of infill pattern on the tensile properties is suggested for future study.

Acknowledgments

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