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Simulation and Experimental Evaluation of Tensile Properties and Macrostructure Changed of 3D printer PLA Filaments

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Abstract
The use of printing products with 3D printing has been widely used in everyday life, but research regarding its strength and performance is still limited. Therefore, simulation and experimental approaches are used in this paper to analyse the characteristics of PLA+ materials produced by 3D printers. *a. Design* tensile test specimens and static stress tests in Autodesk Fusion360; b. Calculate the weight of the tensile test specimen; c. Print tensile test specimens with variations in infill (60, 80, and 100%) and print direction (0, 45, and 90 degrees); and d. Experiment with macrostructure, weight, and tensile tests. The conclusions of this study are; a. PLA+ material properties (macrostructure, weight, tensile strength, tensile strain) have been obtained experimentally and through simulation, b. The tensile strength of the simulated PLA+ material is higher than the experimental test results, c. The level of density (infill), affects the weight and tensile strength, and d. The direction of the impression affects the tensile strength, but weight and tensile strain have no effect.

Keywords:
Characteristic, Filament 3D, 3D Printer, Simulation, and Experiment.

1 Introduction

Efficiency in the process and accuracy of product dimensions are significant in the increasingly fierce global industrial competition. This has a significant effect on the costs incurred in producing quality products. Before a product is made in mass quantities, a product model or prototype is first made to determine its shape, dimensions, and ergonomics, so that evaluation can be carried out. Prototyping can be done by removing some of the material on the workpiece, carrying out the material suppression process, or adding material to the product. Adding material to this product is known as additive manufacturing or layer manufacturing using 3D printing [1].

It has been 35 years since Charies W. Hull had the brilliant idea of using 3D printing technology to create products [2]–[4]. 3D printing is a unique, innovative, and creative additive manufacturing method that uses digital models to create products without expensive traditional cutting or casting machines [5]–[9]. It also outperforms all other technologies in producing multi-material components and components with complex shapes [5], [10]–[13]. Meanwhile, a large number of raw resources can be saved during the printing process. Biomedical, aerospace, automotive engineering, civil engineering, food, and other disciplines frequently use 3D printing components [14]. Too far, a variety of 3D printing technologies have been employed. Stereolithography (SLA) [15], Fused Deposition Modelling (FDM) [16]–[19], and stereolithography (SLA) [20] are the four most frequently used methods.

In the manufacturing environment, 3D printers play a significant role [6], [7], [9]. The flexibility of printing motions in three-dimensional space makes it feasible to construct a range of complicated designs using a 3D printer. Making a product using a 3D printer begins with making a design first using design software such as Autodesk Fusion360, solid work, AutoCAD, and 3dmax. The results of this design are converted into the STereoLithography (STL) programming language and then printed using a 3D printing machine. Thus, the actual product is obtained [6]–[8].

Tensile testing is one way to test 3D Printer products. The product results from the 3D printing machine need to be known how strong the product can accept the load, then the printed product is tested for tensile with a method used to test the strength of the material by applying an axial force load tensile load [2]. The results obtained from tensile testing are significant for engineering and product design because they produce material strength data.

Materials that have received heat treatment and different forming processes will also have different macrostructures. PLA+ plastic material made with a 3D printer machine (infill and print direction variations) will be observed for its macrostructure.

Polylactide (PLA) is a biodegradable aliphatic polyester derived from lactic acid. It has similar mechanical properties to polyethylene terephthalate but has a much lower maximum continuous use temperature. PLA products can be recycled after smelting and processing the material a second time or by hydrolysis to lactic acid, a primary chemical [21].

3D printing is widely used in scientific research and engineering applications, from aerospace to biomedicine. However, little is known about the mechanical properties of 3D printed materials. The primary tensile strengths of PLA+ materials with varying infill and print orientations were explored by simulation and experimentally to aid mechanical analysis and structural design in 3D printing. Simulation models were first created to predict the ultimate tensile strength of PLA materials based on the hypothesis and then verified by tensile experiments.

The purpose of this study was to analyze the tensile properties experimentally and through simulate and observe the macro structure of PLA+ filaments with different filler parameters and printing directions using 3D printing technology.

2 Research Method

2.1 2.1. Materials and Tools

The material used in this study is Polylactic Acid (PLA+) with a gold color (Fig. 1). The specifications for PLA filaments can be seen in Table 1.

Fig. 1. PLA+ Material

Table 1. Properties of PLA+ (Shenzen Esun Industrial Co.Ltd.)

Specification	Value
Technical Name	Polylactic Acid (PLA)
Chemical Formula	(C3H4O2) n
Typical Injection Molding Temperature	205 – 225 °C
Tensile Strength	65 MPa
Flexural Strength	75 MPa
Specific Gravity	1.24 *****
Shrink Rate	PLLA: 0.37 – 0.41% (0.0037 – 0.0041 in/in)

A 3D printing machine with the Anycubic i3 Mega brand was used to manufacture the tensile test specimen (Fig. 2).

Fig. 2. 3D printing machine [22]

2.2 Procedures for Work

The working procedures of this research are; a. Design tensile test specimens (standard ASTM D 638, Fig. 3) and static stress tests on Autodesk Fusion360; b. Calculate the weight of the tensile test object; c. Printing tensile test specimens with variations infill (60, 80, and 100%) and print direction (0, 45, and 90 degrees); and D. Experiment with macrostructure, weight, and tensile test (RTF Universal Testing Machine(RTF)

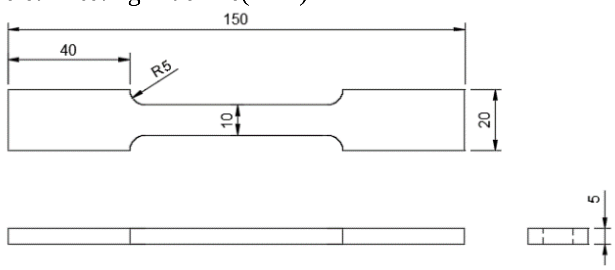

Fig. 3. Dimensions of Tensile Test Specimen

2.3 Printing Parameters

The parameters used to print the tensile test object are; a. nozzle temperature of 210°C; b. the layer thickness of 0.1 mm; c. the printing speed of 50 mm/s; d. travel speed of 100 mm/s; e. bed temperature of 60°C; f. print direction (0 deg, 45 deg, and 90 deg; and g. infill (60, 80, and 100%). The number of specimens used was 27 pieces. as shown in Fig. 4

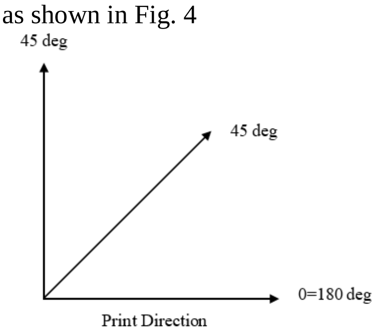

Fig. 4. Print direction parameter.

3 Result and Discussion

Fig. 5 shows a photo of the macrostructure of the PLA+ material with variations in the density level (infill) and variations in the print direction. Based on Fig. 7, it can be seen that the higher the density level, the denser the structure.

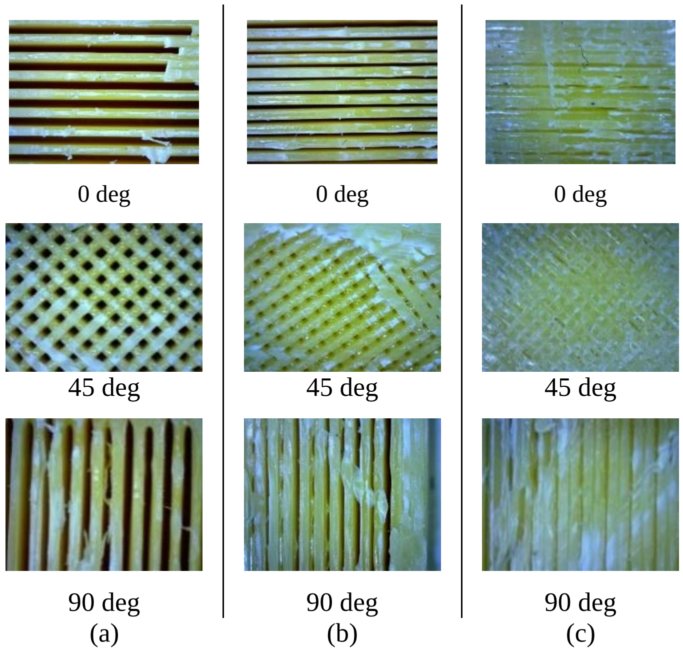

Fig. 5. Macro Structure Observation Results (a) Infill 60%, (b) Infill 80% and (c) Infill 100%

Fig. 6 shows the characteristics of the PLA+ material parameters, the applied load, and the tensile test results data (tensile strength and elongation) on the tensile test specimen (100% infill) in a simulation using Autodesk Fusion360.

Based on Fig. 7, it can be seen that the higher the density level, the denser the structure

Materials

Component	Material	Safety Factor
Body1	PLA +	Yield Strength

PLA +

Density	1.04E-06 kg / mm^3
Young's Modulus	2250 MPa
Poisson's Ratio	0.44
Yield Strength	65 MPa
Ultimate Tensile Strength	65 MPa
Thermal Conductivity	2.25E-04 W / (mm C)
Thermal Expansion Coefficient	1.3E-04 / C
Specific Heat	15000 J / (kg C)

Loads

Remote Force1

Type	Remote Force
Magnitude	3000 N
X Value	-3000 N
Y Value	0 N
Z Value	0 N
Flip Direction	Yes
Position X	-40 mm
Position Y	5 mm
Position Z	2.5 mm

Result Summary

Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	0.6035	7.451
Stress		
Von Mises	5.771 MPa	71.25 MPa
1st Principal	1.46 MPa	85 MPa
3rd Principal	-8.878 MPa	25.38 MPa
Normal XX	-2.979 MPa	77.47 MPa
Normal YY	-5.687 MPa	26.95 MPa
Normal ZZ	-8.87 MPa	26.95 MPa
Shear XY	-21.76 MPa	21.62 MPa
Shear YZ	-1.434 MPa	1.707 MPa
Shear ZX	-3.683 MPa	3.451 MPa

Displacement		
Total	0 mm	4.428 mm
X	-4.42 mm	0 mm
Y	-0.1276 mm	0.1137 mm
Z	-0.2415 mm	0.096 mm
Reaction Force		
Total	0 N	835.1 N
X	0 N	733.4 N
Y	-168.2 N	192.9 N
Z	-484.7 N	616 N
Strain		
Equivalent	0.006401	0.06187
1st Principal	0.006262	0.06417
3rd Principal	-0.03532	-0.002195
Normal XX	3.654E-04	0.04289
Normal YY	-0.01826	0.001207
Normal ZZ	-0.02103	0
Shear XY	-0.04178	0.04152
Shear YZ	-0.002754	0.003277
Shear ZX	-0.007071	0.006626

Fig. 6. PLA+ Material Simulation Test Results

The simulation test results on PLA+ material can be seen in (Table 2).

Based on Fig. 6, it can be seen that the simulation results on PLA+ material obtained maximum tensile strength of 71.25 MPa and an elongation of 4.428 mm. The tensile strength from this simulation (71.25 MPa) is greater than the tensile strength of PLA+ material (65 MPa).

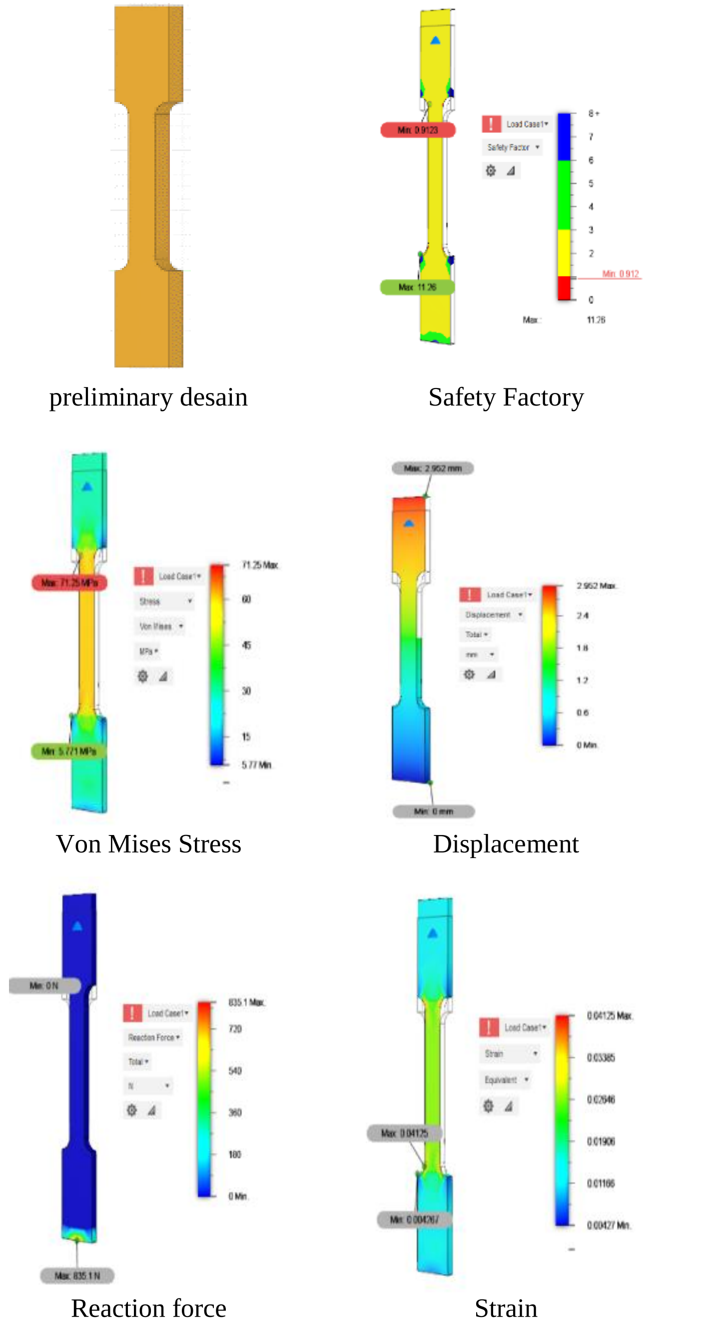

Fig. 7 Simulation results of the tensile test (Static Stress) for PLA+ material

Table 2. Results of Simulation Analysis of PLA+ Materials

Responses	Minimum	Maximum
Von Misses Stress	5.77 MPa	71.25 MPa
Safety Factory	0.912	11.26
Displacement	0 mm	4.428 mm
Reaction Force	0 N	835.1 N
Strain	0.006401	0.06187

The simulation test results on PLA+ material can be seen in Table 2. Fig. 7 shows the tensile test parameters given in the simulation test. Based on the test results in Table 2, it is known that the maximum stress of PLA+ material is 71.25 MPa, a safety factor is 11.2, elongation is 4.428 mm, maximum tensile force is 835.1 N, and strain is 0.06187.

In this study, the weight measurement of the tensile test specimen was also carried out in a simulation (using the Simplify3D application) and the weight measurement using a digital scale. Table 3 shows the results of the simulation and experimental weight measurements.

Table 3. Measurement of PLA+ Material Weight

No	Print Direction (°)	Infill (%)	Weight (Gram)	
			Simulation	Experiment
1	0	60	9.73	8.40
		80	11.55	10.00
		100	13.11	11.30
2	45	60	9.82	8.40
		80	11.53	10.00
		100	13.24	11.30
3	90	60	9.82	8.40
		80	11.53	10.00
		100	13.23	11.40

It is known that the weight of the simulated specimen is more than the weight of the experimental tensile test specimen based on the measurement findings of the weight of the tensile test specimen in Table 3. The density level of 100 percent is heavier than the density levels of 80 percent and 60 percent when seen from the density level (infill) perspective. The weight of the tensile test specimen is roughly the same when seen from the printing direction at varying density levels.

Table 4 shows the tensile testing results on PLA+ materials using a universal tensile testing machine. The relationship between the density/direction of the print and the tensile strength can be seen in Figs 8 and 9.

Table 4. The tensile strength of PLA+ material

No.	Infill (%)	Print Direction (deg)	Weight (gram)	Load (N)	Tensile Strength (MPa)
1	60	0	8.4	2350	47.0
		45	8.4	2660	53.2
		90	8.4	3170	63.4
2	80	0	10.0	2450	49.0
		45	10.0	2890	57.8
		90	10.0	3490	69.8
3	100	0	11.3	2720	54.4
		45	11.3	3100	62.0
		90	11.4	3620	72.4

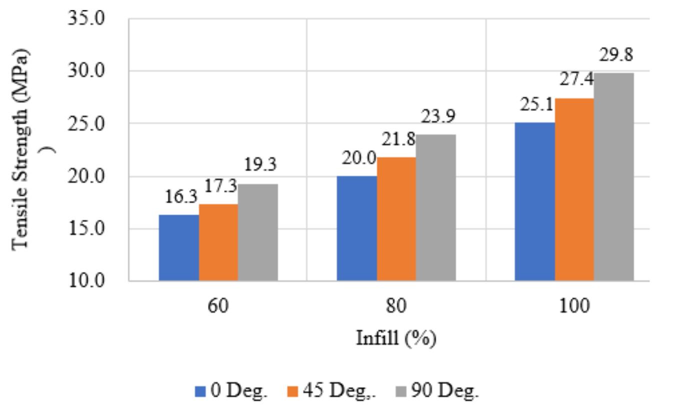

Fig. 8 Graph of the relationship between the density and tensile strength of PLA+ materials

According to the findings of this tensile test, the most significant tensile strength occurs at a density level of 100 percent, followed by 80 percent, and finally 60 percent. This demonstrates that the density level impacts the tensile strength value. The tensile strength of PLA+ plastic filament (65 MPa) is lower than the simulation test results (71.25 MPa) and higher than the experimental test results (29.8 MPa).

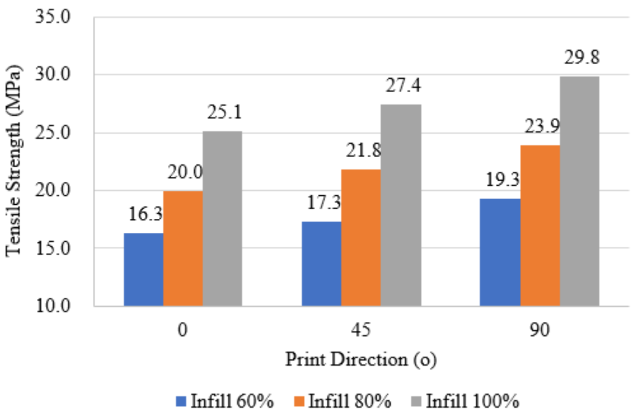

Fig. 9 Graph of the relationship between print direction and tensile strength of PLA+ material

When seen from the printing direction for the same specimen density level, the most extensive tensile strength is at 90^o, followed by 45^o, and finally 0^o. This occurs because the print direction coincides with the direction of the tensile axis, resulting in a higher tensile strength compared to the tensile strength in the printing direction at 45^o and 0 ^{o} angles. This study is based on the findings of prior research [9], [14]. The comparison of test results in reference revealed that the UTS of 3D printed materials changed dramatically with changes in printing angle [14]. The enormous UTS gap is 52.29 percent, between 0^o and 90^o 3D printed materials with a layer thickness of 0.1 mm. Tensile strength response is also investigated in the friction welding process [23], [24].

It is known that the tensile strength of the simulation results is greater than the tensile strength experimentally. There was a substantial difference in the level of tensile strength between the simulation and experimental tests (42 MPa). This shows that there is a phase change of the PLA+ material when it is melted and printed with a 3D machine. In the printing process, each layer is formed with a certain thickness, infill, and print direction so as to form different polymer bonds and have an impact on the tensile strength.

Table 5 shows the results of the measurement of elongation and calculation of tensile strain (elongation) on PLA+ material. Based on the calculation of the tensile strain on the PLA+ material, it is known that the highest tensile strain (4.86%) occurs at an 80% infill parameter with a 45^o printing direction. When viewed from the print direction, the most considerable tensile strain occurs at an angle of 45^o at the same fibre density level.

Table 5. Elongation Properties of PLA+ Materials

No.	*Infill* (%)	Print Direction (deg)	W (gram)	ΔL (mm)	Elongate (%)
1	60	0	8,4	0,89	1,48
2	60	45	8,4	1,3	2,16
3	60	90	8,4	1,02	1,70
4	80	0	10,0	0,96	1,60
5	80	45	10,0	2,92	4,86
6	80	90	10,0	1,73	2,88
7	100	0	11,3	1,12	1,86
8	100	45	11,3	2,25	3,73
9	100	90	11,4	0,94	1,56

Based on the preceding data analysis, it is clear that the density level (infill) and print orientation have an impact on the three replies (weight, tensile strength, and tensile strain). The weight and tensile strength values increase as the density level (infill) increases. Meanwhile, the tensile strain remains generally constant as the density level (infill) increases. The higher the tensile strength in the printing direction, the bigger the angle of the imprint, but the weight of the tensile specimen and the tensile strain are relatively the same.

4 Conclusion

The characteristics of the PLA+ material (macrostructure, weight, tensile strength, tensile strain) have been simulated and experimentally produced through a 3D printer. The conclusions of this study are; a). The characteristics of PLA+ materials (macrostructure, weight, tensile strength, tensile strain) simulated and experimentally produced by 3D printers are different. The difference in tensile strength between the simulation and the experimental is quite significant, b). The density level (infill) and print direction affect the three responses (weight, tensile strength, and tensile strain). The higher the density level (infill), the higher the weight value and tensile strength.

Meanwhile, the higher the density level (infill), the tensile strain is relatively the same, and c). The print direction angle affects the tensile strength; the more significant the print angle, the higher the tensile strength. However, the tensile specimen weight and tensile strain are relatively the same.

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