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Study the crushing behavior of 3D printed Poly Lactic Acid samples

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Abstract: Engineering product designs are becoming more complicated in shape and need sustainability for longer lifetimes; there is a need for new technology like 3D printing for fabricating complex parts. Fused deposition modelling (FDM) is among the widely used additive manufacturing technology to fabricate quality products with effective expenses. This investigation considered significant methodological parameters: layer layouts/ patterns (triangular and rectilinear), wall thickness (1.2,3.6,6) and infilled density (70, 85 and 100%) analyzed to check out right into their results on compression and impact mechanical behaviors of 3D-printed Poly Lactic Acid pulse (PLA+), utilizing FDM 3D printing machine. The Central Composite Face-centered (CCF)technique was conducted to design an optimal number of experiments. The compression and impact tests were applied according to ASTM guidelines. The results showed that the Rectilinear samples were mechanically weaker than the Triangle samples, as the samples with 1.2 mm outer wall and 70% or 85% infill collapsed abruptly. The outer wall thickness was the most effective parameter for all samples, as the triangle sample with 6 mm walls and 85% infill had the highest compression and impact strength.

Keywords: Fused deposition modeling, polylactic acid, Compression, Impact.

1. INTRODUCTION

Additive manufacturing (3D printing) is considered a promising technique which has numerous potentials in the industry. This technology produces end-use products by adding up material to fabricate a product from a 3D CAD file [1].

In comparison with different AM technologies that are commercially available, FDM is the most common and cost-optimization method to print 3D parts [2]. FDM has been utilized and improved rapidly in several fields from automotive, aircraft, electronics to biomedical. Applications in the field of automotive and aircraft like structural components from fiber-reinforced composite, degradable bio-composite structure, unmanned aerial aircraft, some mechatronic control unit prototype, and rapid tooling [3]. However, because of the raster-by-raster melting and accumulating formation characteristics of FDM technology, several pores are formed in the sample, lack of strength, stair-step effect (poor surface finish), higher building time, and the deposited Materials threads are not entirely integrated into one [4].

The commonly used materials in the FDM process are thermoplastic polymers. Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the most usually used for FDM technology [5]. PLA has the advantage of being a biodegradable material, so it is more environmentally friendly and has good mechanical behaviors that are appropriate for biomedical, aerospace, and automotive applications [6].

The important feature of the FDM process for industrial purposes is its ability to produce products with locally controlled properties like build orientation, porosity, nozzle temperature, and printing density, width; layer thickness and material feed rate [7]. The significance of processing parameters and their optimization on the final product mechanical properties were investigated [8].

The mechanical behaviors of 3D printed product by FDM process are extremely influenced by the infill design parameters which are infill density, infill deposition rate, layer thickness, infill pattern, and infill width as mentioned by Takagishi et al. [9]. Letcher et al. [10] showed that mechanical behaviors like the ultimate tensile strength can be enhanced by changing the raster angle orientations of 3D printed PLA products. The yield strength and tensile strength of 3D printed products are influenced by many infill designing parameters (infill deposition rate, infill density, and layer thickness) to the mechanical characteristics. Sukindar et al.

[11] indicated that the tensile strength and yield strength increase by increasing layer thickness for a small layer thickness value, due to small layer thickness decrease the gap among the infill and thus the strength increase. Fernandez et al. [12] showed that the tensile strength, yield strength, and the modulus of elasticity increase with increasing the layer thickness.

This paper primarily investigates the crushing behavior under compression and impact for samples of three infill percentages and wall thicknesses. Developing a study that compares the printing parameters is of great significance for future development of the printing method and the application of its products and thus, this paper puts forward the research on PLA+ materials as the research objects to fabricate test samples separately.

2Experimental procedure

2.1Materials

In this work, Polylactic Acid plus (PLA+) Filament of diameter 1.75 mm (supplied by ESUN, China) used as feedstock. The mechanical characteristics of used (PLA+) Filament as attached in the supplier company data sheet are summarized in Table1.

Table 1 mechanical properties of PLA filament.

PLA + filament			
Mechanical properties	Value	Unit	Test Standard
Tensile Strength	63	MPa	GB/T 1040
Elongation at Break	20	%	GB/T 1040
Flexural Strength	74	MPa	GB/T 9341
Flexural Modulus	1973	MPa	GB/T 9341
IZOD Impact Strength	9	kJ/m²	GB/T 1843
IZOD Impact Strength	9	kJ/m²	GB/T 1843

2.2Specimen design and the 3D printing process

Fused Deposition Modeling (FDM) 3D printer, CREALITY Ender-3 (CREALITY-3D Printing, China), was applied to fabricate PLA+ samples from its original shape as filament. Ultimaker Cura, Ultimaker Cura 4.3 software was utilized to adjust the printing parameters and provide the G-Code required for the FDM process. The FDM printing process parameters for PLA+ (Table 2) were selected as materials supplier recommendations. This FDM printer should perform all the minimum requirements of samples printing process for mechanical experiments.

Table 2 constant parameters during FDM printing process for PLA+.

PLA +	
Parameters	Values
Nozzle Diameter	0.4 mm
Layer Height	0.2 mm
Printing Speed	45 mm/min
Reaction Speed	35 mm/min
Nozzle Temperature	200°C
Bed Temperature	75°C
Fill Angles	45°, -45°

Previous studies suggested 2D rectilinear and triangle structures for best compression properties, so these structures were chosen to study the compression and impact properties of printed samples as shown in Fig. 1. Structures were designed on SolidWorks 2018 software based on parameters such as infill pattern, wall thickness and infill percentage. Specimens were FDM 3D printed with PLA+ filament. All specimens had the same orientation to avoid mechanical performance differences due to print orientation, which affects the mechanical characteristics of 3D printed samples. In this study, three controllable factors from several 3D-printing parameters: wall thickness, infill pattern and infill percentage. They had three levels for infill percentage and wall thickness and two levels for infill pattern. The RSM is a statistical method for model effectiveness. Each independent factor was coded at three levels +1, 0, and -1 for the high-level, mid-level, and low-level respectively, as shown in Table 3. This research had 28 experiments in total.

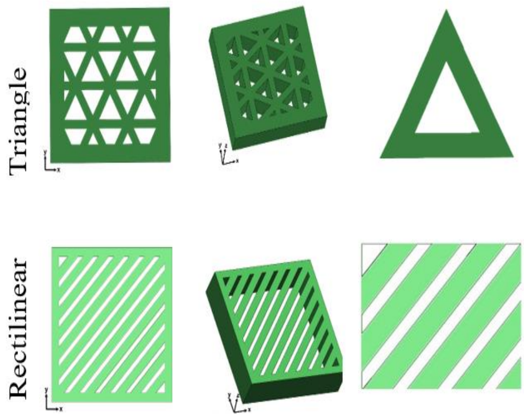


Fig. 1. Geometrical models with infill density 70%, and 1.2-mm wall- thickness.

Table 3 variables, codes, and levels for Central Composite-Face-centered Design.

Triangle				
			Values	
Parameters	code	-1	0	+1
Infill percentage (%)	x1	70	85	100
Wall thickness	x2	1.2	3.6	6
Rectilinear				
Infill percentage (%)	x1	70	85	100
Wall thickness	x2	1.2	3.6	6

2.3Compression tests

This work tested the 3D printed samples under compression to study their crushing behaviors and draw the stress strain diagrams, from which relative crashworthiness parameters such as elastic modulus, initial collapse stress, specific energy absorption (SEA), and crushing force efficiency (CFE) were obtained. This research used a cube specimen shape with dimensions of 20×20×40 mm, following ASTM D695 international standard. The compression tests used a 100 kN load cell and applied uniform pressure at 5 mm/min crosshead speed, as per the same standard. The tests ended when the sample's structure fractured or reached 50% strain.

2.4Impact tests

A drop-weight hammer testing machine with 50 J impact energy was used. The impact samples size followed ASTM D6110 standard, which specified 12.7 mm × 12.7 mm × 127 mm as the maximum notch dimension of specimen. The difference in height between the original and final pendulum position is directly proportional to the amount of energy lost through the sample fracture.

3Results and discussion

3.1Compression properties

Compression tests of PLA+ 3D-printed triangle infill with different wall thicknesses (1.2, 3.6, 6 mm) and infill percentages (70, 85, 100%) showed slightly different deformation patterns and mechanical properties. All samples collapsed by progressive folding and lateral shearing. The samples were FDM-printed without defects. However, rectilinear infill samples were weaker than triangle infill samples due to their lateral shear sensitivity and transverse plastic cracking. The triangle samples had a good bonding structure and acceptable mechanical behavior.

3.1.1Triangular pattern samples

The nominal stress-strain curve of printed PLA+ is shown in Fig. 2. According to Fig. 2, specimen wall thickness affects crush behavior. 6mm samples have the highest endurance stress (A- initial peak force). Crushing of cell walls starts with stress drop and remarkable plastic deformation (B-start of densification), followed by sharp stress rise as the strain rises, resulting in an ideal progressive deformation, as seen in the photographic image, and specified on the curve as (C-densification). 6mm samples have a steeper peak and a strain-hardening zone after a small stress drop. In contrast, samples with 1.2 mm walls thick experience an increase in strain. The failure mechanism is happening in the outer supporting wall, making the structure weaker.

The triangle sample with 6 mm walls and 85% infill had the best plateau zone with the least stress fluctuations among all PLA+ samples. The triangle structure had strong bonds at corners, creating a robust structure to avoid a sudden collapsing of bonds through elastic deformation, thus no unexpected load drops and no tears in the vertical walls are noticed. The structure became stretch-dominated at densification, leading to a sharp increase in hardening modulus.

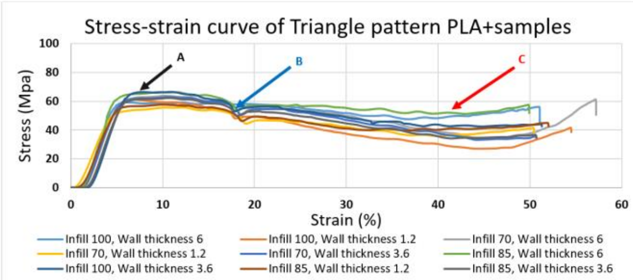


Fig. 2. Compression behavior of the 3D printed samples: Characteristic compression stress-strain curves of Triangle pattern for PLA.

The modulus of elasticity (E) is a critical property of solid materials, indicating stiffness and the relationship between force and elongation. It measures material deformation caused by a load. As elastic moduli decrease, elongation increases. Elastic objects resume their initial shape after load removal. As shown in Figure 3a for the triangle pattern, the sample with a wall thickness of 6mm and an infill percentage of 100% exhibited the highest modulus of elasticity among all PLA+ samples.

SEA evaluates the performance of 3D-printed lightweight products under compression resistance, which indicates the ratio of EA to the mass unit. As shown in Fig. 3b, wall thickness has the highest impact on SEA, enabling a consistent and stable crushing response. Outward global deformation prevents early crashing at interfaces, while outer vertical wall thickness limits excessive deformation. Increasing wall thickness improves SEA capacity. The triangle pattern provides a satisfactory equilibrium between energy absorption and stiffness properties, which are typically antagonistic.

CFE measures the consistency and stability of collapsing force during loading. A high CFE reduces potential damage and scattered acceleration. As shown in Fig. 3c, 6mm wall thickness samples have a clear and stable CFE trend. CFE increases as the infill percentage increases from 70% to 100%. For 6mm wall thickness 3D-printed PA, infill percentage minimally impacts CFE. A 70% infill percentage and 6mm wall thickness sample have a lower CFE (0.74) than those with 85% (0.81) and 100% (0.87) infill percentages.

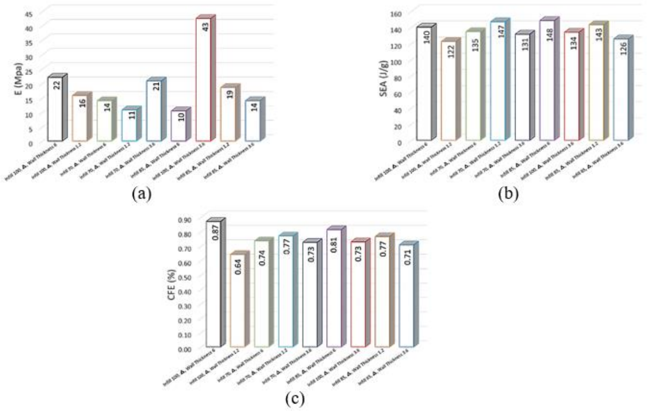


Fig. 3. Graphical comparison of PLA+ samples under compression: (a)modulus of elasticity (E), (b)specific energy absorption (SEA), and (c) crushing force efficiency (CFE).

3.1.2Rectilinear pattern samples

The rectilinear pattern collapses along its axis in two ways: stable for some samples and unstable (catastrophic) for others. The stress-strain curves and collapse modes are similar in the first phase for both types: an elastic region until the maximum stress (a), then a sudden collapse and a sharp stress drop. The specimens with catastrophic collapse stop here (such as Samples with 1.2 mm outer wall and 70% or 85% infill) while those with progressive collapse keep a decreasing stress level until densification onset (b). In the final stage, the load increases because of the sample's densification by the folding of the sample walls (c).

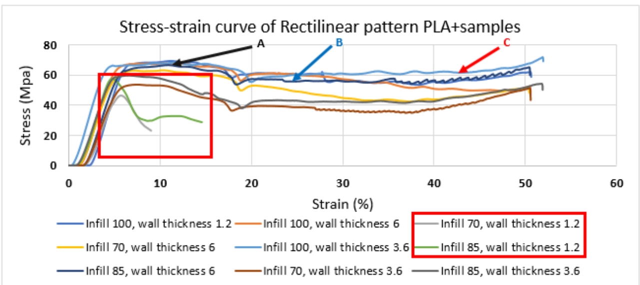


Fig. 4. Compression behavior of the 3D printed samples: Characteristic compression stress-strain curves of Rectilinear pattern for PLA+.

Figure 5 shows the crashworthiness factors (E, SEA, CFE) calculated from the stress-strain responses. The rectilinear pattern was slightly stronger but less stable than the triangle pattern, especially at low infill percentages and small wall thicknesses. The wall thickness affects the sliding effect of samples more than infill percentage. For PLA+, the sample with 70% infill and 1.2 mm outer wall had the lowest E (9 MPa), SEA (14 J/g), and CFE (0.50%).

The triangle has higher strength than the rectilinear pattern due to easier internal structure separation and sliding in small wall thickness rectilinear samples. Samples with 70% and 85% infill and 1.2 mm wall had significant sliding effects and high deformation resistance, as shown by their large height after unloading. In contrast, 85% infill and 6mm wall thickness samples had stable and uniform bulking without noticeable sliding. Disregarding 100% infill samples, which can hide the effects of infill percentage and wall thickness, the PLA+ sample with 85% infill and 6mm wall thickness had the highest values for E (22 MPa), SEA (150 J/g), and CFE (0.87%).

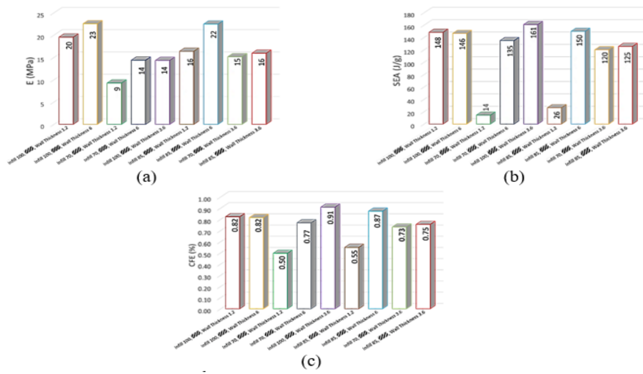


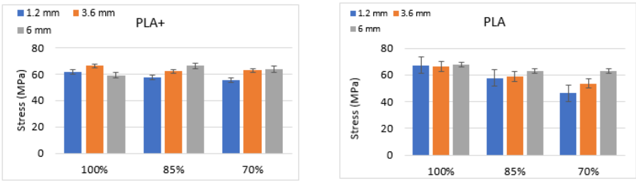
Fig. 5. Graphical comparison of PLA+ samples under compression: (a) modulus of elasticity (E), (b) specific energy absorption (SEA), and (c) crushing force efficiency (CFE).

3.1.3Effect of Outer Wall Thickness on Compression Strength.

The effect of Outer Wall thickness cannot be clearly observed in solid or (100% infill samples), so the impact of layer thickness was noticed for samples of 70% and 85% infill percentage. The compression strength of PLA improved by 15% for the triangle and 37% for the rectilinear pattern when the Outer Wall thickness increased from 1.2 mm to 6 mm at a 70% infill percentage, as shown in Fig. 6.

3.1.4Effect of Infill Percentage on Tensile Strength.

Figures 6 show that compression strength increases with an increase in infill percentage. The highest increase in compression strength was 46% (PLA+ - Rectilinear pattern) and 11% (PLA+ - Triangle pattern) from 70% to 100% infill percentage at 1.2 mm outer wall thickness, the thinnest of the three. The smaller air gap and higher density reduce deformation probability. Stronger bonding between layers from smaller air gaps also affects this behavior. The results of triangular and rectilinear patterns in PLA of other wall thicknesses differ from the 1.2 mm wall thickness results. This confirms that wall thickness affects compression strength more than infill percentage.



(a) (b)

Fig. 6. Comparison of the compression stress results of (a) triangular and (b) rectilinear pattern samples.

3.2Impact properties

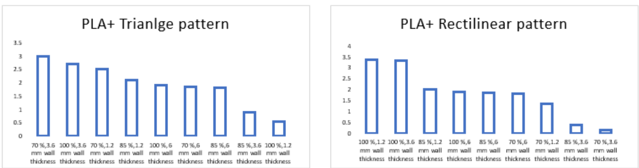
3.2.1Triangular pattern samples

Figure 7 shows that wall thickness significantly influences impact strength in triangular pattern samples, with noticeable anisotropy at higher wall thicknesses. Infill percentage has a smaller effect on impact strength compared to wall thickness, contrary to expectations.

Impact resistance varies with wall thickness and infill percentage. High infill restricts crack propagation, increasing impact resistance. The crack first passed through the triangle pattern's sharp corners after overcoming the wall thickness. The wall thickness and then the infill restricted the crack. High wall thickness enhanced impact resistance. This was because fewer infill layers were needed for the total sample thickness with higher wall thickness. Thus, fewer bonds among layers (potential failure sites) improved impact damage resistance (Fig. 7a). The sample with 70% infill percentage and 3.6 mm wall thickness had the highest impact strength (2.99 kJ/m2). The sample with 100% infill percentage and 1.2 mm wall thickness had the lowest impact strength (0.532 kJ/m2).

Rectilinear pattern samples

Figure 7b shows that impact strength of rectilinear pattern samples depends significantly on infill percentage. Samples with high infill have the best impact strength, while wall thickness has a minor effect. The PLA+ sample with the highest percentage of infill (100%) and a small wall thickness of 1.2 mm had the highest impact resistance (3.3515 kJ/m2).



(a) (b)

Fig. 7 Impact strength results of (a) triangular and (b) rectilinear pattern samples.

4Conclusion

This study investigated the effect of wall thickness and infill percentage on the compression and impact strength of PLA+ 3D-printed samples with triangular and rectilinear patterns. The results showed that wall thickness was a critical parameter for both patterns, while infill percentage had a minor effect for the triangular pattern and a major effect for the rectilinear pattern. The triangular pattern also exhibited a stable crushing mechanism, with no sudden collapse. The highest compression and impact strength for the triangular pattern were achieved by the samples with 6 mm wall thickness and 85% infill (25 MPa and 2.99 kJ/m^2, respectively), while the lowest values were observed for the samples with 1.2 mm wall thickness and 70% or 100% infill (9 MPa and 0.532 kJ/m^2, respectively). These findings suggest that wall thickness and pattern type are important factors for optimizing the mechanical performance of 3D-printed PLA+ structureS.

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