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Influence of 3D-Printing Parameters on Flexural Strength of PLA Plastic Products

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Abstract

3D-printing technologies, also known as AM (additive manufacturing), are playing an important role in the fourth industrial revolution. Among the 3D-printing technologies, Fused Deposition Modeling (FDM) is the most popular. FDM is widely employed to produce components by heating, extruding, and depositing filaments of thermoplastic polymers. The properties of FDM-produced parts are significantly influenced using the processing parameters. These processing parameters have conflicting advantages that need to be investigated. In this study, the process parameters' effect on the flexural properties of components produced by the FDM technique is investigated using polylactic acid (PLA). The vertical shell, solid layer top, temperature extruder, infill density, and infill pattern are considered in the investigation. It is observed that only one parameter (infill pattern) significantly influences the flexural properties of the model among the considered parameters.

Keywords — *Fused deposition modeling (FDM), polylactic acid (PLA), flexural strength.*

I. INTRODUCTION

Material additive technology (AM) is focused on and popular because of the tremendous benefits it offers. 3D printing, a type of additive manufacturing, is a rapidly advancing digital manufacturing technique that produces parts in a layered fashion. The technology has advantages over conventional manufacturing techniques, including being able to produce very complex geometries without any tooling, as well as consolidated (integrated) functional parts, lattice structures, and multi-material (graded-material) components [1]. Among the different types of additive manufacturing (AM) techniques, fused deposition modeling (FDM) is a process in which thermoplastic filaments are melted, extruded, and deposited.

Since several processing parameters influence the mechanical properties of parts manufactured *via* the FDM process, recent research has focused on studying these parameters. Christiyan et al. [2] investigated the effect of process parameters on the mechanical properties of polylactic acid (PLA) and how a small layer thickness can improve the material's mechanical properties. Chacón et al. [3] studied the effect of build orientation, layer thickness, and feed rate on the flexural properties of polylactic acid and concluded that an upright orientation resulted in the poorest mechanical performance, whereas the edge and flat orientations resulted in the highest strength and stiffness. Ziemian et al. [4] studied the dependence of the mechanical properties of PLA parts produced by FDM on the raster orientation. They concluded that the mechanical properties display anisotropic behavior with the orientation of polymeric molecules' rasters and directionality. Durgun and Ertan [5] investigated the influence of different raster angles and build orientations on the surface roughness, tensile strength, and flexural strength of ABSplus-P430 parts and suggested that the build orientation has a more significant effect than the raster angle on the surface roughness and mechanical behavior of the parts. Wu et al. [6] investigated the influence of layer thickness and raster angle on polyether–ether–ketone parts' mechanical properties. They reported that the optimal mechanical properties corresponded to a layer thickness of 300 μm and a raster angle of 0º. Dawoud et al. [7] investigated the effect of raster angle and air gap on ABS materials' mechanical properties, comparing their mechanical properties with injection-molded parts. They suggested that appropriate selection of FDM parameters could result in mechanical properties comparable with those of injection-molded parts. Akessa et al. showed that the highest flexural strength was achieved to build directions using a negative raster air gap. It was also found that using thick filaments for both edge and upright build directions could improve the parts' flexural properties. The above literature shows that FDM technology has made considerable progress in the last three decades regarding investigating the effects of process parameters on FDM materials' mechanical performance. However, further investigation is still required as new systems and materials with different properties are being developed.

Furthermore, studies specific to the mechanical properties of specimens are limited in number, and most of them have considered few process parameters. Investigating the effect of process parameters on mechanical properties is essential for industries that intend to use this material in their product development. This study aims to investigate the effect of FDM process parameters (air gap, raster width, raster angle, contour number, and contour width) on the flexural property of the specimens.

This study concentrates on flexural testing of 3D-printed PLA specimens according to ASTM D790-15. It is structured as follows: In Section 2, the methodology used in the study is discussed, and the results are discussed in Section 3, followed by Section 4 in which some conclusions are drawn.

II. METHODOLOGY

This section provides information regarding the ASTM D790-15 standard used for determining the flexural strength of the FDM 3D-printed specimens. Additionally, the 3D printing manufacturing process and design parameters and the 3D printer (test machine) are described.

Along with developing 3D technology and printers, the development of 3D-printing materials has been no less competitive. The original printing materials that were mainly used were plastic, metal powder, or porcelain powder. Still, along with continued advances in technology, printing materials have become increasingly diverse. They now include plastic, nylon, copper, lead, gold, silver, steel, and titanium and environmentally-friendly material such as food-safe plastics and even edible organic materials like chocolate and sugar glasses. Depending on the 3D product, there are specific materials that can be chosen.

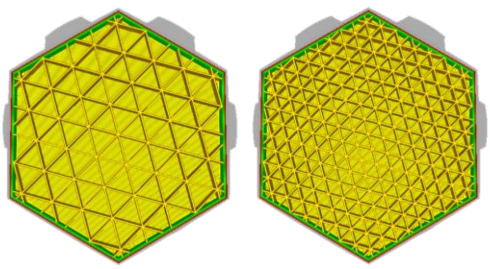

Fig 1: Infill density [8]

In 3D printing, the term “infill” means that the structure is printed inside the object (Figs 1 and 2). It is pressed according to the specified scale and sample that are input into the cutting software. The fill percentage and sample used to affect the print weight, material use, durability, printing time, and decorative properties. Generally, the higher the fill percentage, the stronger the object is printed, but the length is the printing time. A template is used to create a strong and sustainable structure within the printout for any fill percentage. There are a number of different sample options, each with their advantages and trade-offs between the printing time, durability, and material usage.

The 3D-printing software provides sample options for users to choose from. The infill density determines the amount of plastic used on the inside of the printed object. A higher fill density means that the printout inside contains more plastic, resulting in a stronger object.

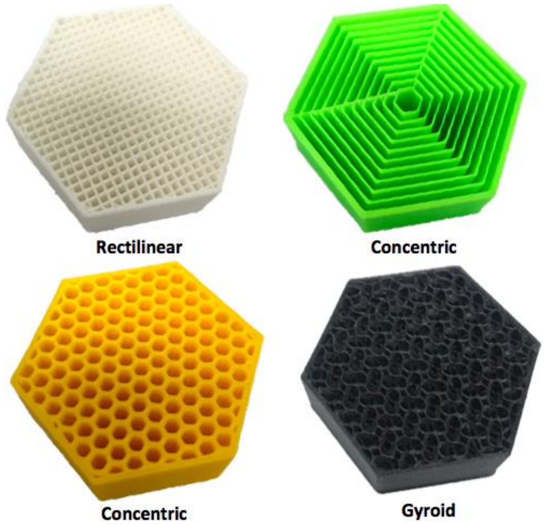

Fig 2: Infill patterns (honeycomb, rectilinear, line, and concentric) [9]

The first step in this study is to design the test specimens for determining strength according to the ASTM D790-15 standard (Fig 3): a 3D model is created in SolidWorks using the geometry and dimensions given in the standard.

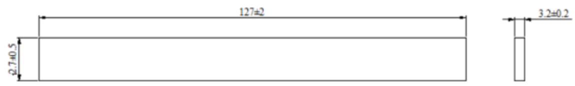

Fig 3: ASTM D790-15 standard

All the specimens are built based on the basic Repetier-Host parameters, and the parameter under test is then varied. As shown in Table 1, the parameters tested were defects in the solid layer top for the specimens A, B, and C; layer height for the specimens D, E, and F; and first layer height for the specimens G, H, and I. Apart from these, the other parameters used to prepare the specimens were left unchanged. These included a vertical shell with a 3 mm thickness, a horizontal shell with 2 mm thickness, layer height with 0.3 mm thickness, a 200°C temperature, and an infill density of 60%. Using the selected process parameters, samples for the investigation were prepared by following the four steps.

1. A three-dimensional (3D) model of the test coupons was prepared using commercial computer-aided design software (SolidWorks) and saved as a stereolithography (.stl) file.
2. The .stl file is then exported to a file on the 3D-printing software (Repetier-Host), and the parameters needed for printing are generated.
3. The sample is produced after adjusting the machine setup (adjusting the building sheet, installing the material, etc.).
4. The constructed sample is removed from the machine, and the support material is also removed if applicable.

Once the specimens' manufacturing was completed, flexural testing was performed to find out their flexural strength and failure strain. A mechanical testing machine (Fig 4) with a constant displacement speed of 5.0% of the strain limit was used for the testing and compression. The specimens were tested to obtain their failure loads and strains, and further statistical analysis was performed to study the mechanical performance of the specimens. This provided crucial information regarding the failure mode and an insight into the ultimate flexural strength values. In the next section, the experimental results, including the stress-strain graphs, are presented. The study ends with a conclusion and recommendations for future work.

TABLE I
Specimen Test Plan

Paramerer	Material		Infill density (%)	Infill pattern
Specimen 1	A	PLA	60	Rectilinear
Specimen 2	B		50	
	C		70	
	D		80	
Specimen 3	G		60	Line
	H			Rectilinear
	I			Honeycomb
	J			Concentric

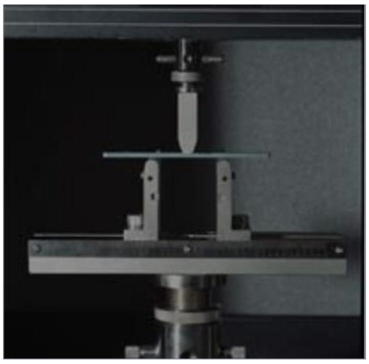

Fig 4: ASTM D790-15 flexural properties

III. RESULTS AND DISCUSSION

The first chart mentioned below (Fig 5) showed the changes in flexural strength when the solid layer top was changed when the number of printed layers on the top was reduced to one layer, the bending flexibility of the parts was reduced by 4.9% (4 Mpa), and when the number of layers on the top layer increased, the flexural strength of the part increased by 6.48%. Therefore, increasing the number of top layers increases the durability of the part.

The second parameter is the infill density (Fig 6). The base specimen is Specimen E, which had a first layer height of 70%, as described in the test plan. Specimen D's flexural strength (50%) and F (80%) are significantly different from those of Specimen H. Specifically, Specimen F shows a 5.3% increase and D a 9.38% decrease compared with that of H. This means that this parameter is important as it can increase the tensile strength. The greater the infill density, the greater is the flexural strength.

A similar chart is also shown for the infill pattern parameter (Fig 7). From the chart, it can be seen that when the pattern type was changed, the flexural strength changed too. Specimen G (line) showed a 15.68% increase, I (honeycomb) 11% increase and J (concentric) 13% increase compared with the base specimen, which was Specimen H (rectilinear). From the investigation results, it can be observed that the pattern type changes the internal structure of the sample, thereby affecting its flexural strength.

The final parameter that was investigated was the perimeter (vertical shell). The chart (Fig 8) shows that when the number of layers in the vertical shell was reduced to two and one (3-1, 3-2), the flexural strength decreased by 11.15% and 4.8%, respectively. In contrast, if the number of layers was increased by one layer (3-4), the flexural strength increased by 5.3% (3.5 MPa). It can be concluded that increasing the number of layers in the vertical shell increases the flexural strength.

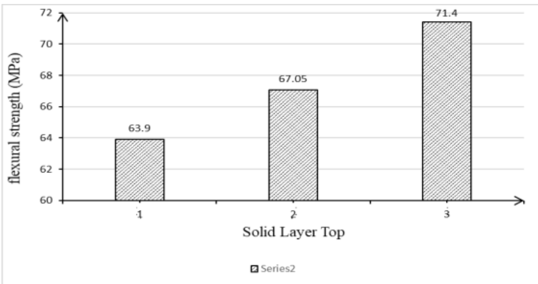

Fig 5: Strength of Specimen 1

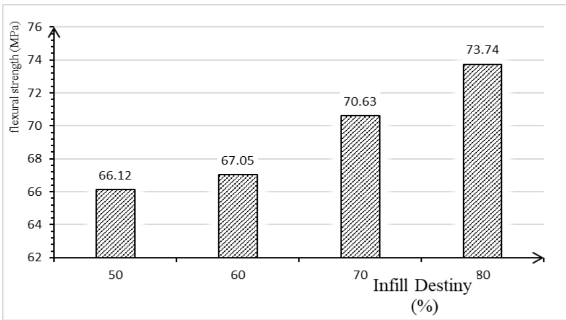

Fig 6: Strength of Specimen 2

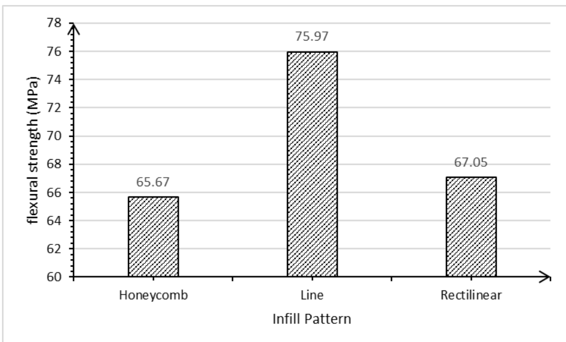

Fig 7: Strength of Specimen 3

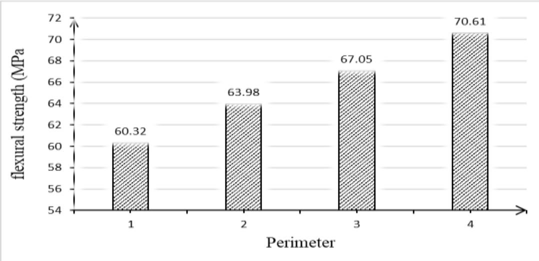

Fig 8: Strength of Specimen 4

IV. CONCLUSIONS

In this study, the effects of FDM process parameters on flexural properties were investigated. Four process parameters, namely the solid layer top, vertical shell, infill pattern, and infill density, were considered in the investigation. Among the parameters considered, the infill pattern's influence was the highest and that of the infill density the lowest. This study's results can be used as data for 3D-printing setup parameters and as the basis for further investigations. Since the current study was limited to the investigation of only four process parameters, it is recommended that in future studies, the number of parameters is increased so that a more accurate result can be obtained.

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