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Fabrication of PLA Structures using Fused Deposition Modelling and Experimental Investigation on Mechanical Properties

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Abstract: Fused deposition modelling is a hastily developing additive production era because of its capacity to construct practical components having complicated geometries. The mechanical contents of a constructed component rely on numerous method parameters. The intention is to symbolize the impact of construct orientation, layer thickness and feed charge on the mechanical overall performance of PLA samples fabricated with a low-value 3-D printer. Tensile and three-factor bending exams are performed to decide the mechanical reaction of the broadcast specimens. From a layer thickness and feed charge factor of view, it's far located that ductility decreases as layer thickness and feed charge boom. In addition, the mechanical contents boom as layer thickness will increase and reduce because the feed charge will increase for the upright orientation. However, the versions in mechanical contents with layer thickness and feed charge are of mild importance for on-edge and flat orientations, besides within side the precise case of low layer thickness.

Keywords: Additive manufacturing, Fused deposition modelling, PLA, Layer thickness.

I. INTRODUCTION

Additive production (AM) technology are one of the maximum promising regions with inside the production of additives. Furthermore, they allow the manufacture of a massive variety of prototypes or purposeful additives with complicated geometries, consisting of the ones received from a topology optimization procedure or generated from a becoming procedure in Computer-Aided Design. AM generation is a totally wide time period encompassing several techniques consisting of Stereo lithography (STL) of a photopolymer liquid, Fused Deposition Modeling (FDM) from plastic filaments, Laminated Object Manufacturing from plastic laminations, and Selective Laser Sintering from plastic or metallic powders. However, the FDM method is of precise hobby because of its affiliation to computing device three-D printers. FDM paperwork a three-D geometry with the aid of using assembling man or woman layers of extruded thermoplastic filament, consisting of acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA), that have melting temperatures low sufficient to be used in soften extrusion in out of doors non-devoted facilities.

II. METHOD

The aim of this look at is to research the mechanical overall performance of PLA samples as proven in Figure 3.1. In this look at, the economic SMARTIE PLA filament fabricated with the aid of using Smart Materials 3-D with a diameter of 1.75 mm was used. Typical values of the principle mechanical contents of PLA substances fabricated with the aid of using FDM era are provided in Table Ⅰ. PLA samples had been fabricated with the usage of a Wilcox computer three-D printer evolved with the aid of using B. Wilcox is a low-value computer printer that makes use of PLA cloth with a 0.4 mm nozzle size. Inbox may be managed with any open-supply software program. In this look at, Cure software program became used to generate G-code documents and to command and manage all the process parameters. There aren't any general check techniques for tensile and flexural houses of elements synthetic in the usage of FDM. In this look at, the ASTM D638and D790methods had been implemented for checking out tensile and flexural specimens, respectively. The geometry of the three-D published specimens had been modelled in the usage of SolidWorks software program exported as an STL report and imported to the three-D printing software program. The fundamental dimensions of the specimens are proven in Figure 1.

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TABLE Ⅰ MECHANICAL PROPERTIES OF PLA MATERIAL

Properties	**PLA**
Tensile Strength (MPa)	15.5-72.2
Tensile Modulus (GPa)	2.020-3.550
Elongation at Break (%)	0.5-9.2
Flexural Strength (MPa)	52-115.1
Flexural Modulus (GPa)	2.392-4.930

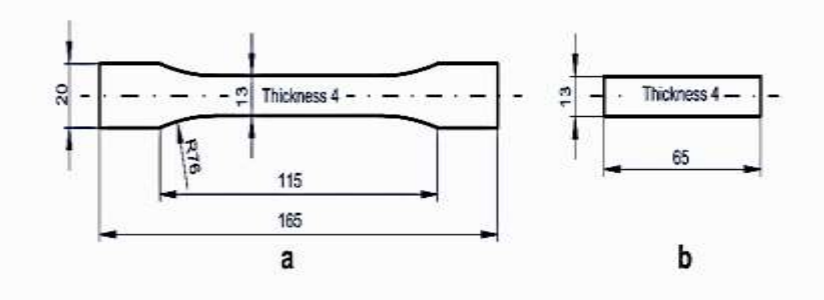

Fig. 1 A sample graph Standard specimens for mechanical testing. (a) Tensile specimen. (b) 3-point bending specimen. Dimensions are in mm

A. *Process Parameters*

The mechanical properties of components fabricated in the use of FDM era depend upon the choice of method parameters. Table Ⅱ outlines the FDM method parameters used on this study. Three construct orientations had been assessed as proven in Figure 2a, flat (F) and On-Edge (O), in which the fused filament deposition is placed with inside the identical path because the pull path and Upright (U) wherein layers had been deposited perpendicular to the pull path. In addition, 4 exceptional layer thicknesses had been taken into consideration to investigate the impact of this parameter. Layer thickness turned into measured with inside the Z course as proven in Figure 2b.

TABLE Ⅱ MECHANICAL PROPERTIES OF PLA MATERIAL

Parameter	**Value**
Build orientation	Flat (F), On-edge (O), Upright (U)
Layer thickness (mm)	Lt = {0.06, 0.12, 0.18, 0.24}
Feed rate (mm/s) (Flow Rate mm3/s)	Fr = {20 (1.9), 50(4.8), 80(7.7)}

These values had been decided on in line with the Wit box 3-d printer variety. The minimal layer thickness that might be decided on with inside the 3-d printer turned into L_t= 0.06 mm. This layer thickness value is decrease than the minimal fee of the variety of layer thickness studied in maximum of the associated research determined with inside the literature, in which the standard minimal layer thickness turned into L_t= 0.1 mm. Furthermore, the impact of feed charge (F_r) on mechanical houses turned into evaluated. Three exceptional feed costs had been taken into consideration: F_r={20, 50, 80} mm/s. The flow rate of the extruded material was changed in order to keep a constant width of the perimeter lines.

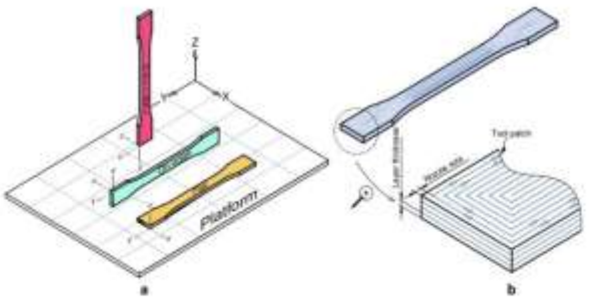

Fig. 2 Process parameters: a) Build orientation. b) Layer thickness and perimeter raster

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The influence of the raster pattern, air gap, raster angle or raster width in the mechanical performance of FDM printed parts has been extensively studied. There is a broad spectrum of infill patterns, making it difficult to analyse the influence of raster patterns. In this study, solid samples filled with a perimeter raster were analysed, which is where the tool paths are the offsets from the perimeter with a distance equivalent to the nozzle size as shown in Figure 8.b Hence, shell thickness was selected long enough to fill the sample with a raster angle of 0 degree. Certain parameters such as air gap, raster angle or temperature were fixed for all the samples in order to focus on the influence of the previous three parameters as shown in Table Ⅲ.

TABLE Ⅲ FIXED PARAMETERS

Parameter	**Value**
Air gap (mm), Raster angle	0, 0 degree. Solid sample. Perimeter Raster
Temperature (degree C)	210

III. EXPERIMENTAL DETAILS

Each sample set consisted of three specimens for a given group of process parameters, with a total of 6 specimens (tensile and flexural specimens). It is well known that moisture absorption adversely affects the mechanical performance of PLA printed materials. Once the vacuum packaged PLA filament was opened, it was stored in a dry boxing order to minimize moisture absorption in the same way as the manufactured specimens prior to testing. Average strength and stiffness values of the mechanical test were taken as the results. Since the physical properties of many materials (especially thermoplastics) can vary depending on ambient temperature, tests were carried out according to the standards for room temperature.

A. *Tensile Test*

The uni axial tensile tests were performed following the standard ASTM D638-10 standard. A 50 kN universal electro-mechanical testing machine with a 5 kN load cell at a fixed loading rate of 2 mm/min was used for both the tensile and 3-point bending tests. This displacement rate was within the proposed ASTM test speed range: D638-10and D790 proposes a test speed range of $1 - 5$ mm/min. The selection of this displacement rate was in agreement with the displacement rate used in other studies. Strain was measured using a MTS 634.14high-performance axial extensometer. The experimental data were processed following the recommendations of the previous standard, for the determination of the maximum tensile strength (σ_t) and the tensile Young's modulus (E). Young's modulus was determined considering the linear part of the stress-strain curve and the slope was estimated by a linear fit. σ_t was calculated as a ratio between the maximum load reached during the test and the cross-sectional area.

B. *Bending Test*

The 3-point bending tests were performed following the ASTM D790-10 procedure using a three point bending test fixture. The radius of the loading nose and the radii of the support noses of the 3-point bending specimen test fixture were 3 mm.

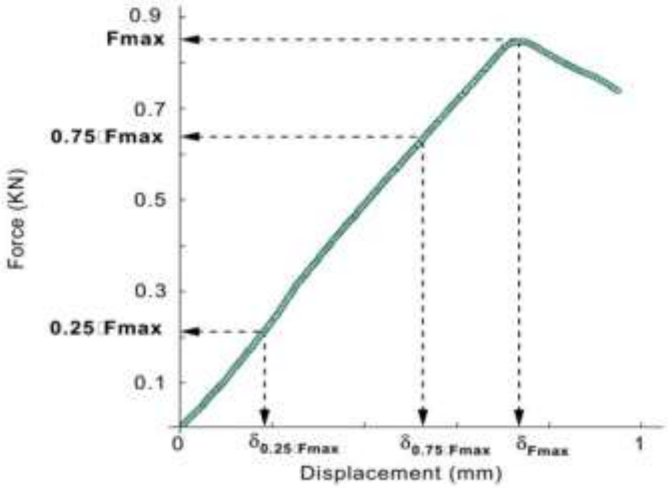

Fig. 3 Procedure for calculating slope *m* of the force-displacement curve

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The flexural modulus of elasticity (E_f) was determined following the previous standard, based on the Classical Beam Theory, supposing that shear effects are negligible. We can define the maximum normal stress σ f in the three-point bending test as

$$\sigma_f = \frac{3PL}{2Wt^2}$$

Where P is the fracture force, L is the support span, w is the width of the specimen, t is the thickness of the specimen and the maximum strain ε of the outer surface at mid-span which was calculated as follows

$$\varepsilon = \frac{6\delta t}{L^2}$$

Where δ is the mid-span deflection. The flexural modulus of elasticity E f is the ratio of stress to the corresponding strain at a given point on the stress-strain curve. Hence, it can be calculated as

$$E_f = \frac{L^3 m}{4Wt^3}$$

Where m is the slope of the secant of the load-displacement curve. The slope m was measured between the 25% and75percent of the maximum load. It is also recommended to prescribe a strain range instead of a load range. If the ultimate strain of the material is higher than 1%, a 0.3 − 0.5% strain range or even higher can be used.

IV. RESULTS AND DISCUSSION

Shore Average and standard deviation of the test results of the maximum strengths (σ_t ,σ_f)and stiffnesses (E, E_f) for the printed PLA samples are tabulated for the tensile tests and for 3-point bending tests. The comparison of the minimum and maximum average values of tensile and flexural strengths (σ_t ,σ_f) and stiffnesses (E, E_f) showed variations between specimens manufactured under different printing conditions in the range of σ_t= [20.2, 89.1] MPa, E = [2765.5, 4409.7] MPa, σ_f= [14.3, 65] MPa, E_f= [1282, 1886] MPa, respectively. In other words, process parameters had significant influence on strength and stiffness properties. These results were in line with those reported in literature for the PLA material manufactured under different printing conditions.

A. *Effects of Build Orientation on Mechanical Properties*

A first glance at the results reveal that the PLA samples exhibited a remarkable anisotropy. Build orientation significantly affected the mechanical properties and, in particular, ductility and failure behaviour. On-edge and flat orientations showed the highest values for maximum tensile and flexural strength and stiffness, while upright orientation resulted in the lowest ones. For example, the maximum tensile strength for the upright orientation $\boldsymbol{\sigma_t}$was about 78% ($\boldsymbol{L_t}$= 0.06 mm, $\boldsymbol{F_r}$= 80 mm/s) to 37% ($\boldsymbol{L_t}$= 0.24 mm,$\boldsymbol{F_r}$ = 20 mm/s) lower than on-edge and flat orientations, whose values were similar. These results have confirmed the observations of previous studies. In the case of the flexural samples, on-edge orientation depicted the highest value for the maximum flexural strength, with an average $\boldsymbol{\sigma_f}$ about 38% ($\boldsymbol{L_t}$= 0.24 mm, $\boldsymbol{F_r}$= 80 mm/s) to 350% ($\boldsymbol{L_t}$= 0.06 mm, $\boldsymbol{F_r}$= 80 mm/s) higher than flat and upright orientations, respectively.

B. *Effects of Layer Thickness on Mechanical Properties*

Layer thickness is directly related to the number of layers needed to print a part and hence to printing time. Thus, manufacturing costs decrease as layer thickness increases. The effect of layer thickness on the mechanical properties due to the build orientation was different for upright samples and on-edge and flat samples. In the case of upright samples, higher layer thickness tended to promote higher strength. These results were in accordance with previous works. This effect cane explained by considering that with increased layer thickness, fewer layers were needed for a given total thickness and, therefore the number of layer bonds was reduced and strength increased. In addition, this trend was heightened when the feed rate increased.

C. *Effects of Feed Rate on Mechanical Properties*

Significant drop-in printing time with increased feed rate, i.e., manufacturing costs decreased as feed rate increased. For the upright orientation, the maximum tensile and flexural strength decreased as the feed rate increased. These results were in agreement with previous findings. In the case of on-edge and flat orientations, the effect of feed rate on the tensile and flexural strength was of slight significance, except in the case of high feed rate (F_r= 80 mm/s) under tensile loading, and two atypical situations for the on-edge oriented samples with L_t = 0.06 mm: the tensile performance with F_r = 20 mm/s and the flexural performance with F_r= 80 mm/s.

D. *Effects of Process Parameters on Printing Time*

As discussed above, printing time was directly related to manufacturing costs and hence it is crucial to bear this in mind. It is also clear from the previous results that printing time was directly related to the build orientation. Upright

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samples had the longest printing time and on-edge samples the shortest one. Furthermore, layer thickness and feed rate were the main process parameters to have the biggest impact on printing time.

V. CONCLUSION

We have studied the impact of construct orientation, layer thickness and feed charge on the mechanical properties of PLA samples fabricated with a low value laptop 3-D printer. Different degrees of the 3 manner parameters have been analyzed: construct orientation (Flat, On-edge, Upright), layer thickness ($\boldsymbol{L_t}$= mm, and feed charge ($\boldsymbol{F_r}$= mm/s). Manufacturing value is without delay associated with layer thickness and feed charge, i.e., printing time decreases as layer thickness and feed charge increase. Tensile and 3-factor bending check collection have been executed to decide the mechanical reaction of the published specimens following the ASTM well-known recommendations.

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