Compression Behavior of FFF Printed Parts Obtained by Varying Layer Height and Infill Percentage

Dragos Gabriel Zisopol
Mechanical Engineering
Petroleum – Gas University
Ploiesti, Romania
zisopol@zisopol.ro

Ion Nae
Mechanical Engineering
Petroleum – Gas University
Ploiesti, Romania
inae@upg-ploiesti.ro

Alexandra-Ileana Portoaca
Mechanical Engineering
Petroleum – Gas University
Ploiesti, Romania
alexandra.portoaca@upg-ploiesti.ro

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Abstract-In this research, two polymeric materials, PLA-(polylactic acid) and ABS (acrylonitrile butadiene styrene) were used to 3D print compression samples at 3 layer heights (0.10, 0.15, and 0.20mm) with 3 infill percentages (50%, 75%, 100%). In order to determine the material's behavior under applied crushing loads, 135 samples were fabricated and tested. The built compression PLA specimens were subjected to common annealing treatment just above glass transition temperature and it was proved that the set of 45 samples exhibited higher resistance to the compressive load applied to the material before fracturing by an average of 9.20%.

Keywords-3D printing; annealing; compressive test; post-porcessing treatments

I. INTRODUCTION

Additive manufacturing has a wide range of applications and the advantage of specific application tailored part fabrication. The most common additive layer by layer technology is FFF (Fused Filament Fabrication), which consists in successively depositing filaments layer by layer. In order to meet the physical and mechanical requirements various additive manufacturing processes have been developed and a wide variety of materials have been used and studied with emphasis on compression tests (NiTi shape memory alloys processed via the laser-based directed energy deposition technique [1], fiber-reinforced PLA/TPU (thermoplastic polyurethane) [2], polymeric materials [3, 4], Ni-rich NiTi alloys [5], PA-12 nylons produced by multi-jet fusion technology [6]). Regarding tension or compression loading, significant functional risks are generated by the microstructure of 3D printed materials, characterized by an important degree of anisotropy [1]. However, industrial manufacturing processes aim to eliminate waste and to obtain higher stress, flexibility, and energy absorption. So, besides considering full volume structures, recent researchers make reference on lattice structures [6-9]. Additive manufacturing offers the opportunity to design and create various configurations of lattice structures by controlling relative densities, material components, and microstructure [6, 7, 10]. Similar to subtractive technologies [11-13], several post treatments can be applied to additive manufactured parts depending on the processes used, with the aim to partially reduce porosity and relief internal stress. In this context, the present paper presents compression test results also on a set of PLA samples subjected to thermal treatment [1, 6] that consists in heating materials at a temperature between the glass transition and melting point temperature and by slow cooling in the oven.

II. MATERIALS AND METHODS

A. *Parameter Set Up*

Significant 3D printing parameters have been analyzed in the recent scientific literature:

- raster orientation and printing speed [14],
- layer height and infill percentage [15-18],
- building orientation: flat, on edge, and upright oriented [19, 20].

For this research, the considered parameters were the layer height and the infill percentage, their values are shown in Table I. The material specifications were provided through manufacturers' data sheets and are also depicted in Table I. In this experimental study, the samples were fabricated with three infill percentages, i.e. 50%, 75%, 100% and in order to asset the mechanical characteristics (Table II), compressive tests were conducted made on both considered materials (PLA and ABS). For PLA polymer heat treatment was experimented in order to compare the compressive stress values. The annealing

Corresponding author: Alexandra-Ileana Portoaca

treatment for PLA consisted in maintaining a temperature of 75^{0}C for a period of 3h, succeeded by slow cooling in the oven.

B. Sample Preparation

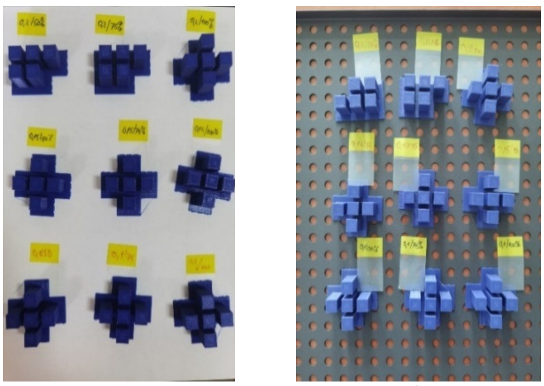
A Raise E2 3D printer was used to fabricate the samples with a volume capacity of 330×240×240mm. The design of the samples, later converted in STL format, was drawn in Solid Edge Software [21] and the slicing parameters, such as internal structure pattern, infill percentage, and layer thickness were adjusted in the Idea Maker software. Samples were X-Z orientated and printed with a bed platform for better adhesion to the printing table as shown in Figure 1.

TABLE I. PRINTED SAMPLE CHARACTERISTICS

Parameters	**Material specifications**	
	PLA	**ABS**
Nozzle diameter	0.40mm	0.40mm
Build orientation	Flat	Flat
Top solid layers	4 layers	4 layers
Bottom solid layers	4 layers	4 layers
Outline/perimeters shell	3 outlines	3 outlines
Internal fill pattern	Lines	Lines
External fill pattern	Rectilinear	Rectilinear
Internal infill angle offsets	45°-135°	45°-135°
Extruder temperature	210°C	240°C
Heated bed temperature	60°C	110°C
Default printing speed	70mm/s	45mm/s
Cooling fans	on	on
Filament diameter	1.75mm	1.75mm
Filament density	1.24g/cm^3	1.04g/cm^3

TABLE II. 3D PRINTED INFILL PARAMETERS

Constant parameters	**Variable parameters**				**Materials**		
Building orientation X, Y	Layer hight (H_s-mm)	Infill procentage (P_u-%)			ABS	PLA AS	PLA AN
Extrusion temperature (T_e)					samples		
Bed temperature (T_p)	0.10	50	75	100	15	15	15
Speed (V_p)	0.15				15	15	15
Filling model	0,20				15	15	15



(a) (b)

Fig. 1. Sample pictures: (a) as built PLA, (b) annealed PLA.

The samples were tested on a Zwick Roell Universal Machine to obtain their compressive stress values. The preload was 20N and the test speed was 10mm/min, according to Plastics — Determination of compressive properties, ISO 604:2002(E) [21].

C. Compressive Test

Sets of 5 specimens were printed for each of the characteristics considered in the current study, as can be seen in Figure 2. The compression tests were done at the Liea laboratory, within ISIM Timişoara, on a MU 400Kn testing machine, type ZD 40/90.

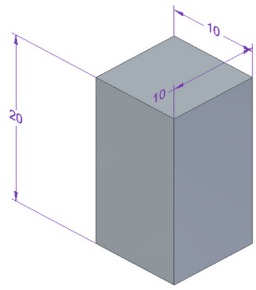


Fig. 2. Geometrical features of the compressive test samples.

III. RESULTS AND DISCUSSION

A. Results

Values and averages of compressive stress are depicted in Tables III-V for each combination of layer height and infill percentage for the as built PLA.

TABLE III. COMPRESSIVE STRESS TEST VALUES OF AS BUILT PLA FOR 0.10 THICKNESS LAYER

Infill, %	**Compressive Stress, MPa**					
	Sample					
	1	2	3	4	5	Average
50%	34	35	34	35	35	34.6
75%	48	48	47	46	46	47
100%	64	62	66	67	98	71.4

TABLE IV. COMPRESSIVE STRESS TEST VALUES OF AS BUILT PLA FOR 0.15 THICKNESS LAYER

Infill, %	**Compressive Stress, MPa**					
	Sample					
	1	2	3	4	5	Average
50%	32	33	31	32	31	31.80
75%	45	45	47	46	45	45.6
100%	65	63	63	63	61	63

TABLE V. COMPRESSIVE STRESS TEST VALUES OF AS BUILT PLA FOR 0.20 THICKNESS LAYER

Infill, %	**Compressive Stress, MPa**					
	Sample					
	1	2	3	4	5	Average
50%	30	30	32	32	29	30.6
75%	43	43	44	43	43	43.2
100%	59	59	60	59	61	59.6

As can be seen in Tables VI-VIII, the compressive stress values of the annealed tested samples are higher, which reveals that annealing has a positive effect in the microstructure of the material, by releasing internal stress and decreasing the porosity of the parts obtained by 3D printing. The thermal annealing post-process technique applied for improving properties of polymer extrusion-based parts has been intensively studied recently [1, 5, 6].

TABLE VI. COMPRESSIVE STRESS TEST VALUES OF ANNEALED PLA FOR 0.10 THICKNESS LAYER

Infill, %	**Compressive Stress, MPa**					
	Sample					
	1	2	3	4	5	Average
50%	39	38	29	39	38	36.6
75%	52	50	52	51	52	51.4
100%	67	67	69	67	66	67.2

TABLE VII. COMPRESSIVE STRESS TEST VALUES OF ANNEALED PLA FOR 0.15 THICKNESS LAYER

Infill, %	**Compressive Stress, MPa**					
	Sample					
	1	2	3	4	5	Average
50%	35	36	37	36	37	36.2
75%	53	52	52	51	51	51.8
100%	71	72	71	71	71	71.2

TABLE VIII. COMPRESSIVE STRESS TEST VALUES OF ANNEALED PLA FOR 0.20 THICKNESS LAYER

Infill, %	**Compressive Stress, MPa**					
	Sample					
	1	2	3	4	5	Average
50%	37	33	34	35	34	34.6
75%	47	47	47	48	48	47.4
100%	69	65	64	64	65	65.4

TABLE IX. COMPRESSIVE STRESS TEST VALUES OF ABS FOR 0.10 THICKNESS LAYER

Infill, %	**Compressive Stress, MPa**					
	Sample					
	1	2	3	4	5	Average
50%	21	22	21	22	23	21.8
75%	60	50	31	55	52	49.6
100%	61	60	63	61	62	61.4

TABLE X. COMPRESSIVE STRESS TEST VALUES OF ABS FOR 0.15 THICKNESS LAYER

Infill, %	**Compressive Stress, MPa**					
	Sample					
	1	2	3	4	5	Average
50%	26	26	27	22	24	25
75%	42	42	46	43	47	44
100%	68	62	33	60	54	55.4

TABLE XI. COMPRESSIVE STRESS TEST VALUES OF ABS FOR 0.20 THICKNESS LAYER

Infill, %	**Compressive Stress, MPa**					
	Sample					
	1	2	3	4	5	Average
50%	31	31	27	31	23	28.6
75%	26	26	45	25	44	33.2
100%	66	18	60	61	60	53

Similar average compression stress results with [20] were obtained for 50% infill: 34.67MPa and 43.67MPa and for 100% infill: 71MPa and 93.34MPa. Values and averages of compressive stress for ABS samples are depicted in Tables IX-XI for each combination of layer height and infill percentage studied in this research. As shown in [23], compressive stress values are scattered due to the variation of the process parameters like orientation, layer thickness, raster angle, raster width, and air gap with an average of 14.63MPa comparable with 50% average ABS values - 21.8MPa. Significant influences regarding the infill percentage can be noticed in the drawn stress-strain curves of as built PLA, annealed PLA, and ABS sample. As assumed, 100% infill percentage samples have the greatest resistance to compressive stress.

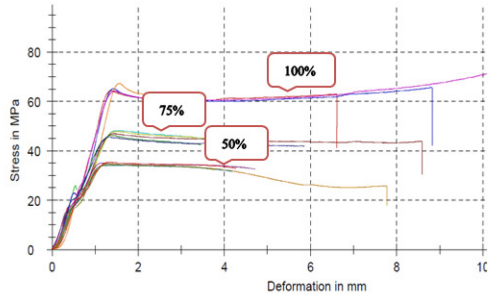


Fig. 3. Compressive stress variation of 0.10 layer thickness of as built PLA.

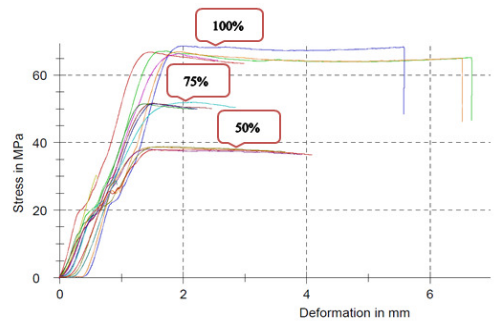


Fig. 4. Compressive stress variation of 0.10 layer thickness of annealed PLA.

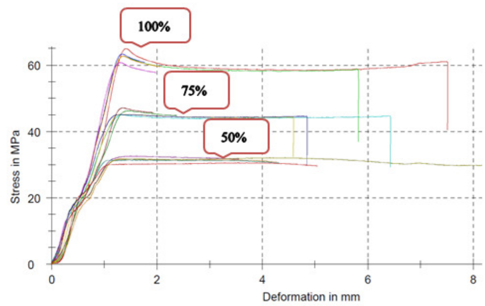


Fig. 5. Compressive stress variation of 0.15 layer thickness of as built PLA.

As can be seen in Figures 3-8 the curves of the annealed set of samples have clearly higher compressive stress supported in the case of failure. The percentage of the average increase in compressive stress of the thermal treated PLA with 0.10mm layer thickness is 3.70%, for the 0.15mm layer thickness the average increase is 13.39%, and for the 0.20mm layer thickness the increase is 10.49%. It is noted that the compressive strength values of the annealed PLA are higher than those of plain PLA (Tables III-VIII). This can be explained by the influence of the annealing treatment that led to the homogenization of the structure and the increase of the adhesion of the deposited layers.

Analyzing the force-deformation diagrams (Figures 3-11) obtained by the test machine following the compression load, the following areas of the load-specific curve can be observed:

- A linear zone - characteristic of the behavior of the material in the elastic domain.
- A convex curve - which corresponds to the yield strength.
- A constant level - which corresponds to the flow zone at which the force remains relatively constant, the deformation increasing significantly.

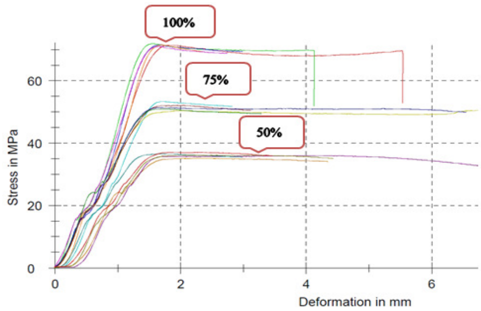


Fig. 6. Compressive stress variation of 0.15 layer thickness of annealed PLA.

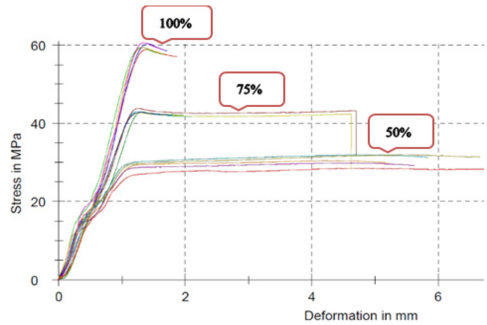


Fig. 7. Compressive stress variation of 0.20 layer thickness of as built PLA.

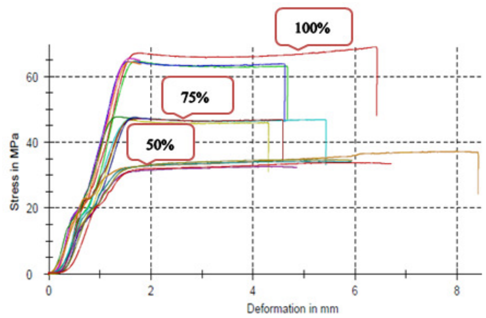


Fig. 8. Compressive stress variation of 0.20 layer thickness of annealed PLA.

After a slight increase in the compression force, the breaking phenomenon occurs (cracks appear in the material structure). This is marked on machine-drawn diagrams by a peak. Then a decrease in force with a minimum is noted on the diagram after which the force increases significantly. This growth is probably produced due to the compaction of the material after the cracks appear. Regarding the ABS material, similar results are revealed in Figures 9-11. Also, the infill percentage has a great emphasis in the character of the stress-strain curves. The curves for ABS with 0.10 layer thickness reveal more instable graphics than the other layer thickness samples, that can be the result of a more brittle behavior also noticed in the tensile behavior studied in [15-18, 24, 25].

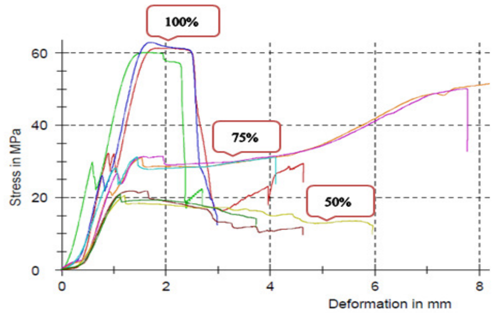


Fig. 9. Compressive stress variation of 0.10 layer thickness ABS.

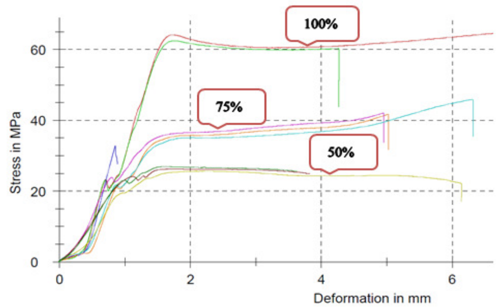


Fig. 10. Compressive stress variation of 0.15 layer thickness ABS.

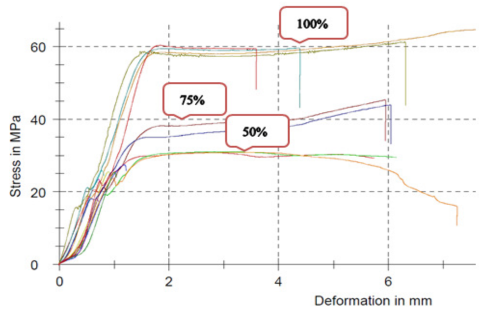


Fig. 11. Compressive stress variation of 0.20 layer thickness ABS.

B. Disscusion

This paper aims to highlight the variation of mechanical characteristics (compressive stress) of annealed PLA 3D and ABS, with different parameters of the printing process. The general mechanical properties of plastics have been introduced to facilitate comparison with other classes of materials or with the same materials but having different chemical compositions. The study presents the experimentally determined values for the compression test of ABS and two types of PLA. The initial mechanical characteristics of the tested materials correspond to the specifications of the filament manufacturers (PLA-Raise and ABS-Verbatim) shown in Table I.

The research plan consisted in fabricating the samples on a Raise E2 3D printer. The considered variable research parameters were infill degree (50, 75, 100%) and layer thickness (0.10, 0.15, 0.20mm). The samples were compression tested on a Zwick Roell universal machine. The preload was 20N, and the test was performed at a speed of 10mm/min, according to ISO 604:2002(E) determination of compression properties. The shape of the researched samples is parallelepiped (Figure 2), having a square cross-section of 10×10mm and 20 mm height. Due to the elasticity of the researched materials, it was adopted that the length (height) of the test piece should be twice the side of the square.

IV. CONCLUSIONS

In the case of a plastic material that does not yield in compression by a break (crack), the compressive strength is arbitrary, depending on the degree of distortion that is considered to indicate complete failure of the material. Situations may arise where plastic specimens will continue to deform in compression until they are reduced to a flat disk, the (nominal) compressive stress increasing steadily, without any well-defined material cracking. For this research, the failure criterion was considered the appearance of cracks on the surface of the studied specimen. According to the experimental research carried out, for one type of material (PLA, ABS) if the thickness of the deposited layer is kept constant with the increase of the degree of filling, the magnitude of the compression stresses increased (Tables III-V). This can be explained by the higher rigidity of the structure formed by 3D printing. To sum up, for each material type (PLA, ABS) and at the same degree of filling, the increase in the thickness of the deposited layer leads to a decrease of the magnitude of the compressive stress (Tables III-V). This can be explained by cracking at the level of the structural blocks, having a height equal to the thickness of the deposited layer.

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