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OPTIMIZATION STUDY ON THE INFILL DENSITY OF 3D PRINTED PETG COMPONENTS

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Abstract

3D printing is a modern manufacturing technique based on the layer-by-layer deposition of material. The technological conditions of printing are of high importance to the resultant function properties of the manufactured components. Other than the function properties the economical footprint of the latter is also of high importance to manufacturers. Due to this it is highly important to find the optimal printing conditions such that the cost of printing is the lowest without compromise on the functional, and particularly the mechanical, properties of the components. In the present work, multiple different components were produced using different infill densities in order to determine the economical-technical-functional relationship and find the best printing conditions. Based on the obtained results three different optimal choices were formed – 10 %; 50-60 %; 95-100% infill density. Increasing the infill density increases the mechanical properties significantly, but also increases production costs. The choice of an optimal infill density has to be made by the component designer emphasizing either mechanical strength or production costs. An infill density of 50-60 % offers a medium ground between both considered component parameters.

Keywords: optimization study, infill density, PETG, 3D printing, additive manufacturing.

INTRODUCTION

Computer numerical control (CNC) is one of the most common methods for fabricating metallic components. This method is based on the subtraction of material from a solid metal block. This process characterizes with high accuracy and speed, however, a large waste of material [1]. Recently, in the last few decades, the possibility of producing both polymeric and metallic components using additive manufacturing based on the layer-by-layer addition of material to a structure, as opposed to subtraction was investigated [2]. Regarding the manufacturing of polymeric materials one of the first and most commonly used methods is fused filament fabrication (FFF). It characterizes with good speed and accuracy [3]. Problems such as poor adhesion and accuracy of printing existed back in the day, however, with new optimized systems these problems were negated [4].

Polymers, due to their unique properties, and low cost have found great application in almost every field of human endeavor – aviation, automotive industry, manufacturing of household items, medicine, packaging, and many more [5]. Due to this the possibility of 3D printing polymeric materials with minimal (ideally none) loss was very well received by both

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industrial branches and the scientific community. However, some of the conventional polymeric material were inapplicable for 3D printing as they were and needed structural modifications. One such material was the well-known and highly used polyethylene terephthalate (PET), which has great mechanical strength, and excellent chemical stability, however, a high melting temperature and high brittleness. To enable the employment of this material in the field of rapid prototyping it was mixed with the glycol modifier 1.4-cyclohexanedimethanol (CHDM), which as a result formed polyethylene terephthalate glycol (PETG), which has a characteristic amorphous structure and lower melting temperature, yet still good mechanical properties, and chemical inertness [6].

Previous investigations on the applicability of PETG in the field of 3D printing have been performed. The studies show that the infill density, the printing orientation, the geometry of the samples, and more all have an effect on the resultant mechanical properties [7, 8]. However, despite the abundant amount of studies regarding the applications of PETG, no real optimization of the infill pattern density has to this day been proposed.

Due to this in this work, the influence of the infill density on the mechanical properties was studied in detail. Based on the obtained results an optimal economic-practical choice of printing conditions was made.

EXPERIMENTAL SETUP

The setup used was based on the fused filament fabrication (FFF) method. The filament is fed through a small diameter extruder nozzle with a diameter of 0.4 mm. The filament is melted and deposited on the printed substrate. An adhesive spray is applied to the print bed in order to guarantee the adhesion between the substrate and the formed component.

In the present work, some of the technological conditions of specimen fabrication were constant. The temperature of the extruder nozzle was 240 ºC, the temperature of the print bed was 80 ºC, the printing speed was 300 mm/s in all cases. Based on previous investigations [9] is was proven that a 90° orientation of the rectilinear infill pattern was optimal for the production of components with the highest tensile and flexural properties. Due to this the same strategy was applied in this case as well.

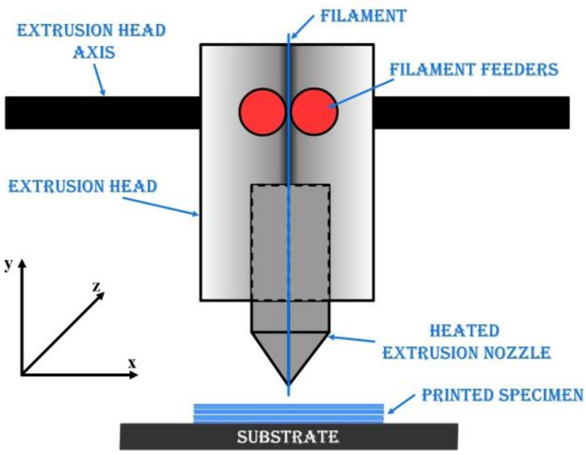

Fig. 1. *Experimental setup for fused filament fabrication.*

In order to find the optimal infill density 19 tensile test, and 19 flexural test samples were produced labeled as A1-A19, and B1-B19, correspondingly. The infill density was varied from 10 % up to 100 % with a 5 % step. The print time, the mass, and the total print cost of the tensile and flexural test samples are summarized in tables 1 and 2. The print cost includes the cost of the material and the cost of the electrical power. The cost of the material was estimated to be 0.02 €/g based on local market prices. The used printer's rated power output is 350 W. The electrical power cost was based on the daytime tax of electrical energy in Bulgaria, which as of 1st of January 2025 in the time period from 07:00 h to 23:00 h is 0.09 €/kWh.

Table 1. Tensile test samples print time, weight, and cost.

Sample (density)	Print time	m, g	Total print cost, €
A1 (10 %)	14m38s	7.22	0.151640
A2 (15 %)	15m01s	7.37	0.154840
A3 (20 %)	15m54s	7.86	0.165302
A4 (25 %)	16m42s	8.24	0.173719
A5 (30 %)	17m31s	8.69	0.183146
A6 (35 %)	17m59s	8.96	0.188389
A7 (40 %)	18m48s	9.42	0.197816
A8 (45 %)	19m33s	9.82	0.206207
A9 (50 %)	20m24s	10.30	0.216651
A10 (55 %)	21m10s	10.69	0.225052
A11 (60 %)	21m58s	11.14	0.234469
A12 (65 %)	22m26s	11.41	0.239713
A13 (70 %)	23m13s	11.86	0.249122
A14 (75 %)	23m59s	12.24	0.257522
A15 (80 %)	24m49s	12.72	0.266957
A16 (85 %)	25m33s	13.12	0.275340
A17 (90 %)	26m21s	13.58	0.285758
A18 (95 %)	27m02s	13.98	0.293115
A19 (100 %)	28m02s	14.20	0.298637

Table 2. Flexural test samples print time, weight, and cost.

Sample (density)	Print time	m, g	Total print cost, €
B1 (10 %)	6m14s	2.62	0.0617
B2 (15 %)	6m18s	2.69	0.0632
B3 (20 %)	6m23s	2.88	0.0671
B4 (25 %)	6m28s	2.95	0.0687
B5 (30 %)	6m39s	3.13	0.0723
B6 (35 %)	6m49s	3.21	0.0744
B7 (40 %)	7m10s	3.39	0.0785
B8 (45 %)	7m19s	3.45	0.0799
B9 (50 %)	7m40s	3.64	0.0843
B10 (55 %)	7m47s	3.71	0.0859
B11 (60 %)	8m07s	3.89	0.0899
B12 (65 %)	8m16s	3.96	0.0916
B13 (70 %)	8m37s	4.15	0.0959
B14 (75 %)	8m46s	4.22	0.0976
B15 (80 %)	9m04s	4.39	0.1014
B16 (85 %)	9m13s	4.46	0.1031
B17 (90 %)	9m33s	4.65	0.1073
B18 (95 %)	9m42s	4.72	0.1089
B19 (100 %)	10m02s	4.86	0.1123

The macrostructure of the samples was investigated using an optical microscope Drawell MIT 300/500 series.

Tensile tests were performed using the ZwickRoell Vibrophore 100 unit according to the ISO 527-1:2019 [10] standard. The shape, size, and dimensions of the samples were discussed in a previous work [9]. A static strain mode was used with a pre-load of 0.1 MPa and a speed of testing of 50 mm/min.

Using the same unit flexural tests were performed according to the ISO 178:2019 standard [12]. A speed of testing of 1 mm/min was used. The shape and size of the samples are given in the following work [9].

RESULTS AND DISCUSSION

Tensile testing is highly important as it serves as a tool to describe the characteristics of a material based on numerical data. Also using this test, the close relationship between the technological conditions of PETG components built using FFF and the physical properties can be established. The results of the tensile experiments are summarized in table 3. A large number of experiments were performed for each individual set of samples (at different infill densities). The samples, as mentioned previously, were denoted as A1-A19, which corresponds to the indexing of the samples during the production stage. The obtained results vary from 17.6 MPa to 34.7 MPa, depending on the sample. At face value the increase of the tensile properties with the increase of the infill density seems linear and logical, based on common material science knowledge [13]. A more in depth analysis though shows that four different zones of interest are present in the data. The last can be divided based on the obtained values as follows: up to 20 MPa; from 20 up to 25 MPa; from 25 to 30 MPa; from 30 to 35 MPa. In order to select an optimal choice from each group of samples the following criteria will be used (in order of importance): tensile strength; total print cost; print time.

Based on that in the first group of samples (with tensile strength up to 20 MPa) surprisingly the best price/performance ratio had the sample prepared with a 10 % infill density with a tensile strength of 19.6 MPa, which is about the same of that of the component prepared with a 30 % infill density. These results are superb from an economic standpoint since that sample also characterizes with the lowest total print cost. This is not only favorable for manufacturer’s costs, but also correlates to the lowest amount of material used, thus this choice is the most ecologically friendly one as well.

Considering the second group of samples (with tensile strength up to 25 MPa) the optimal choice is believed to be applying an infill density of 60 % when 3D printing PETG components using FFF. In this case a maximum tensile strength of 23.2 MPa was obtained.

The optimal choice from the third group (with tensile strength up to 30 MPa) was using an infill density of 85 %. The obtained maximum tensile strength was 28.1 MPa. In this case that is the maximum infill density from that group, so the price of production is higher, however, this choice is completely rational since the first and most important quality required for printed components is excellent strength and functional properties.

In the last group (with tensile strength up to 35 MPa) the most obvious choice is building components using 100 % infill density, which resulted in the highest reported tensile strength amongst all sample – 34.7 MPa. In this case, the functional properties are fully prioritized and production cost is completely negated.

Table 3. Tensile test results.

Sample (density)	**R_m, MPa**	**ε_m, %**
A1 (10 %)	19.6 ±1.0	1.9 ±0.09
A2 (15 %)	17.6 ±0.8	1.5 ±0.07
A3 (20 %)	18.2 ±0.8	1.6 ±0.08
A4 (25 %)	18.9 ±0.9	1.5 ±0.07
A5 (30 %)	19.5 ±1.0	1.6 ±0.08
A6 (35 %)	18.4 ±0.9	1.6 ±0.07
A7 (40 %)	22.6 ±1.1	1.6 ±0.06
A8 (45 %)	20.5 ±1.0	1.5 ±0.08
A9 (50 %)	21.5 ±1.1	1.4 ±0.07
A10 (55 %)	22.5 ±1.1	1.4 ±0.07
A11 (60 %)	23.2 ±1.2	1.4 ±0.08
A12 (65 %)	23.1 ±1.1	1.4 ±0.06
A13 (70 %)	27.8 ±1.4	1.5 ±0.08
A14 (75 %)	26.4 ±1.3	1.4 ±0.08
A15 (80 %)	27.5 ±1.3	1.5 ±0.07
A16 (85 %)	28.1 ±1.4	1.4 ±0.07
A17 (90 %)	30.8 ±1.5	1.5 ±0.06
A18 (95 %)	33.6 ±1.6	1.6 ±0.04
A19 (100 %)	34.7 ±1.6	1.6 ±0.05

Of course as mentioned in a previous study [9] it is important to find technological conditions of 3D printing that favor all (or as much as possible) mechanical properties of the components. Another very important characteristic of structural components are their flexural properties. The flexural properties of 3D printed PETG samples using the FFF technology were determined and the obtained results are shown in table 4. The samples were all denoted from B1-B19, which corresponds to the samples described previously, produced with a variable infill density from 10 % to 100 %. In this case the results varied from 33 MPa to 51.3 MPa, depending on the samples. Again the samples can be grouped based on their flexural strength. There are two notable groups of samples: with flexural strength up to 40 MPa and with flexural strength up to 50 MPa. In order to select an optimal choice from each group of samples the following criteria will be used (in order of importance): tensile strength; total print cost; print time.

Regarding the first group of samples (with flexural strength up to 40 MPa) the optimal choice seems to be the sample prepared with 50% infill density. In this case good price/ performance was achieved with a maximum flexural strength of 38.1 MPa.

Considering the second group of samples (with flexural strength up to 50 MPa) the optimal choice is building components with 95 % infill density. This set of samples had a maximum flexural strength of 51.3 MPa.

Table 4. Flexural test results.

Sample (density)	**R_{fm}, MPa**	**ε_{fm}, %**
B1 (10 %)	33.2 ±1.7	6.1 ±0.30
B2 (15 %)	33.0 ±1.6	6.4 ±0.32
B3 (20 %)	35.4 ±1.8	6.2 ±0.31
B4 (25 %)	33.8 ±1.7	7.1 ±0.35
B5 (30 %)	35.6 ±1.8	5.9 ±0.29
B6 (35 %)	36.3 ±1.8	6.3 ±0.31
B7 (40 %)	36.0 ±1.9	5.8 ±0.32
B8 (45 %)	37.4 ±1.9	6.1 ±0.27
B9 (50 %)	38.1 ±2.0	5.8 ±0.33
B10 (55 %)	40.3 ±2.0	6.3 ±0.31
B11 (60 %)	40.7 ±2.0	5.4 ±0.31
B12 (65 %)	41.2 ±2.2	6.5 ±0.30
B13 (70 %)	43.6 ±2.1	6.1 ±0.29
B14 (75 %)	43.6 ±2.2	6.1 ±0.33
B15 (80 %)	45.7 ±2.3	6.0 ±0.29
B16 (85 %)	46.9 ±2.5	5.9 ±0.28
B17 (90 %)	48.6 ±2.4	6.6 ±0.31
B18 (95 %)	51.3 ±2.5	5.7 ±0.32
B19 (100 %)	50.4 ±2.4	5.6 ±0.32

Studying the results of both experiments a good relationship between the tensile and flexural properties of the samples can be seen. Evidently, the infill density influences the flexural properties more directly due to their more linear increase. In that case only two notable zones of interest were selected, whereas in the case of the tensile test samples more notable zones were detected. In either case three optimal choices for the infill density of 3D printed components using FFF can be favored: building components with a 10 % infill density; building components using 50-60 % infill density; building components using 95-100 % infill density. This also correlates excellently with economic and ecological reasoning. The emphasis on the last is determined based on the requirement for structural integrity of the components and the environment they will be subjected to. Higher strength demand favors higher production and material costs, but lower production and material costs result in lower strength. Regardless the obtained results for the lowest infill density of 10 % are nothing less than surprising. Considering this these components can be used in special lightweight applications where special emphasis is paid to lightweight constructions with marginal strength.

CONCLUSION

During the present research a number of conclusions were drawn such as:

1. Increasing the infill density is an effective method for increasing the mechanical properties of 3D printed PETG samples using FFF;
2. The increase in the mechanical properties is more linear concerning the flexural strength of the samples;
3. The highest tensile strength obtained was 34.7 MPa and the highest flexural strength obtained was 51.3 MPa, both obtained at 95 – 100 % infill density;
4. Three optimal infill densities were selected based on the mechanical properties and economic considerations – 10 %; 50–60 %; 95–100 %.

Lowering the density lowers the production costs, but at the expense of the mechanical properties. Increasing the infill density increases production costs, but also increases the mechanical properties significantly. Based on the present results an optimal choice can be made regarding the correct infill density of 3D printed PETG samples using an FFF technology based on the application.

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