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CORRELATION OF PRINTING SPEED AND LAYER HEIGHT WITH THE GEOMETRICAL ACCURACY OF FDM-FABRICATED PETG RESOLUTION RIBS

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Abstract: *PETG (Poly Ethylene Terephthalate Glycol) is used in Fused Deposition Modeling (FDM), as it gives excellent layer bonding. Many different process parameters affect the final object, so they should get correlated with the mechanical and geometrical properties of the printed PETG. In the bibliography, most studies focus on the mechanical properties of FDM products, whereas fewer are the studies of geometrical accuracy. In this paper, 6-ribs PETG features were FDM-fabricated, by following the ISO ASTM 52902-2021 standard. The ribs had a wall thickness of 6 mm, 5 mm, 4 mm, 3 mm, 2 mm, and 1 mm and were created with printing speeds of 20 mm/s, 50 mm/s, and 80 mm/s and layer heights of 0.2 mm, 0.25 mm, and 0.3mm. Then, they were measured with a handheld caliper, statistically analyzed, and commented.*
Keywords: *Fused Deposition Modeling (FDM); Poly Ethylene Terephthalate Glycol (PETG); Resolution ribs; Printing speed; Layer height; Geometrical accuracy of ribs' wall thickness; Statistical analysis.*

1. INTRODUCTION

The thermoplastic resin Polyethylene Terephthalate Glycol (PETG) is a member of the polyester family [1]. PETG is created when Glycol and the well-known polyethylene terephthalate (PET) are combined [2]. This combination gives PETG exceptional chemical resistance, flexibility, durability, and strength, making it a material that is far superior to other commercial polymers like ABS and PLA [3]. Other noteworthy characteristics of PETG include its minimal moisture absorption, light weight, recyclability, and UV radiation resistance. As a result, the Regulation (EC) No. 1935/2004 of the European Parliament classifies the substance as "generally safe". Because of this, PETG is frequently used in food and beverage containers, cosmetics packaging, and medical and pharmaceutical applications (implants, packaging of medical and pharmaceutical devices) [1,4]. Additionally, it should be remembered that PETG-filament is the perfect material for 3D printing because it prints quickly and emits little smell [5].

The Fused Deposition Modeling (FDM) technique is a popular 3D printing technique that produces thermoplastic materials including PETG, PLA, and ABS. FDM uses a nozzle on the 3D printing platform to extrude thermoplastic filament that has been heated to its melting temperature in a reservoir [6]. The mechanical characteristics and geometrical accuracy of the finished product are influenced by a number of parameters in FDM. The printing speed, layer height, build orientation, infill density and pattern, raster angle, extrusion temperature, and nozzle diameter (the diameter of nozzle impacts the drop of pressure along the liquefier. To maintain a consistent flow of the extruding material usage of an optimum nozzle diameter is necessary) are some of the most important variables [7,8]. To make accurate predictions of the outcomes of any FDM process, it is therefore important to connect all these characteristics with the mechanical and geometrical behavior of the finished products.

This will enable FDM to be widely used in the industry. On the other hand, there is not yet much literature on the dimensional accuracy of FDM-printed items. The impact of raster angle, part orientation, layer height, air gap, and raster width on the dimensional accuracy of ABS specimens created using FDM was examined by Mohanty et al. [9]. The outcomes demonstrated that for 30^o part orientation, 0.127 mm layer height, 30^o raster angle, 0.004 mm air gap, and 0.5064 mm raster width, the dimensional accuracy is maximized. Additionally, it was proved that the most important factor for dimensional accuracy was part orientation. Agarwal et al. [10] investigated the dimensional accuracy of ABS specimens manufactured with FDM at various wall thicknesses, infill densities, build plate temperatures, print speeds, layer heights, and extrusion temperatures. They concluded that between these six parameters the most important variables for dimensional accuracy are layer height and printing speed. For relatively simple models without the need for supports or use of two filaments, the best dimensional precision is specifically achieved by using high printing speeds and low layer heights. Mwema et al. [11] investigated the dimensional accuracy of PLA specimens that were FDM printed in diamond, square, round, hollow, and S shapes. The thickness of the S-shaped specimens showed the highest dimensional errors, while the diameters of the circular parts showed the lowest. With an FDM printer, Hanon et al. [12] manufactured PLA cylinders and dogbones. Different print orientations, raster angles, and layer heights were used to make the samples. Dog bones (width and thickness) and cylinders (diameter and length) both have dimensions with up to 98.81% accuracy. The layer height parameter was also discovered to have the greatest impact on dimensional accuracy. Printing PLA cubes with various infill patterns and densities using FDM, Maurya et al. [13] tested the dimensional accuracy of the cubes. It was discovered that hexagonal infill patterns and 50% infill density provide improved dimensional accuracy. According to the publications mentioned above, some research attempt to relate FDM parameters to the precision of the final ABS and PLA products' dimensions. Although, the literature regarding the correlation of printing parameters with the dimensional accuracy of ABS and PLA is extending, the research on PETG is still very limited. However, the results regarding the PLA and ABS cannot be transferred to PETG, so individual investigation focused on PETG should be conducted.

The full bibliography on the mechanical characteristics of PETG printed by an FDM machine is also available at the same time. The impact of feed rate, infill density, and layer height on the flexural and tensile strength of PETG produced by FDM was investigated by Durgashyam et al. [14]. The findings demonstrated that low layer heights, high infill densities, and medium feed rates produce the greatest tensile qualities, while low infill densities, low layer heights, and medium feed rates produce the best flexural properties Additionally, layer height has a more significant impact on flexural and tensile strength than feed rate and infill density. Yadav et al. [15] investigated the tensile strength of ABS, PETG, and 50%ABS-50%PETG specimens that were FDM produced with various infill densities, extrusion temperatures, and part densities. The findings demonstrate that the tensile strength is influenced by the extrusion temperature and infill density in the same manner. Additionally, PETG material outperformed ABS or 50% ABS/50% PETG in terms of tensile strength under particular conditions. The impact of infill density on the tensile strength and surface roughness of PETG specimens manufactured using FDM was investigated by Srinivasan et al. [16]. The results of the studies demonstrated that as infill density is increased, tensile strength is increased and surface roughness is decreased. Different printing parameters were used by Khosravani et al. [3] to print PETG samples in the shape of dumbbells using FDM (raster angle, raster width, and layer height). According to uniaxial tensile tests, cohesive failure was the most common type of failure, and 0.2 mm was the ideal layer height for the maximum fracture load. However, according to the detailed review work [17], these studies correlate the process parameters only to the mechanical properties and not to the dimensional precision. The reason these investigations were presented into the current paper is that these studies are very useful, as they can be used as guidance regarding the process needed to be followed in order to create the PETG parts for the current experiments. Although, Santana et al. [2] correlated the process parameters of deposition strategies and number of perimeters to the dimensional accuracy, still the correlation of all the other process parameters with the dimensional precision of the produces FDM object is uninvestigated. Due to this and the fact that PETG is a material that is frequently used in the industry, it is vital to conduct studies on PETG to relate the FDM-printing parameters to the final products' dimensional precision.

In this study, PETG resolution ribs were printed with FDM, according to the ISO ASTM 52902-2021 standard, with different nominal wall thicknesses (6 mm, 5 mm, 4 mm, 3 mm, 2 mm, and 1 mm), printing speeds (20 mm/s, 50 mm/s and 80 mm/s) and layer heights (0.20 mm, 0.25 mm and 0.30 mm). The specimens' wall thicknesses were measured with a caliper and the results were statistically analyzed. This study aims to determine which combination of the above process parameters gives an optimum process precision (combination of both good accuracy and good repeatability) for creating PETG ribs into this specific 3D-printer used for the experiments (Creality Ender 3 3D Printer).

2. EXPERIMENTAL METHODS

According to the ISO ASTM 52902-2021, the FDM-printed coarse specimens (Fig. 1.) consist of six ribs (6.0 mm, 5.0 mm, 4.0 mm, 3.0 mm, 2.0 mm and 1.0 mm) which have been printed on a Creality Ender 3 3D Printer. The coarse ribs were chosen from the ISO as the medium and fine ribs would be much more difficult or impossible to print with a 0.6 mm nozzle diameter.

Printing speed and layer height values, which are the investigated process parameters, were chosen so that they cover a wide range of the abilities of the current 3D printer. Extruding Nozzle Temperature and Build Platform Temperature were chosen regarding the authors' previous experience with PETG.

Fig. 1. ISO ASTM 52902-2021 specimen-feature with coarse resolution ribs.

The printing settings are the following (Table 1):

Table 1

Printing settings and their values used in the current study.

Printing Settings	Values of printing settings
Printing Speed (mm/s)	20, 50, 80
Extruding Nozzle Temperature (ºC)	240
Build Platform Temperature (ºC)	80
Layer Height (mm)	0.2, 0.25, 0.3
Infill Pattern	Lines
Infill Density	100%
Wall Number of Lines	3

Each specimen was printed five times, so in total, there have been printed 45 specimens, 5 for each print speed and layer height. The ribs that were to be measured were in total 270. The measurements were carried out with a digital handheld caliper as the ISO ASTM 52902-2021 suggests, with each rib measured in three different areas, in order to eliminate the human error (Fig. 2.).

Fig. 2. Measurements taken by digital caliper (with MPE ≤0.02 mm).

3. RESULTS AND DISCUSSION

According to the Ph.D. thesis of Haidegger [3] the precision of a manufacturing system is represented by its accuracy [19] and its repeatability [20]. Accuracy is defined as the ability of the machine to create products with dimensions as close as possible to the nominal dimensions, whereas repeatability is defined as the ability of the machine to create products with as close as possible dimensions to each other (Fig. 3.).

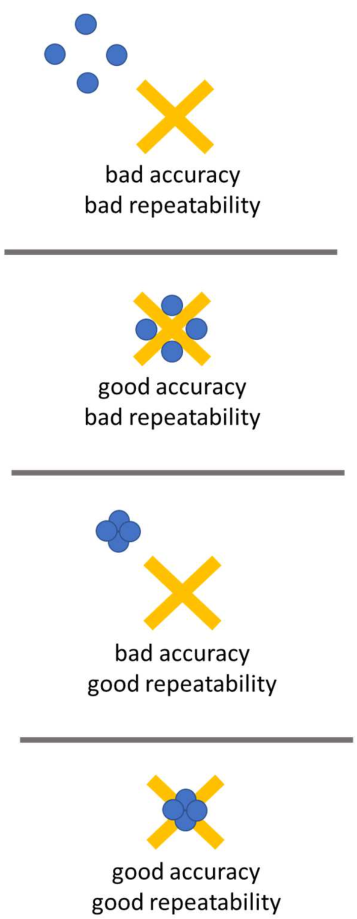

Fig. 3. Accuracy and repeatability differences.

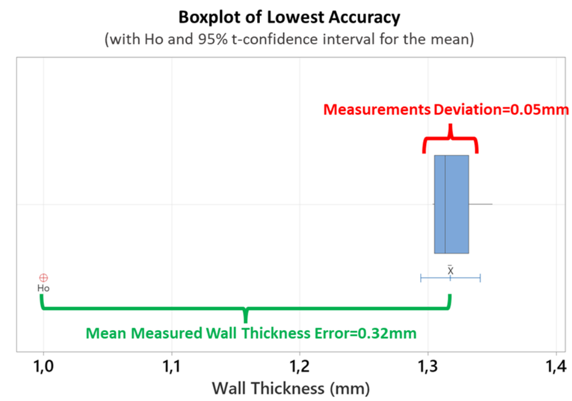

Fig. 4. Boxplot of the case 1mm nominal wall thickness 20 mm/s printing speed - 0.2 mm layer height (lowest accuracy). [Software: MiniTab Statistical Software]

On the other hand, in the case of 6mm nominal wall thickness-80 mm/s printing speed-0.25 mm layer height, where one of the lowest mean measured wall thickness error is appeared, the repeatability is the worst compared to all the other measurements (Fig. 5.):

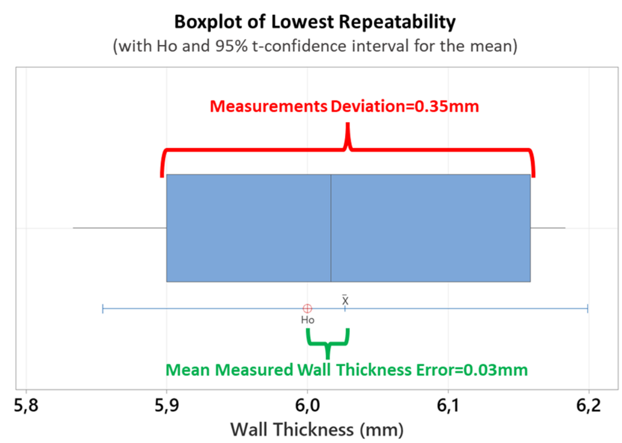

Fig. 5. Boxplot of the case 6mm nominal wall thickness-80mm/s printing speed-0.25mm layer height (lowest repeatability). [Software: MiniTab Statistical Software]

To find the optimum process parameters (between the parameter values tested in this study), so that both good accuracy and good repeatability are achieved, it is necessary to understand how much each one of the parameters (nominal wall thickness, printing speed, layer height) affect the accuracy (via the mean measured wall thickness error) and the repeatability (via the deviation of the measurement) of the process. For these reasons, the following Tuckey tests were carried out

(Table 2, Table 3). Tuckey tests are statistical procedures that are used to find means that are significantly different from each other [21].

From table 2, it is observed that the mean measured wall thickness error is very high for the nominal wall thickness of 1mm, whereas for nominal wall thicknesses of 2 mm, 3 mm, 4 mm, 5 mm, and 6 mm, the mean measured wall thickness error does not differ significantly. Moreover, for the printing speed of 20 mm/s, the mean measured wall thickness error is high, whereas, for 50 mm/s and 80 mm/s, it does not significantly differ. Finally, the mean measured wall thickness error does not seem to significantly differ for any of the layer heights.

Table2

Results of Tuckey tests for Mean Measured Wall Thickness Error, regarding a) Nominal Wall Thickness, b) Printing Speed and c) Layer Height.

(a)

Nominal Wall Thickness (mm)	N	Mean	Grouping	
1	9	13,81	A	
2	9	9,33	A	B
3	9	5,04		B
4	9	3,71		B
5	9	1,76		B
6	9	1,16		B

Means that do not share a letter are significantly different.

(b)

Printing Speed (mm/s)	N	Mean	Grouping	
20	18	9,34	A	
50	18	5,40	A	B
80	18	2,66		B

Means that do not share a letter are significantly different.

(c)

Layer Height (mm)	N	Mean	Grouping
0,25	18	6,82	A
0,30	18	5,98	A
0,20	18	4,61	A

Means that do not share a letter are significantly different.

According to the deviation of the measurement (Table 3), it is observed that there is no significant difference for all the different values of nominal wall thickness and layer height. On the other hand, the measurement deviation is too high for the printing speed of 80 mm/s, whereas for 20 mm/s and 50 mm/s, the measurement deviation is acceptable.

Table 3

Results of Tuckey tests for Measurements Deviation, regarding a) Nominal Wall Thickness, b) Printing Speed and c) Layer Height.

(a)

Nominal Wall Thickness (mm)	N	Mean	Grouping
6	9	0,14	A
5	9	0,14	A
2	9	0,13	A
3	9	0,12	A
4	9	0,12	A
1	9	0,11	A

Means that do not share a letter are significantly different.

(b)

Printing Speed (mm/s)	N	Mean	Grouping	
80	18	0,18	A	
20	18	0,10		B
50	18	0,10		B

Means that do not share a letter are significantly different.

(c)

Layer Height (mm)	N	Mean	Grouping
0,25	18	0,13	A
0,30	18	0,13	A
0,20	18	0,12	A

Means that do not share a letter are significantly different.

To achieve good accuracy and good repeatability, the above conclusions (Table 2 and Table 3) are combined in the Venn diagrams of figure 6. A Venn diagram is a diagram that represents all the possible logical relations between a finite collection of different sets. In these diagrams elements are depicted as points in the plane, and sets as regions inside closed curves, which may be overlapped with each other.

According to the Venn diagrams (Fig. 6.), it is observed that the specific 3D printer used for the experiments is capable of printing resolution ribs of the nominal wall thickness of 2 mm, 3 mm, 4 mm, 5 mm, and 6 mm with high precision, whereas for 1mm, it is suggested to use a more advanced 3D-printer. Moreover, the optimum printing speed (to achieve the best possible precision) is 50 mm/s, whereas the layer height does not seem to affect the precision of the process.

Finally, according to the authors' best knowledge, no previous studies that correlate layer height and printing speed with the dimensional accuracy and repeatability of the FDM-printed PETG parts were found. Thus, the accuracy and repeatability of the results of the current study were compared with them of PLA and ABS [9-13]. The comparison showed that PETG can achieve the same good accuracy and repeatability of PLA and ABS.

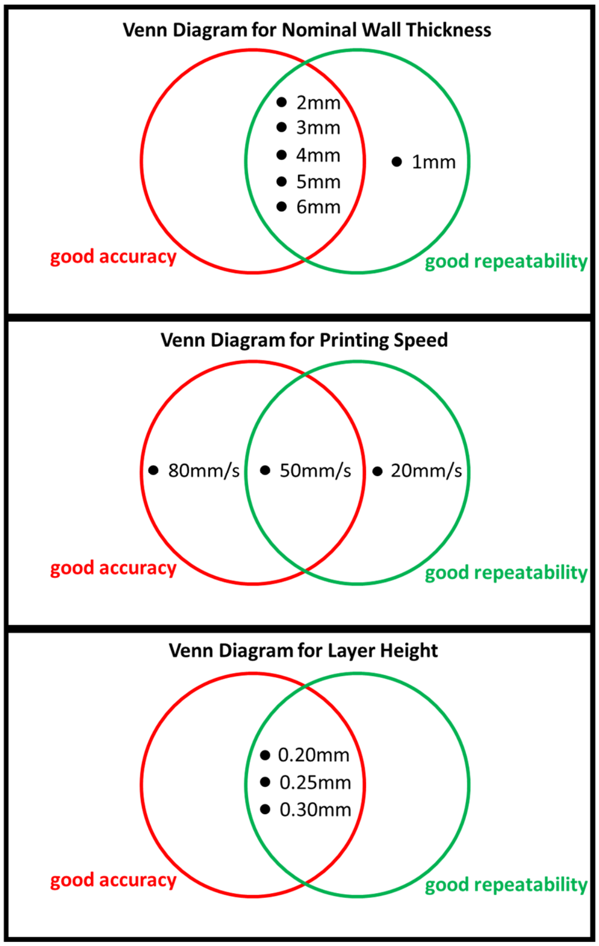

Fig. 6. Venn diagrams for good accuracy AND good repeatability.

4. CONCLUSION

In this study, PETG resolution ribs were FDM-printed, according to the ISO ASTM 52902-2021 standard, with different nominal wall thicknesses, printing speeds, and layer heights. Specifically, the nominal wall thicknesses are 6 mm, 5 mm, 4 mm, 3 mm, 2 mm, and 1 mm, the printing speeds are 20 mm/s, 50 mm/s, and 80 mm/s and the layer heights are 0.2 mm, 0.25 mm, and 0.3 mm. The experimental wall thicknesses were then measured with a caliper and the results were statistically analyzed.

The statistical analysis aims to find out which of the above process parameters gives an optimum combination of accuracy and repeatability. For this reason, Tuckey tests were carried out and Venn diagrams were created. The results showed that all the tested nominal wall thicknesses (6 mm, 5 mm, 4 mm, 3 mm, and 2 mm) give high accuracy and repeatability, except for the 1 mm nominal wall thickness, for which it is suggested to use a more advanced 3D printer. On the other hand, regarding the printing speeds, only the 50 mm/s gives both good accuracy and good repeatability, whereas, regarding the layer heights, all of them (0.2 mm, 0.25 mm, and 0.3 mm) is suitable for this specific process.

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CORELAREA VITEZEI DE IMPRIMARE ȘI A GROSIMII STRATULUI CU PRECIZIA GEOMETRICĂ A NERVURILOR DE SIGURANȚĂ OBȚINUTE DIN PETG PRIN FDM

PETG (glicol-tereftalatul de polietilenă) este utilizat în generarea de obiecte prin depunere de material topit (Fused deposition modelling - FDM), întrucât aceasta asigură o aderență excelentă a straturilor depuse. Caracteristicile piesei imprimate sunt influențate de mai mulți parametri diferiți ai procesului, astfel încât valorile lor ar trebui corelate cu proprietățile mecanice și geometrice ale probei imprimate din PETG. În literatura de specialitate consultată, majoritatea studiilor se concentrează pe proprietățile mecanice ale pieselor imprimate prin depunere de material topit, studiile privind precizia geometrică fiind mai puține. În această lucrare, s-au studiat 6 probe din PETG cu nervuri, fabricate prin FDM, în concordanță cu prevederile din standardul ISO ASTM 52902-2021. Nervurile au avut grosimi ale pereților de 6 mm, 5 mm, 4 mm, 3 mm, 2 mm și 1 mm și au fost realizate cu viteze de imprimare de 20 mm/s, 50 mm/s și 80 mm/s, respectiv cu grosimi ale straturilor depuse de 0,2 mm, 0,25 mm și 0,3 mm. Ulterior, probele au fost măsurate manual, cu ajutorul unui șubler, iar rezultatele au fost analizate statistic și comentate.

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