Tensile testing of samples printed on Delta and Cartesian 3D printer

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Abstract. This paper exposes the initial part of a research consisting in the study of the tensile behavior of the 3D parts printed on two type of 3D printers, one Delta model FLSun QQ-S PRO and other one Cartesian model Tevo Tornado, by using three types of plastic materials, PLA, PLA-CF and PET-G. After a short introduction and a literature review on previous studies reffering to the subject, in the experimental section are exposed the printing parameters selected for printing the samples, toghether with the explanation of the testing procedure. The first set of results obtained is presented, consisting in the values achieved for two parameters, the load sustained by the test specimens at yield and at break, some graphic reprezentation of their variation, respectively a short interpretation of the results. Further tests and analysis will be developed in future work, in order to realize a comparative characterization of the 3D printed parts in function by the printers and materials used.

1. Introduction

The Additive Manufacturing Technologies (AMT) and 3D printing are widely used today in manufacturing processes, especially, due to their advantages, offering a high level of digitization, customization and availability, being able to respond in a short time to an urgent need, in any sector, in unforeseen situations. The most commonly types of materials used for 3D printing are PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), PET-G (Polyethylene Terephthalate Glycol), Nylon, PC (Polycarbonate), PEEK (Polyether Ether Ketone), PP (Polypropylene), HIPS (High-Impact Polystyrene), base materials, or, in order to improve certain caracteristics of the filament, different combinations of basic materials or filled with various inserts, such as carbon fiber, glass fiber, wood or metal, till the biodegradable or soluble in water 3D printer filaments. Depending on particular interests and needs, a lot of studies and experimental researches are developed in recent years, by using the knowledge about the properties of the plastic materials and their testing methods and standards.

One of the most widely recognized indicator for the characterization of the plastics strength is considered the tensile testing, a destructive test in wich is measured the force that break a plastic sample and the elongation of the test specimen until to thatthe breaking point. The tensile testing provides results such as tensile strength, elongation and tensile modulus, wich are useful for the selection of a certain materials for some specific applications. For the evaluation of the mechanical behavior at the tensile, of the 3D printed parts, it is generally accepted, by the majority of authors, the standard test method for tensile properties of the plastic materials, ISO 527-1 [1] or ASTM D638-02 [2], that are technically equivalent [3], and used certain standardized test specimens. There are an cooperation agreement between ISO and ASTM, from 2011, in order to develop and adopt, together, international standards in the field of AMT [4]. Some studies use national standards, for exemple in [5] the tensile testing is performed according to the Spanish standard for additive manufacturing, and the results show a much better repeatability by using UNE 116005:2012 than by testing according to the standard ASTM D638–14. In the same time, there are studies that try to offer useful guidelines for developing new standards for characterization of the mechanical properties of the FDM printed parts [6]. In another research, following an extensive literature study and some comparative experimental tests regarding the optimization of the manufacturing parameters and the geometry of the tensile specimens, it is suggests the using of ISO-modified geometry for characterization of mechanical response of the 3D printing parts [7].

2. Short review on previous studies

After an extensive review and a comparative study by using four types of materials, PLA, PC, PEEK and ABS, Gordelier [8] makes some key recommendations for the optimization of the 3D printing process, by following the achievement of the maximum tensile strength of the test specimens, reffering to: material, print orientation raster angle, air gap/raster width, layer height, infill, printing temperature, feed rate. Based on these recommendations, and after studying other recent research in this field, we can expose some results, but with the mention that is difficult to compare the results, because of many differencies between the experiments.

2.1. Material

Through printing process optimization, aditivation of the base material, even through right choosing of the colour of the filament, the tensile strength of the materials can be improved. Reported to ABS, PLA have 1.1 to 2 times the tensile strength, PC 1.9, and PEEK 2.1 [8]. For instance, ABS plus, a polymer with improved mechanical properties, has on average 15% higher strength than ABS [9]. In the same time, the results of another comparative study show that the tensile strength of PETG and CF - PETG are comparable, but the flexural strength of CF - PETG is significantly higher than that of PETG, and the PETG specimens have a ductile fracture [10]. Adequate strength and high ductility, with a slight brittleness in tensile test results were observed in PET-G samples, in comparison with PLA and ABS, in [11]. The tensile strength of some PLA samples records the best average value as against HD PLA Green and Impact PLA Gray and comparable with those of other printed thermoplastic materials such as Carbon Nano structure ABS, ABS, ASA (Acrylonitrile Styrene Acrylate), and PETG [12]. But, the result of a comparative study shows that the tensile strength values for PLA material varie between samples and have a lower consistency in mechanical properties during tensile tests relative to ABS [13]. The different behavior of printed PLA specimens at tensile testing is confirmed, also, in another study, through variat values for the Young modulus, proportional limit and maximum strength [14]. The multi-materials used for 3D printing significantly extend the capabilities of the conventional single-material, the combination between different materials, ranging from a rigid-brittle material to a compliant-rubbery one, and printing orientation, showing the values for the interface strength reduced by 50% or increased by 20% [15].

2.2. Print orientation

Generally, better tensile performance is obtain by printing in the flat or on-edge orientation, with minimal variation between, and the upright orientation should be avoided [8]. Based on the tensile tests results of some ABS specimens, it is shown that the 0° printing direction specimens are stronger by 44.7% than that printed at 90°, the printing direction having no influence on the modulus of elasticity [16]. The results of an extensive experiment with PLA samples and a comparison made with previous publications show that the printing orientation and raster angles have a high impact on the tensile properties of the printed parts, the X90°/Z0° specimens among three types of specimens and the 45/−45° of flat-type specimens having the strongest tensile properties [17].

2.3. Raster angle

For ABS samples, there are many studies that consider the highest tensile strength for 0° raster angle, for PLA exist fewer studies, that consider either 0° or 45°, and for PC only few studies, variyng betwen 0° and ±45° raster angle. [8]. A FEM analysis on the tensile test specimens from ABS shown that the model at 45° orientation has maximum tensile stress, compared with 0° or 90° [18]. At the same material and the same printing parameters, the building direction does not significantly affects the tensile strength of the samples, in an experimental study with ABS [19]. In an experimental study, with PLA, the highest values of the tensile strength are found for specimens printed at 0◦, then for 90◦, and the lawest for 45◦ [20], and, as contrary, in another study [21], for the specimens built with 45° the tensile strength is greater than for those built with 0°. In an approache with two novel theoretical models, the strength and Young's modulus were predicted with a relative errors smaller than 0.14, for 105 specimen from PLA, and the results shown that the tensile strength increases with the increasing of the printing angle, from 0° to 90° or the decreasing of the layer thickness, from 0.3 mm to 0.1 mm [22].

2.4. Air gap and raster width

To ensure a high quality inter-raster bonding, without overfill, the air gap and raster width should be optimised together, consideration a negative air gap to achieve this [8]. In fact, more printing parameters, comprising part orientation, raster angle, raster width and air gap have to be optimized in order to obtain a better tensile strength [23]. After an investigation on five printing parameters, air gap, raster width, raster angle, contour number and contour width, of a high-performance polymeric material, was found that only one, the raster angle, influence significant the tensile properties of the test specimens [24].

2.5. Layer height, infill, printing temperature and feed rate

In order to achieve the maximum tensile strength, for flat and on-edge orientations, the layer height should be minimized, for both ABS and PLA samples, while in upright samples only, a greater layer height achive a better tensile performance. An infill of 100% offers a higher tensile strength, but has to be find a balance between printing time and the achieved tensile strength. Regarding the printing temperature, an increase in extruder temperature means an improve of tensile strength performance, due to improved inter-raster and inter-layer bonding. The feed rate should be optimised mainly to minimise the printing time, rather than optimise the material properties [8]. For the tensile strength value and the elastic modulus, a linear decreasing is obtained by decreasing the infill density, for three three types of materials but, referring to the infill design, in addition to the infill density, it is important to be examined the infill pattern and infill angle in relation to the direction of loads. [25]. The optimum level of layer thickness for ABS is considered 0.15 mm, with 230°C temperature, and 16 mm/s feed rate, for achive the maximum tensile strength [18]. But, the average tensile properties of some samples printed from PLA on a desktop printer are presented in [26] in comparison with strength properties reported in other studies, and an important result shows the possibility of printing whith 0.3 mm, as against with 0.1, 0.15 or 0.18 mm layer thicknesses, so, in a shorter printing time, without significant decrease in mechanical properties. An ideal balance between desired mechanical properties and material costs could be achieved by printing objects from PLA with 20% support grid volume, oriented in +45° and -45° to sample major axis, and layer thickness 0.15 mm, as presented in [27]. At an infill density of 80%, thicknesses of 0.1 mm and 0.2 mm, and the print angle is ± 45°, the PLA specimens have the highest stiffness and strength, but present a brittle behavior [28].

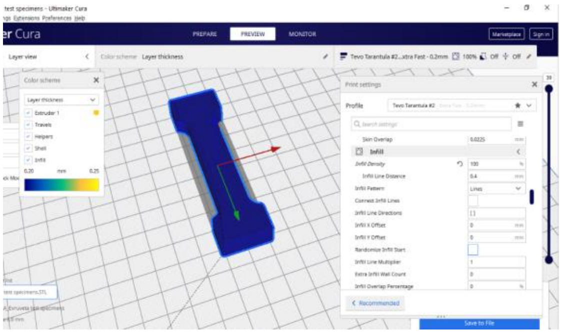
Based on the study of numerous publications regarding the infuence of the printing parameters on tensile properties of PLA samples, and using a design of experiment analysis, in [29] the result is presented in an illustrative diagrame, by considering seven parameters, infill pattern, layer height, infill density, printing velocity, raster orientation, outline overlap, and extruder temperature, and three interactions, infill pattern/layer height, infill pattern/infill density and, layer height/infill density.

Referring to the dimension of the test specimens, the smaller specimens have greater strength than the full sizes specimens [21].

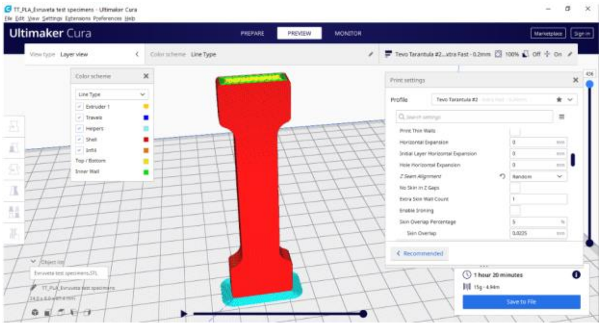
After studying a lot of researches referring to the tensile testing of 3D printed parts, some of them mentioned above, was establish the research criteria and, by using the available equipment, two 3D printers, one Delta and other one Cartesian, and three types of materials, the samples was printed, with certain printing parameters. The experimental procedure and a first set of results obtained from the tensile testing of the specimens are further presented in this paper.

3. Experimental section

For printing the test specimens, two 3D commercial printers, available in our laboratory, one Delta, model FLSun QQ-S PRO and other one Cartesian, model Tevo Tornado, was used. The technical specifications of the printers and the software used, toghether with the printing settings and printing parameters, are shown in [30]. The test specimens were designed in SolidWorks 2017, and the gcode creation software Ultimaker Cura 4.7.0 was used, for both printers. In figure 1 is presented the virtual model of the sample in flat orientation, and in figure 2 in upright orientation.



Skin Overlap 0.0225 mm
Infill
Infill Density 100 %
Infill Line Distance 0.4 mm
Infill Pattern Lines
Connect Infill Lines
Infill Line Directions [ ]
Infill X Offset 0 mm
Infill Y Offset 0 mm
Randomize Infill Start
Infill Line Multiplier 1
Extra Infill Wall Count 0
Infill Overlap Percentage 0 %



Print Thin Walls
Horizontal Expansion 0 mm
Initial Layer Horizontal Expansion 0 mm
Hole Horizontal Expansion 0 mm
Z Seam Alignment Random
No Skin in Z Gaps
Extra Skin Wall Count 1
Enable Ironing
Skin Overlap Percentage 5 %
Skin Overlap 0.0225 mm
1 hour 20 minutes
15g · 4.94m

Figure 1. Sample model in flat orientation.

Figure 2. Sample model in upright orientation.

The experimental specimens for tensile testing were printed, piece by piece, from three types of material, PLA, PLA-CF, with 20% carbon fiber insertion and PET-G, with the printing parameters presented in table 1.

Table 1. Printing parameters of the samples

3D printer / Material / Printing parameters	Delta model FLSun QQ-S PRO			Cartesian model Tevo Tornado		
	PLA	PLA-CF	PET-G	PLA	PLA-CF	PET-G
Infill density	100 %	100 %	100 %	100 %	100 %	100 %
Layer height	0.2 mm	0.2 mm	0.2 mm	0.2 mm	0.2 mm	0.2 mm
Number of shells	2	2	2	2	2	2
Nr of wall line count	4	4	4	4	4	4
Print speed	85 mm/s	85 mm/s	85 mm/s	52 mm/s	52 mm/s	42 mm/s
Wall speed	40 mm/s	40 mm/s	40 mm/s	51 mm/s	51 mm/s	21 mm/s
Initial layer speed	28.5mm/s	28.5mm/s	28.5mm/s	22 mm/s	22 mm/s	22 mm/s
Nozzle temperature	225 °C	225 °C	225 °C	215 °C	215 °C	230 °C
Bed temperature	60 °C	60 °C	80 °C	70 °C	70 °C	80 °C
Print time	41 min	41 min	41 min	59 min	59 min	1h6min

A lot of forty-two specimens, dumb-bell-shaped / dog-bone-type, according to ISO 527 and ASTM 638 were printed, fourteen for each type of material, seven for each printer and material, in order to proceed the tensile testing for experimental investigation and evaluation of the the tensile behavior and to ensure the repeatability. All samples were printed in flat orientation and one, in addition, from PLA-CF, in upright orientation. The infill density is 100%, the print angle ± 45°, with the pattern of the printed infill structure cubic subdivision, as is shown in figure 3. The dimensions of the samples are modified compared to those provided in the standards, adopting smaller lengths and larger widths and thicknesses, as can be seen in figure 4.

Figure 3. Sample model cubic subdivision.

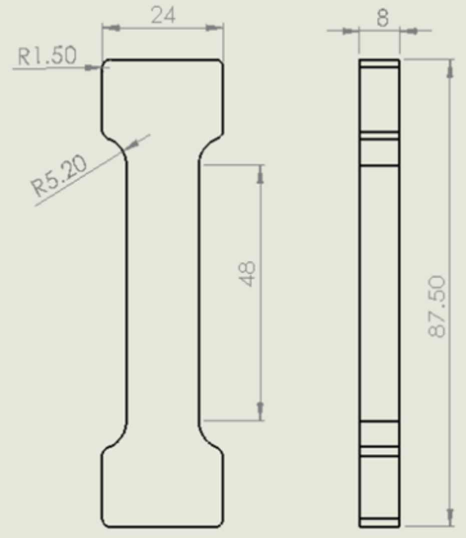
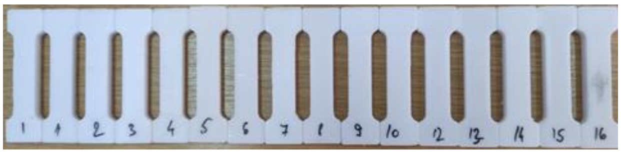


Figure 4. Sample dimensions.

Figures 5 and 6 show the test specimens, before testing, and after tensile testing, respectively.

PLA

PLA-CF



PET-G

Figure 5. Samples before testing.

PLA

PLA-CF

PET-G

Figure 6. Samples after testing.

Referring to the machines for tensile testing, many experimental studies are proceed with modern equipments, but not all. From the experimental data obtained after the tensile testing procedures aplied, for four common polymers, with three machine types, with nonsophisticated and nonexpensive measuring systems, wereachieved the comparable results [Romero]. Thus, the tensile testings for this experimental study were performed on a 200 kN Heckert-EDZ-20 testing machine, presented in figure 7, which is in the endowment of our laboratory, an old model, but functional, that can be used after a simple adaptation to the gripping system, as can be seen in figure 8. The test speed adopted is 0,8 mm/s.

Figure 7. Heckert-EDZ-20 testing machine.

Figure 8. Gripping system of testing machine.

4. Tensile testing results

According to ISO527-1, in tensile testing, “the test specimen is extended along its major longitudinal axis at a constant speed until the specimen fractures or until the stress (load) or the strain (elongation) reaches some predetermined value”. Applying this procedure, as presented in above section, two values were measured, the load sustained by the specimens at yield and at break, respectively, as presented in table 2.

Table 2. Tensile loading: Load at yield [daN] and Load at break [daN]

Nr. sample	Delta model FLSun QQ-S PRO			Nr. sample	Cartesian model Tevo Tornado		
	PLA	PLA-CF	PET-G		PLA	PLA-CF	PET-G
1	168	120	140	8	161	140	170
	250	155	150		230	165	215
2	170	125	142	9	162	148	145
	235	175	152		258	172	150
3	150	150	142	10	161	145	130
	191	180	148		262	173	140
4	162	120	130	11	165	140	148
	220	162	140		240	163	152
5	162	125	120	12	162	138	160
	230	160	128		250	160	210
6	170	122	120	13	150	140	160
	235	155	125		270	168	250
7	160	125	140	14	150	140	128
	230	150	150		268	171	130

The graphical illustration of the measured value sets is shown in the charts from the following figures, the load at yield for samples printed on Delta printer in figure 9, respectively on Cartezian printer in figure 10, and the load at break for samples printed on Delta printer in figure 11, respectively on Cartezian printer in figure 12.

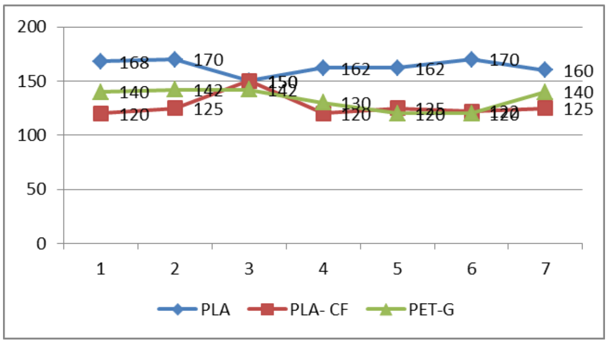


Figure 9. Load at yield [daN] - Delta samples.

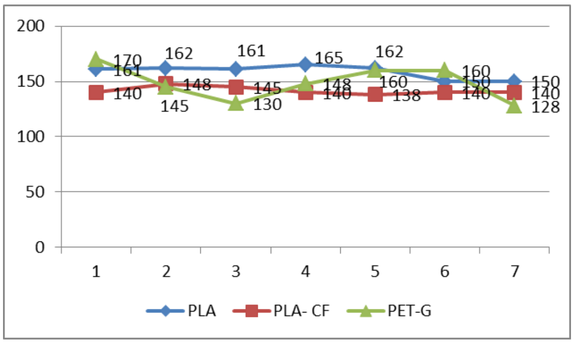


Figure 10. Load at yield [daN] - Tevo samples.

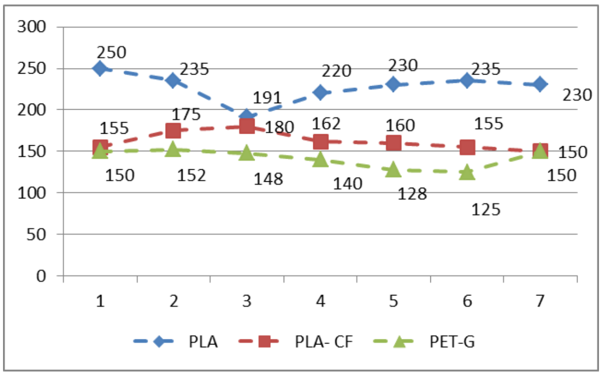


Figure 11. Load at break [daN] - Delta samples.

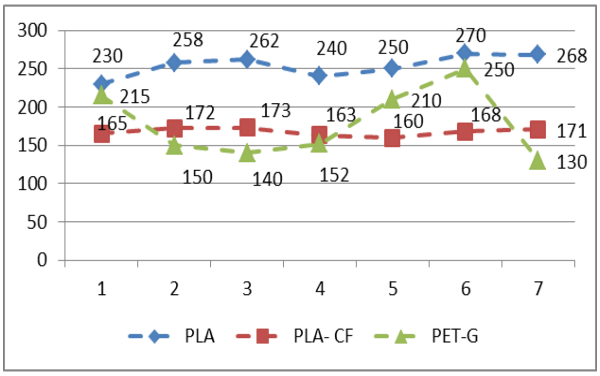


Figure 12. Load at break [daN] - Tevo samples.

The values obtained for the PLA samples are generally higher and have comparable values for PLA-CF and PET-G, the difference being greater at break.

The results obtained depending by printer have comparable values, with slightly higher ones, at yield, at the samples printed on the Cartesian printer from PLA-CF, at breaking, for PLA, and, both at yield and at break, for PET-G.

For the same material, the results are quite homogeneous, for PLA and PLA-CF, with some small exceptions, and for PET-G they vary a little more from one sample to another.

The differences between the values obtained for yield and those for break are smaller in the case of PLA-CF and PET-G and larger in the case of PLA.

5. Conclusion

After a consistent literature review regarding the tensile testing of the 3D printed test specimens, an experimental study was developed, with established research criteria and printing parameters. It consists in the 3D printing, by using two types of 3D printers, one Delta model and other one Cartesian model, and tensile testing of one lot of test specimens. Were used three types of common and commercial materials, PLA, PLA-CF and PET-G. In this paper are presented the measured values for two parameters, the load sustained by the specimens at yield and at break, respectively, and a short interpretation of their variation. After the presentation of this first set of results, a more detailed analysis will be developed in future work, in order to realize a comparative characterization of the 3D printed parts in function by the printers and materials used.

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