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Procedia Structural Integrity 41 (2022) 670–679

Structural Integrity Procedia

www.elsevier.com/locate/procedia

2nd Mediterranean Conference on Fracture and Structural Integrity

Experimental investigation on mechanical properties of FFF parts using different materials

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Abstract

Fused filament fabrication (FFF) is one of the additive manufacturing processes that provides parts with finest mechanical properties. Different materials offer different mechanical properties of the part. In this research we investigated parts fabricated with polylactic acid (PLA), polycarbonate (PC) and polyethylene terephthalate glycol, PETG. Samples are designed according to the ASTM standards and fabricated under the same process parameters. The mean effect on the tensile strength and flexural strength have been studied. From the study it can be concluded that there is a difference in the results as expected. But we cannot say that there is one material with superior properties, simply different materials are suitable for different applications.

Keywords: fused filament fabrication (FFF); tensile strength; flextural strength; test speciments; mechanical properties.

1. Introduction

Additive Manufacturing (AM) technologies gain in popularity because of the many advantages that they offer as oppose to the traditional manufacturing technologies (Thompson et al., 2016). The major difference of the AM and the traditional manufacturing technologies is the working manner, were the AM add material while in the traditional technologies the materials is subtracted. This results in many advantages for AM, mainly presented in the complexity of the shape. We as a society are still learning how to exploit all the possibilities offered by these technologies.

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10.1016/j.prostr.2022.05.076

Nomenclature

AM	Additive Manufacturing
FFF	Fused filament fabrication
FDM	Fused deposition modelling
ABS	Acrylonitrile butadiene styrene
PLA	Polylactic acid
PC	Polycarbonate
PETG	Polyethylene terephthalate glycol

One of the widespread AM processes, fused filament fabrication (FFF) process mainly to its affordability, low cost in use and maintenance (Liu et al., 2019). One of the areas that are of interest for scholars are the mechanical properties of the parts produced and fabricated with FFF. The layer-by-layer working manner is affecting the mechanical properties of the parts causing different results for parts produced with the same material with the traditional technologies. Also, working with FFF the guilty of the final output as well as the mechanical properties are under the influence of the process parameters. Therefore, numerous scholars are working on the connection between the process parameters and the mechanical properties (Es-Said et al. 2000; Masood et al 2010; Knoop, 2015; Shubham, 2016; Maloch et al. 2018;). Es-Said et al. (2000) investigate the effect of layer orientation on mechanical properties (tensile strength, modulus of rupture and impact resistance) of ABS specimens. The authors found that the 0° orientation, with layers along the length of the specimens has superior properties. Maloch et al. (2018) studied the influence of the extrusion nozzle and the layer thickness on the mechanical properties (tensile and flexural strength, tensile and flexural modulus) of fabricated ABS specimens. The authors notice that the best properties are obtained for small layer thicknesses and higher nozzle temperature ensuring better melting between adjacent layers. Other studies are also confirming on this. As the layer thickness increases, tensile strength reduced by 46% for ABS specimens (Shubham, 2016). Masood et al (2010) found that the tensile strength of fabricated PC parts is in 70-80% high as the strength obtained from injection molding or extruded PC parts. They achieved this best result of 58.8 MPa for raster angle 45° of raster width 0.6064 mm with air gap type solid normal. Knoop (2015) analyzes the impact of process parameters in mechanical properties of specimens fabricated with Nylon 12. The highest tensile strength was recorded in X-direction and the upright specimens have 14 to 20 % lower properties. Vălean et al. (2021) examined the tensile strength of PLA specimens using different printing parameters such as build orientation and layer height. The result from their experimental investigation was that the PLA specimens oriented along X and Y axis have tensile strength as injection molding parts. On the other hand the results obtained in study by Afrose et al. (2015) shows that PLA parts fabricated with 45° printing orientations have the best fatigue property. Fountas et al. (2020) also conduct experimental investigation of the tensile strength of PLA specimens and the results are applied in to generate a statistical validated regression model. They analyzed the connection between the tensile strength and the process parameters such as: layer height, infill density, shell thickness, orientation angle and printing speed. The result from their research is that the infill density is a dominant parameter that influences the tensile strength of the PLA specimens. For the layer height is advised to be as low as possible. Patel et al. (2017) investigate the influence of the infill pattern and percentage on the tensile strength. Their results show that the line patterns with 60% infill density (highest used) got the highest tensile strength of the fabricated PLA parts in comparison to the other specimens. Lanzotti et al. (2015) conduct a study for mechanical properties on part fabricated on open-source Rep-Rap machine. They observed that the UTS values, decreases in strength as the infill orientation approaches 90° degrees and an increase as the perimeters increase. An initial increase is evident as the layer thickness approaches 0.18 mm. Beyond this value, a reduction in strength values occurs. In later study Lanzotti et at. (2019) examine the connection between the mechanical properties of specimens fabricated with virgin and recycled PLA. The one-time and twice recycled specimens showed a short-beam strength which was similar to that of the virgin specimens. However, a third recycling process negatively affected the values of the short-beam strength also producing a great variability in the results. Rodríguez-Panes et al. (2018) present a comparative study of the tensile behavior (tensile yield stress, tensile strength, nominal strain at break and modulus of elasticity) of different parts fabricated with FDM using PLA and ABS. The PLA specimens are stiffer and have a tensile strength higher than the ABS specimens. In comparative study of three materials (PC, ABS and PLA) for tensile strength they found out that the most significant factor is the material itself. Also the brittleness and the calculated elongation of the FDM samples in all the cases is lower than the elongation of samples produced conventionally from the same material (Beniak et al., 2015). Ozen et al (2021) investigates different specimen designs of PETG fabricated with FDM and conclude that the PETG performs linear elastic characteristic and a brittle fracture at room temperature. They also emphasize that the slicing technique influences the performance of the final product significantly. Warnung et al. (2018) conducted a study of the mechanical properties of eight different materials using the FDM process. Their results showed that the PA wire is the strongest, while the PET reinforced with carbon fibers was the stiffest material.

It is clear that the performances of the FDM specimens are under high influence of the process parameters. This why in our case we did not change any of the process parameters in order to compare solely the performances of the three materials that we are comparing. Results obtained from the materials manufacturers can be used, but they are usually conceived in special conditions, and as it is stated in the text above, when AM technologies are concern, process parameters have a high impact on the results.

In this paper we are comparing three different materials according to their tensile and flexural strength. During our research we did not come across this kind of research and for us it is important since we are planning to use this approach for composite structures.

2. Method

Two different tests were performed in order to research the properties of printed parts: tensile tests and 3-point-bending tests. A tensile test is the most fundamental type of mechanical test where a testing sample is subjected to uniaxial tension until failure. The results from the test are widely used to gain a better understanding of different materials and to select the proper material for a particular application.

In a 3-point bend test, the convex side of the sheet or plate is placed in tension, and the outer fibers are subjected to maximum stress and strain. Failure will occur when the strain or elongation exceeds the material's limits. The 3-point-bending test was used to provide values for the modulus of elasticity in bending E_f, flexural stress σ_f, flexural strain ε_f and the flexural stress–strain response of the material.

These two tests in combination were used to determinate the specific behavior of the polymers to loads in different planes and their mechanical strength.

3. Specimens design & fabrication

Specimens are designed according to the appropriate standardization and presented below. Fabrication is conducted on same machine Prusa Mk3, with deference in the material. For this specific research, an infill of 100% was used in every specimen, with a layer height of 0.2 mm for both tests. A total of 9 specimens (3 per material) were made for the tensile test and an additional 9 (3 per material) for the 3-point-bending test.

3.1 Design

Specimens used for tensile strength samples are designed according the ISO 527-1:2019 Plastics — Determination of tensile properties, Part 2 – Test conditions for moulding and extrusion plastics. Parts fabricated with AM technologies are tested according the available standard for the material used for fabrication, so in this study we used the measurements provided for 1BA specimen, as can be seen on Figure 1a.

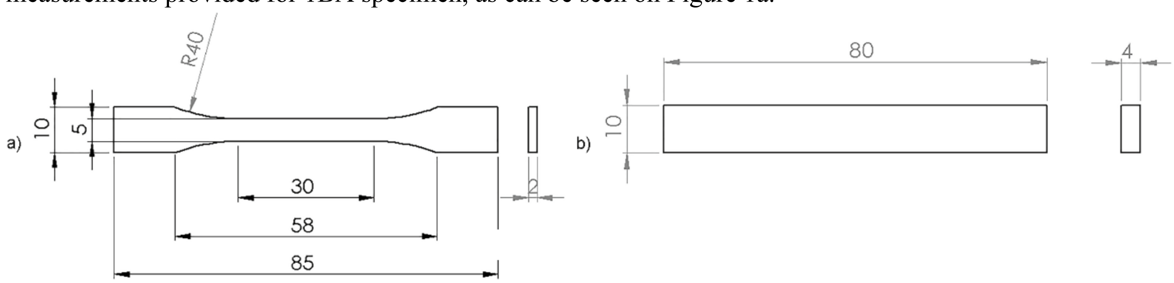


Fig. 1. Samples used for testing (a) tensile strength specimen; (b) flexural strength specimen

Specimens used for flexural strength are designed according the ISO 178:2019 Plastics — Determination of flexural properties. In Figure 1b measurements of the specimen are presented.

3.2. Fabrication

All the specimens are fabricated on same machine, Prusa i3 MK3S, using the FFF process. Material used for the fabrication is Prusa's in-house material, in order to ensure optimal results. The number of samples is provided in the standards. Fabrication parameters are kept same for the fabrication of all the specimens, except for the bed temperature and nozzle temperature, as presented in Table 1. During the fabrication, same material specimens are fabricated at once, laid flat on the print bed (Fig. 2).

Table 1. Fabrication parameters

	PLA	PC	PETG
Material	PLA Prusament	PC blend Prusament	PETG Prusament
Layer height	0.2	0.2	0.2
Nozzle size	0.4	0.4	0.4
Nozzle temperature	215	275	250
Bed temperature	60	110	80
Infill	100%	100%	100%

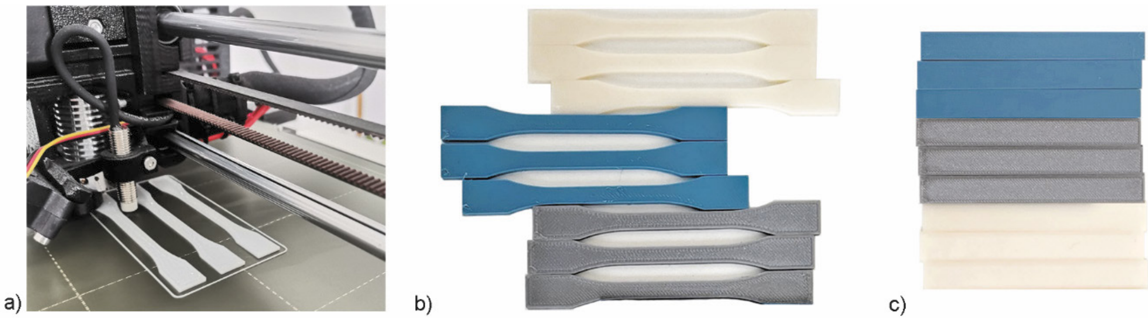


Fig. 2. Fabrication process a) fabrication of PLA specimens for tensile strength test; b) specimens for tensile strength test; c) specimens for flexural strength test

From our experience PETG samples were the most difficult to fabricate because of the stringing. But the geometry is pretty basic so there were no any major issues during the fabrication.

4. Experimental analysis

Experimental analysis are conducted on Shimadzu testing machines (Fig. 3), Shimadzu AGX-S for tensile strength and Shimadzu AG-X for flexural strength i.e. 3-point bending tests. Two different tests were performed in order to research the properties of printed parts: tensile tests and 3-point-bending tests. A tensile test is a most fundamental type of mechanical test where the specimen is uniaxial loaded until failure. The results from the test are widely used to gain a better understanding of different materials and to select the proper material for a particular application.

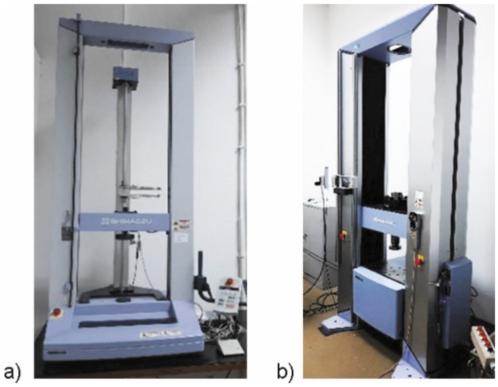


Fig. 3. Machines used for the experimental analysis
a) Shimadzu AGX-S for tensile strength; b) Shimadzu AG-X for flexural strength

4.1. Tensile test

Tensile tests were performed on the specimens using a Shimadzu AGX-S tensile test machine that has a 10-kN load cell. Each sample was subjected to a crosshead speed of 1 mm/min until failure of the specimen. Using the TRAPEZIUM-X software it was possible to visualize and record the force–extension curves of each of the specimens.

From each one of the curves obtained, four mechanical parameters were calculated: the elastic modulus, the ultimate tensile strength (UTS), the elongation at break and the fracture stress. Young's modulus for each specimen was calculated by considering the stress values at the strains of 0.005 and 0.02. The load–displacement outputs from the tensile test machine were normalized to stress– strain data.

The nominal stress for all specimens was calculated using the following equation:

$$\sigma = \frac{F}{A_0} \tag{1}$$

σ [MPa] – tensile stress; F [N] – applied force; A_0 [mm^2] – specimen cross-section

The tensile strain for all specimens was calculated using the following equation:

$$\varepsilon = \frac{\Delta l}{l_0} \tag{2}$$

ε – tensile strain; Δl [mm] – elongation; l_0 [mm] – specimen gauge length;

4.2. 3-point-bend flexural test

Bend testing, sometimes called flexure testing or transverse beam testing, measures the behavior of materials subjected to simple beam loading. It is commonly performed on relatively flexible materials such as polymers, wood, and composites. At its most basic level a bend test is performed on a universal testing machine by placing a specimen on two supports and bending it through applied force on 1 or 2 loading anvils in order to measure its properties.

In a 3-point bend test the force is applied by a single upper anvil at the midpoint of the specimen. The area of uniform stress in this test is quite small and concentrated under the center loading point. This test was performed on the specimens using a Shimadzu AG-X machine that has a 250-kN load cell. Each sample was tested using a crosshead speed of 5 mm/min and specimen deflection was measured by the crosshead position.

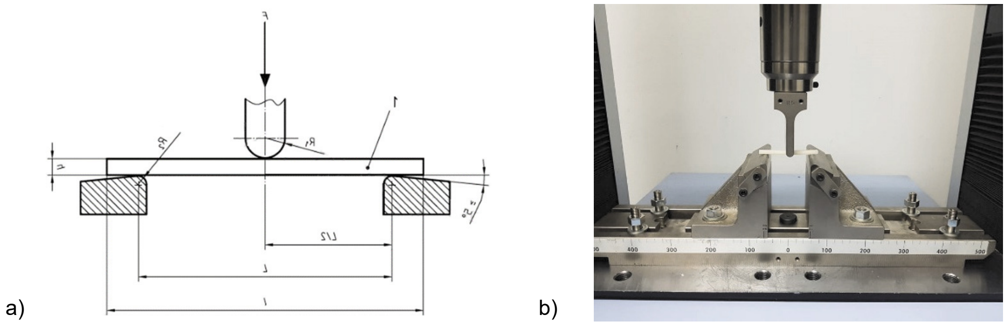


Fig. 4 Flexural test setup a) 3-point-bending schematic; b) PC specimen set up on the Shimadzu AG-X

The following test results were obtained from the testing:

The flexural stress for all specimens was calculated using the following equation:

$$\sigma_f = \frac{3FL}{2bh^2} \tag{3}$$

σ_f [MPa] – flexural stress; F [N] – applied force; L [mm] – supports span; b [mm] – specimen width; h [mm] – specimen thickness

The flexural strain for all specimens was calculated using the following equation:

$$\varepsilon_f = \frac{6sh}{L^2} \tag{4}$$

ε_f – flexural strain; L [mm] – supports span; s [mm] – deflection; h [mm] – specimen thickness

To determine the flexural modulus, the s_1 and s_2 deflections were calculated for the corresponding flexural strains of $\varepsilon_{f1} = 0{,}0005$ and $\varepsilon_{f2} = 0{,}0025$.

$$s_i = \frac{\varepsilon_{fi} L^2}{6h} \qquad (i = 1; 2) \tag{5}$$

s_i [mm] – deflection; ε_{fi} – flexural strain; L [mm] – supports span; h [mm] – specimen thickness

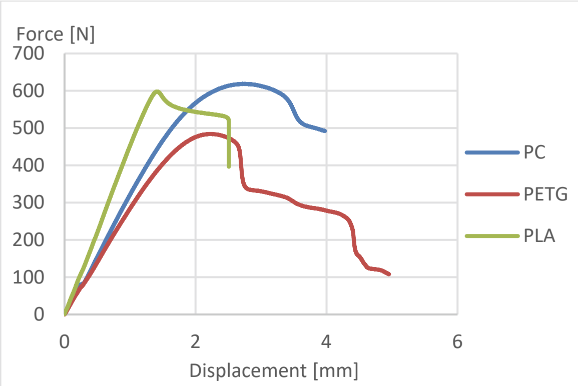
The flexural modulus E_f is then calculated using the equation:

$$E_f = \frac{\sigma_{f2} - \sigma_{f1}}{\varepsilon_{f2} - \varepsilon_{f1}} \tag{6}$$

5. Results & discussion

5.1. Tensile strength

The results from the tensile tests presented in Figure 5 showed that the PLA the most rigid plastic out of the three with the largest mean Young's module. The PC blend had the highest ultimate tensile strength, while the PETG showed the highest elongation. The stress-strain curves and the tested specimens shown in Figure 5a reflect this conclusion. The most rigid PLA material resulted with a clear fracture after the tensile test, while on the PC blend and PETG specimens a contraction occurred before the end. This was most evident in the PETG specimens where a clear break did not occur and the tests had to be stopped manually. This occurrence is evident on the PETG stress-strain curve as the specimens presented in Figure 5b. The results presented in Table 2 and Table 3 only prove everything said above.



a)

b)

Fig. 5. Tensile strength test a) force-displacement graph for tensile strength; b) specimens after the conducted tests

Table 2. Values obtained from the tensile strength analysis

	Specimen	F_{max} [N]	Δl_{max} [mm]	σ_{max} [MPa]	ε_{max}	$E\ [MPa]$
PLA	1	597,95	1,416	59,7954	0,04721	442,707617
	2	583,49	1,465	58,3485	0,04882	432,6994872
	3	621,15	1,475	62,1149	0,04918	443,5104721
PC	1	618,36	2,732	61,8359	0,091052233	311,3209088
	2	605,40	2,722	60,5399	0,090742233	293,3946219
	3	625,79	2,703	62,579	0,090102233	312,9584283
PETG	1	484,11	2,229	48,4107	0,074305567	282,0741669
	2	469,69	2,010	46,9689	0,06701	268,4399378
	3	476,20	2,289	47,6198	0,076302233	256,5606257

Table 3. Average values from the tensile strength analysis

	F_{max} [N]	Δl_{max} [mm]	σ_{max} [MPa]	ε_{max}	$E\ [MPa]$
PLA	600,86	1,45	60,09	0,05	439,64
PC	616,52	2,72	61,65	0,09	305,89
PETG	476,66	2,18	47,67	0,07	269,02

5.2. Flexural strength

Similar results were obtained during the flexural bending test. The maximal stroke was achieved with the PC and PETG specimens, while the PLA plastic specimens showed a clear break before the maximal stroke as it is presented in Figure 6. The results for all tested specimens for the three materials are presented in Table 4 and Table 5.

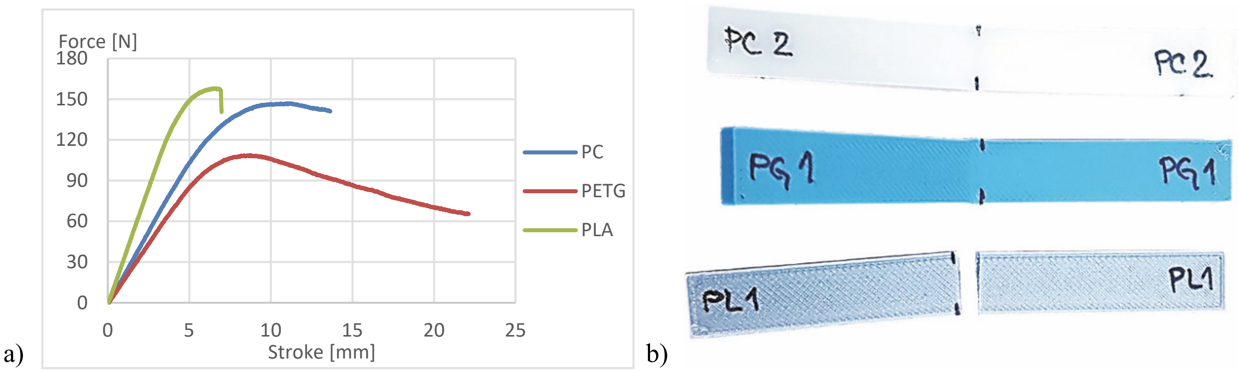


Fig. 6. Flexural strength test a) force-stroke graph for tensile strength; b) specimens after the conducted tests

Table. 4. Values obtained from the flexural strength analysis

	Specimen	F_{max} [N]	$Stroke_{max}$ [mm]	σ_f [MPa]	ε_f	E_f [MPa]
PLA	1	157.9523	6.387094	473.8569	0.0374244	5563.1005
	2	156.7602	6.338229	470.2806	0.0371381	5980.331
	3	160.6544	6.410229	481.9632	0.0375599	5722.045
PC	1	146.8261	11.19591	440.4783	0.065601	3735.2243
	2	145.4353	10.93589	436.3059	0.0640775	3635.8832
	3	147.899	10.94289	443.697	0.0641185	3635.883
PETG	1	108.7586	8.76724	326.2758	0.0513705	3099.4418
	2	106.5334	9.03924	319.6002	0.0529643	2880.8912
	3	104.1492	8.908218	312.4476	0.0521966	2880.8912

Table 5. Average values from the tensile strength analysis

	F_{max} [N]	$Stroke_{max}$ [mm]	σ_f [MPa]	ε_f	E_f [MPa]
PLA	160.6544	6.410229	481.9632	0.0375599	5722.045
PC	147.899	10.94289	443.697	0.0641185	3635.883
PETG	104.1492	8.908218	312.4476	0.0521966	2880.8912

The results of the experiments are shown in Tables 2, 3, 4 and 5. For both the tensile test and the flexural tests the relevant strength parameters as well as the registered strain for all specimens were without significant variance. PETG showed the largest elongation before breaking in both test cases which makes its use more plausible in composite application when the goal is to add some filler material in the FDM interface layers.

Comparing the UTS (ultimate tensile stress) values for the three materials, presented in Figure 7, shows that the PC specimens have the highest values, whereas the PETG specimens have the lowest values. For the maximum flexural stress PLA specimens have the highest values as presented in Figure 8, followed by PC specimens with slightly lower values.

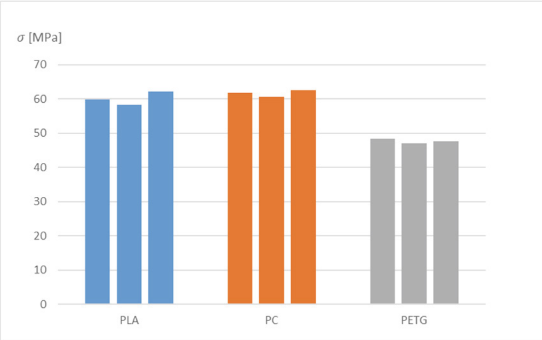


Fig. 7. Ultimate tensile stress (σ_{max}) on all measured specimens

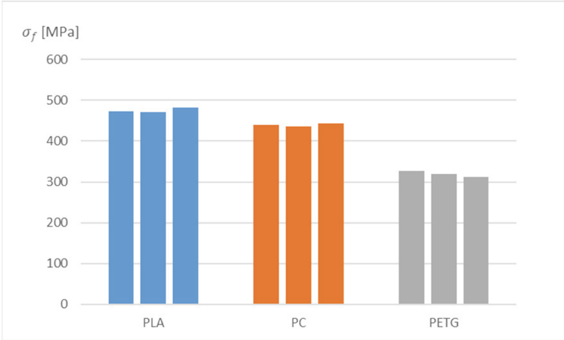


Fig. 8. Maximum flexural stress on all measured specimens

6. Conclusion

As presented in the paper the mechanical properties of the parts fabricated with FFF are under influence of the process parameters. When working with open-source systems the factors that influence the results are the humidity and temperature of the environment. But of interest for this research were the mechanical properties of the three materials. In order to have results that can be compared, same process parameters were used for fabrications of the specimens. Results presented in this paper present different behaviour of the different specimens, making them compatible for different applications.

The research is part of the Project "Hybrid composite structures" conducted at the Faculty of Mechanical Engineering in Skopje.

For further research it is plan to fabricate the specimens in various orientation along the x, y and z axis since the micro structure of the FFF parts shows significant anisotropy.

The experimental results from this paper will be compared with the results of the FEA analysis that are planned for further researches. If the results from the FE model show high correlation to the physical tests, we can use only FEA analysis for further researches, as are more efficient and save resources.

Acknowledgements

Authors would like to thank the Faculty of Mechanical Engineering in Skopje, for financing this project.

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