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The impact of 3D printing parameters on the tensile strength of polycarbonate (PC)

Danijela Pezer, Šimun Ćelić, Zvonimir Katić
University Department of Professional Studies, University of Split, Split, Croatia
Corresponding Author: dpezer@oss.unist.hr

Abstract
The research aims to investigate the impact of 3D printing parameters on the tensile strength of polycarbonate (PC) polymer material. Fused Deposition Modeling (FDM) 3D printing technology was used to make the test specimens. The 1B test specimens were made according to the EN ISO 527-2:2012 standard. A central composite design (CCD) was conducted with variable parameters, layer thickness and raster angle, while the material infill is constant and its value is 100% for all test samples. The tensile test was conducted on in-house tensile test machine. The conducted experiment determined the behavior of PC polymer material with different printing techniques and parameters

Keywords: *Tensile strength, Polypropylene, Additive manufacturing, FDM.*

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I. INTRODUCTION

Additive technology is increasingly represented in all spheres of life with various possibilities of application. The advantages of this technology are manifested through the possibility of manufacturing parts (products) with extremely complex geometry and the cost-effectiveness of manufacturing even small production series. In addition, the products obtained by additive technology are small in weight, and due to the above-mentioned characteristics, they are increasingly used in practice. It is also possible to combine materials with different properties and a wide range of colors is available. The choice of materials is still limited in relation to, for example, their availability in the injection molding process, and there is space for an improvement. It is still not possible to achieve high dimensional accuracy with additive technology, however, such a requirement is not placed on every product, and the widest application for now is in the production of prototypes. Considering the specifics of manufacturing and the various available production processes (technologies), by adjusting the parameters (of which there are a significant number), it is possible to significantly influence on mechanical properties of the product.

The author's previous research was based on testing the tensile strength of PLA and HI-PLA materials with regard to different layer thicknesses, the percentage of material infill and the type of filling [1, 2]. In this work, the impact on the tensile strength of polycarbonate (PC) will be examined on test samples obtained by FDM additive manufacturing technology with 100% material infill and variable parameters, layer thickness and raster angle (angle relative to the X axis of the printer substrate).

Considering the interesting area still insufficiently researched, there is an interest of other scientists on this topic. In the paper [3], the authors investigated the effect of raster angle on tensile strength, elastic modulus, flexural strength, flexural modulus and fracture toughness obtained by fused filament fabrication (FFF) for ABS material. In paper [4], the influence on the tensile strength of PLA material for 100% material infill by FDM process with a variable raster angle (0°, 30°, 45°, 60°, and 90°) was investigated, whereby the highest values were achieved at 0° and continuously decreased towards the angle of 90°. °. Effects of raster orientation (0°, 30°, 45° and 90°), infill rate (20%, 40%, 60%, 80% and 100%) and infill pattern (Fast Honeycomb, Full Honeycomb, Wiggle, Triangular, Grid and Rectilinear) was investigated in [5] for ABS polymer material. The results of tensile test show that the ultimate strengths are the largest for wiggle, 90°, and 0° patterns in descending order. Raster orientation along the printing direction lead to the largest tensile strength and specimen strength increases with infill rate. In [6] tensile and bending strength for PLA polymer material was investigated. The variable parameters that were used in an experiment infill ratio in % (50, 75, 100) and raster angle, ° (-45/+45, 0/90) with various printing speed, mm/s (30, 60, 90). Results for the tensile strengths of samples produced at 0/90° raster angle were higher than samples (-45/+45. The authors concluded that high print speed for FDM printed technology should be avoided because it leads to reduction of mechanical properties and there is no saving printing time. Also, the authors [7] investigated an impact of mechanical properties for PETG, PLA and ABS materials with variable factor raster angle (0°, 90°, 0/90°, 45° and 45/135°)

for all three materials and 75 test samples. PLA material achieved higher values of tensile strength than ABS and PETG. The optimum mechanical properties for PETG were achieved at 0° and 0/90° raster angles. ABS had the optimum properties at 0° and 45/135° raster orientations. For PLA material, 45° and 45/135° raster angles hold higher mechanical properties than other angles due to lower inter-bead voids.

II. MATERIAL AND METHODS

The test samples are made according to the EN ISO 527-2 standard [8] for the test sample type 1B (Figure 1) and dimensions of 1B specimen are shown in Table 1. The test samples are made of polycarbonate (PC) polymer material with FDM method on a 3D printer manufactured by Prusa i3 MK3S+. The diameter of the filament used is 1.75 mm. Recommended printing temperature is 270 - 310 °C, heated substrate temperature (bed temperature) is in the range 100 - 120 °C and printing speed 30-60 mm/min. A nozzle temperature in the amount of 275 °C, a bed temperature of 115 °C and a printing speed of 45 mm/s were selected for printing all test samples. For better adhesion between the first layer and the substrate, glue was used. The specimens were printed using a rectilinear infill with 100% infill density. The used software (slicer) is PrusaSlicer which is used to define the desired print parameters and generate G code.

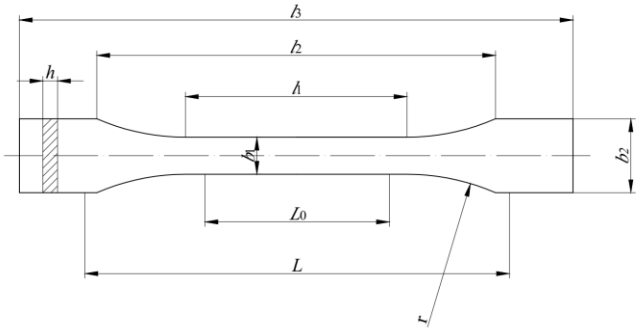
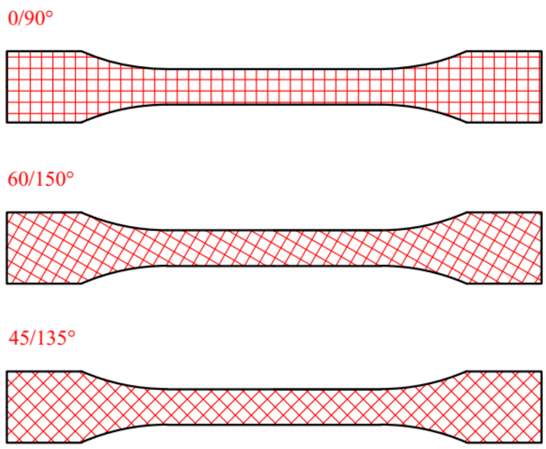


Figure 1: Test specimen type 1B according EN ISO 527-2 standard

Table 1: Dimensions of type 1B test specimen in millimeters, according to ISO 527-2 standard

Specimen type 1B, dimension in millimetres		
l_3	Overall length[a]	≥150
l_1	Length of narrow parallel-sided portion	60 ± 0.5
r	Radius	60 ± 0.5
l_2	Distance between broad parallel-sided portions[b]	108 ± 1.6
b_2	Width at ends	20.0 ± 0.2
b_1	Width at narrow portion	10.0 ± 0.2
h	Preferred thickness	4.0 ± 0.2
L	Initial distance between grips	115 ± 1

Figure 2 shows the selected parameters on the basis for which tests were performed (material infill 100%, layer thickness 0,2 mm and raster angle 45/135°) for the test specimens 1.3, 1.5, and 1.7 according to Table 2, that achieved the highest tensile strength.



Test specimen print parameters	
Print parameters	**Value**
Layer height (mm)	0.1, 0.2, 0.3
Infill percentage (%)	100
Infill orientation - raster angle (°)	0/90, 45/135, 60/90
Infill Pattern	Rectilinear
Number of infill layers	39, 20, 14
Shell thickness	0.9, 1.35
Number of shells	2, 3
Number of floor layers	0
Number of ceiling layers	0
Number of solid layers	39, 20, 14
Total number of layers	39, 20, 14

Figure 2: Test specimens with tree type of raster angle and print parameters value

In the Table 2 are listed FDM used printer parameters.

Table 2: FDM parameters

FDM parameters	
Parameter	**Value**
Nozzle diameter	0.4 mm
Prmary layer height	0.1 mm, 0.2 mm, 0.3 mm
Number of contours	2, 3
Printing speed	45 mm/s
Nozzle temperature	275 °C
Bed temperature	115 °C

In this study, as a part of the student master thesis, a central composite design was performed on 2 levels with two factors (k=2) and three repetitions (N_0=5) in the center, so the total number of measurement will be $N=2k+2k+N_0=22+2\cdot2+5=13$ states of the experiment. The main goal of the experiment is to determine the influence of independent variables, in this case layer thickness (mm) and raster angle (°) on tensile strength (MPa) for constant infill percentage 100% for all test specimens.

After the central composite design and the test specimens were made a tensile test experiment was conducted on the test specimens. The tensile test was conducted under temperature 23 ± 2 °C. The tensile test was performed at a test speed of 5 mm/min. The elastic modulus for all test specimens of PC polymer material used 2400 MPa. Figure 3 shows the 3D printed test samples 1.3, 1.5, 1.7 (according to Table 2) with same parameters (material infill 100%, layer thickness 0.2 mm and raster angle 45/135°).

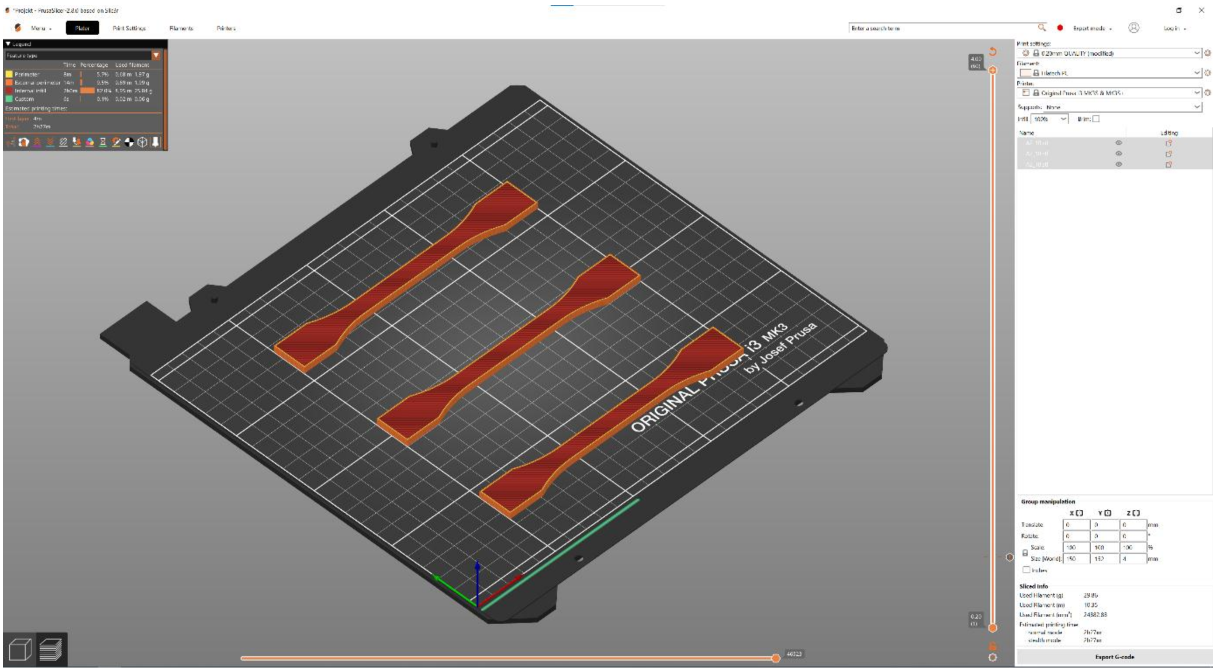


Figure 3: Parameter selection for the test specimens with same parameters 1.3, 1.5 and 1.7

III. EXPERIMENTAL STUDY

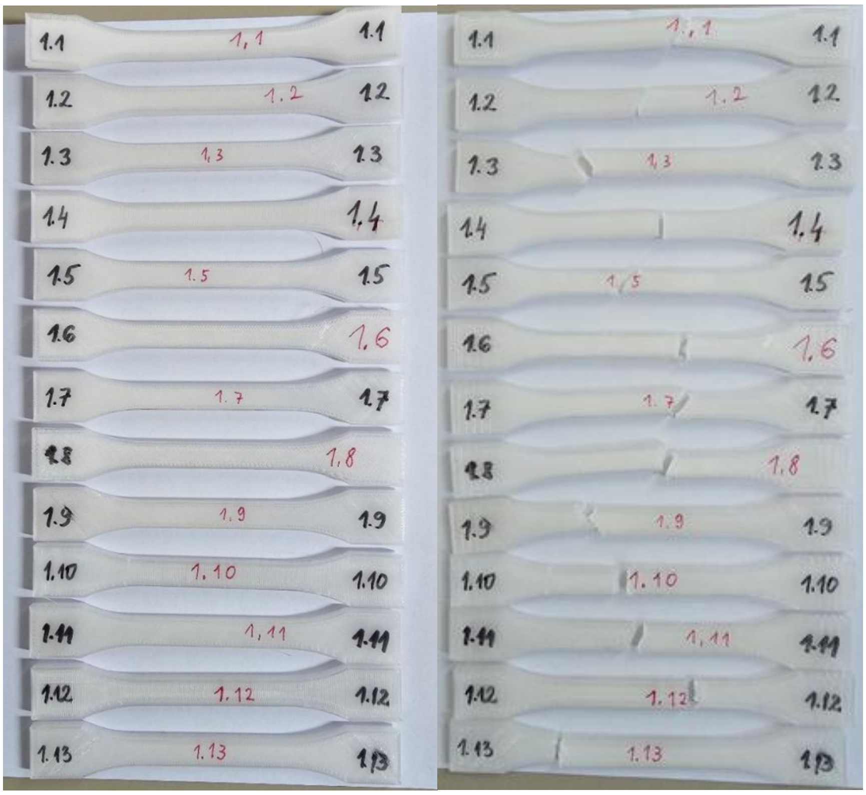
Table 3 shows the dimensions (b_1, h) of the test specimens which are measured before the tensile test experiment and the values which are measured after the tensile test experiment (achieved force F_m and tensile strength R_m). We can observe deviations (for elongation Δl) for test samples with the same parameters (1.3, 1.5, 1.7, 1.9 and 1.13) that are 3D printed with a time lag. Test specimens 1.3, 1.5 and 1.7 were printed simultaneously, while samples 1.9 and 1.13 were printed also together but with a time delay compared to the previous one which certainly contributed to the structure and properties of the test sample given the slightly different test conditions (temperature and relative humidity). The use of a closed 3D printer housing would also contribute to traceability, which would reduce heat losses.

Polycarbonate polymer material also proved to be a challenging material for 3D printing due to the need to adhere to the printer substrate, and the use of magnets was resorted to reduce the warpage of the test samples.

Before the experiment, it is necessary to mark each 13 test specimen on both ends. Figure 4 shows the test specimens before (4a) and after (4b) the tensile test performed. From Figure 4b we can see that the test specimen fractures are oriented as the same as the defined raster angle.

Table 3: Dimensions of the test specimens with the achieved values of force and tensile strength

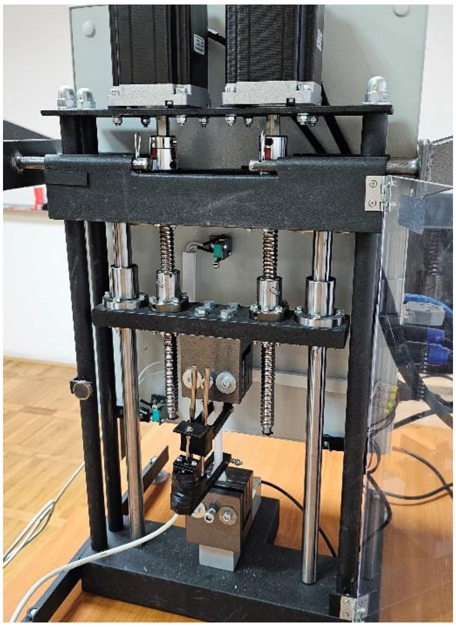
Test specimen	b_1 (mm)	h (mm)	A (mm)	Δl (mm)	F_m (N)	R_m (N/mm^2)
1.1	10.13	4.01	40.62	2.11	1983.58	**48.83** (min)
1.2	10.12	4.05	40.97	2.36	2261.19	**55.19** (max)
1.3	10.05	4.06	40.81	3.28	2194.43	53.77
1.4	10.13	4.03	40.82	0.86	2193.51	53.74
1.5	9.98	4.08	40.72	3.24	2080.26	51.09
1.6	9.92	4.16	41.27	5.03	2056.83	49.84
1.7	10.17	4.13	42.00	3.85	2192.42	52.20
1.8	10.12	4.02	40.68	3.60	2155.58	52.99
1.9	10.08	4.05	40.82	1.83	2161.18	52.94
1.10	10.17	4.08	41.49	3.18	2207.24	53.19
1.11	10.07	4.04	40.68	1.31	2119.64	52.11
1.12	10.02	4.16	41.68	2.11	2166.06	51.97
1.13	10.18	4.02	40.92	0.44	2072.67	51.03



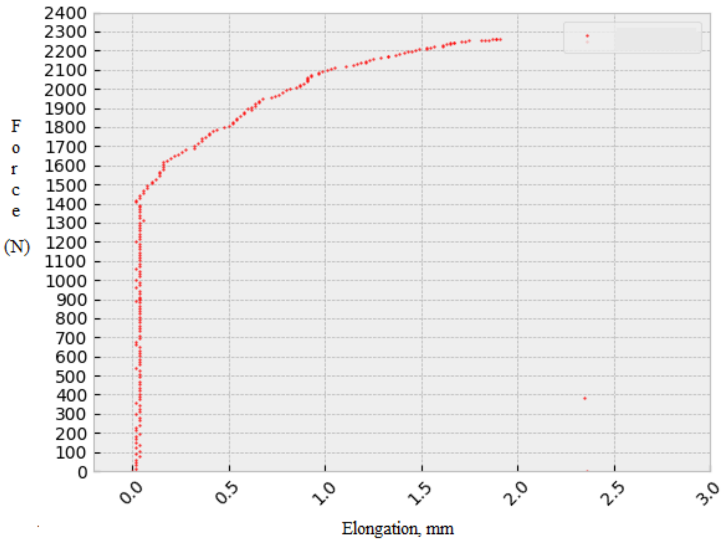
a) b)

Figure 4: Tensile test specimens before a) and after b) tensile test performance

The tensile test was performed on in-house tensile test machine [2] designed for loads up to 6 kN with force accuracy is ± 0.1 N (Figure 5a). The tensile test gives the force-elongation diagram as output results for all tested samples. Figure 5b show the stress-strain diagram and results for the test sample that achieved the highest tensile strength (test sample 1.2 according to Table 3). The maximum force F_m was achieved in the amount of 2261.19 N, while the maximum elongation was approximately 2,36 mm. Based on the maximum force and the cross-sectional area of the selected test sample, the tensile strength R_m was calculated and its value is 55.19 N/mm^2.



a)



b)

Figure 5: In-house performance of tensile test machine (a) with stress-strain diagram (b)

Table 4 shows the obtained results for tensile strength values for test specimens with different parameter values, layer thickness and raster angle which are generated using the Design-Expert software.

Table 4: Resultant matrix with corresponding response

Rectilinear 100% infill		Factor 1	Factor 2	Response
Std	**Run**	**Layer thickness**	**Raster angle**	**Tensile strength**
		mm	**°**	**MPa**
5	1	0.1	45/135	48.83 (min)
3	**2**	**0.1**	**60/150**	**55.19 (max)**
12	3	0.2	45/135	53.77
1	4	0.1	0/90	53.74
11	5	0.2	45/135	51.09
6	6	0.3	45/135	49.84
13	7	0.2	45/135	52.20
4	8	0.3	60/150	52.99
9	9	0.2	45/135	52.94
7	10	0.2	0/90	53.19
8	11	0.2	60/150	52.11
2	12	0.3	0/90	51.97
10	13	0.2	45/135	51.03

The F-value was used to determine the appropriateness of the obtained models and also using the maximum value of the coefficient of determination. The significance of the model was determined by analysis of variance – ANOVA (Table 5) for "Quadratic model" for tensile strength response. The Model F-value of 1.11

implies the model is not significant. There is 43.13% chance that an F-value this large could occur due to noise. The p-values less than 0.05 indicate that the model terms are significant.

In order to obtain a mathematical model for describing the influence of 3D printing parameters on the tensile strength of polycarbonate (PC) polymer material depending on the input technological parameters, will be able to calculate and predict the tensile strength, it is necessary to statistically process the results obtained experimentally.

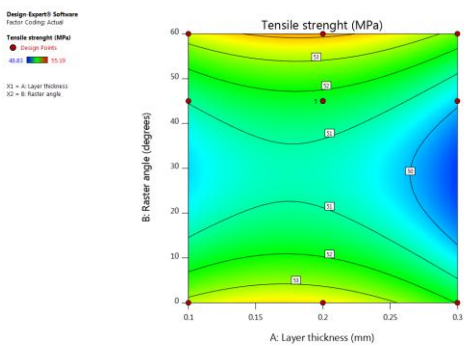
The given model is not significant for analysis in experimental space which means that experimental values have some deviations or some parameters are not set well. Additional tests need to be conducted and new data added to the model to determine if there is an impact on the significance of the model.

Table 5: Results of analysis of variance for Quadratic model for Tensile strength response

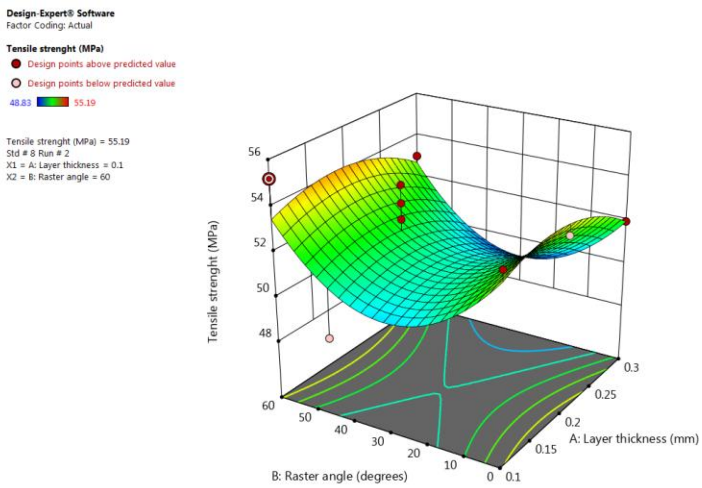
Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	15.74	5	3.15	1.11	0.4313	**not significant**
A- Layer thickness	1.53	1	1.53	0.5430	0.4852	
B-Raster angle	0.3220	1	0.3220	0.1140	0.7455	
AB	0.0745	1	0.0745	0.0264	0.8755	
A²	3.27	1	3.27	1.16	0.3177	
B²	13.60	1	13.60	4.81	0.0643	
Residual	19.77	7	2.82			
Lack of Fit	14.16	3	4.72	3.36	0.1360	**not significant**
Pure Error	5.61	4	1.40			
Cor Total	35.51	12				

The Lack of Fit F-value of 3.36 implies the Lack of Fit is not significant relative to the pure error. There is a 13.60% chance that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good because it is desirable model to fit.

Figure 6 shows a two-dimensional (6a) and three-dimensional (6b) representation of the response surface for tensile strength expressed in MPa for PC polymer material as a function of layer thickness expressed in millimeters (mm) and raster angle expressed in degrees (°).



a) two-dimensional graph representation



b) three-dimensional graph representation

Figure 6: 2D and 3D representation of the response surface

IV. CONCLUSION

The tensile strength of polycarbonate (PC) ranges from 55 to 75 MPa, and we can conclude that 3D printing technique provides satisfactory tensile strength (according to Table 4) with 100% material infill, and the results vary only slightly depending on the infill type and the defined raster angle. From Table 4, we can conclude that lower tensile strength values in a slightly smaller percentage, for layer thicknesses of 0.2 and 0.3

and also the raster angle 60/150° were achieved. The less favorable properties were achieved by the test sample with parameters of layer thickness 0.1 mm and raster angle 45/135°, where the tensile strength is R_m = 55.19 MPa. The obtained results do not deviate significantly from each other considering the set parameters, and the highest value of tensile strength Rm = 55.19 MPa was achieved for the raster angle 60/150° and the layer thickness 0.1 mm for test sample 1.2, and the force F_m = 2261.19 N was achieved.

By analyzing the results of all test samples, it can be concluded that with smaller values of layer thickness, higher values of tensile strength are achieved for the raster angle 0/90° and 60/150°. The results would certainly be affected by a change in the type of printer, a closed instead of an open housing type in order to maintain a constant temperature of all layers during printing.

For the test samples with raster angle 0/90°, the thickness of the layer has almost no effect on the tensile strength values, while the biggest differences for different layer thicknesses were achieved for the test samples with raster angle of 45/135°.

The results from the ANOVA showed that various combinations of the raster angle in combination with the variable layer thickness do not have a significant impact on the tensile strength, and for additional conclusions it is necessary to add new data to the model.

Table 3 also shows that the elongation for test samples 1.3, 1.5 and 1.7 is approximately, however for test samples 1.9 and 1.13 (which have the same 3D printed parameters as the previous 1.3, 1.5 and 1.7) they have significantly less elongation compared to each other. With this, we come to the conclusion that polymer materials are significantly subject to external influences, which certainly affects to the mechanical properties of the material, and the same should be taken into account during design the product and also during the exploitation.

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