

Experimental Study of Tensile Strength for 3D Printed Specimens of HI-PLA Polymer Material on In-house Tensile Test Machine

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Abstract. In the paper, a tensile test was performed on in-house made tensile test machine. Test specimens are 3D printed and made according to the ISO 527-2 standard. The specimens are made of HI-PLA (High Impact Polylactide) polymer material with pronounced resistance to impact toughness which is closer, according to its characteristics, to ABS material properties. The test specimens were printed by FDM additive technology with different layer thickness and material infill percentage, and a central composite design (CCD) was conducted. The conducted experiment resulted in force-elongation diagrams for 11 states of the test specimens, on the basis of which the tensile strength of the HI-PLA material was calculated. The obtained values were compared with the tensile strength values for ABS material.

Keywords. Tensile test, polymer materials, mechanical properties, tensile strength, PLA strong

1. Introduction

The mechanical properties of materials are extremely important when designing parts (elements), because they are used to determine the dimensions of construction elements, and are defined by experiments in the laboratory. The most important property of the material, strength, is determined by the tensile test. The test results are used to select a material that meets the given conditions and to predict the behavior of the influence of other types of force. Properties directly measured by the tensile test are yield strength, tensile strength, elongation and modulus of elasticity. Uniaxial tensile testing is most often used to obtain the mechanical characteristics of isotropic materials. During testing, standard test specimens are used according to ISO 527-1/2 or ASTM D 638 for polymer materials.

This paper deals with testing the tensile strength properties of HI-PLA (High Impact Polylactide) material, whose properties, according to the specified characteristics of the material manufacturer, approximately correspond to the properties of ABS material.

With HI-PLA, a higher value of strength and stiffness has been retained with improved toughness of the material (a property that is more pronounced in ABS), in regards to PLA material, which has less toughness, i.e. the material is brittle. Based on the above, HI-PLA material belongs to the group of hard and tough materials, according to polymer materials classification, considering stress – strain curves. [1].

2. Related works

In paper [2], a tensile test of PLA material was also performed, in which the values of maximum force in the amount of 1489,53 N and tensile strength 54,46 N/mm² were achieved on a standard test specimen with the print parameters layer thickness 0,3 mm and material infill 100%.

According to [3], tensile test was performed on four test specimens and four different printing angles along all axes (X, Y, Z) and five different raster angles. It is established that the printing angle significantly affects the mechanical properties of PLA material. It was also determined that a lower percentage of material infill can reduce material costs but it leads to instability of the mechanical properties of the tested specimens.

In paper [4], a tensile test was performed on type 4 test specimens, according to the ASTM D638 standard for PLA material. The parameters taken into account during 3D printing are: layer thickness, infill percentage, flow rate. The highest achieved tensile strength was achieved at a layer thickness of 0,15 and material infill 100%. In fact, by increasing the thickness of the layer at 100% material infill, the tensile strength value was lower. The possibility for such results lies in the fact that the cohesion of the deposited layers is low. The printing speed is directly proportional to the thickness of the layer.

The influence of 10 different filling patterns of 3D printed PLA material was investigated in [5]. The following parameters were taken into account: speed 60 mm/s, layer height 0,1 mm, infill density 80%. It was determined by experiment that the pattern of material infill significantly affects the tensile strength. It was shown that the highest tensile strength value (32,174 MPa) was achieved on the "concentric" specimen, while the lowest tensile strength value (was achieved with the "triangles" specimen).

In paper [6], a tensile test was performed on PLA material, where four parameters were taken into account during printing: model filling, filling shape, layer thickness and model orientation. The experiment found that the infill percentage has the greatest influence on the tensile strength. The next influencing parameters are the thickness of the layer and the shape of the filling. The ANOVA statistical analysis determined that the model orientation factor (0 and 45 degree) has no influence on the tensile strength.

In [7], testing was performed on in-house PLA filament (from granules), produced by the extrusion process, for different printing orientations (Flat, Flat-45, Edge, Edge-45, Upright, Upright-45) and a layer thickness of 1,2 mm, 2,0 mm and 2,8 mm. The results were compared with the results of the tested commercial PLA material, where there is no significant difference in the results considering the materials used. A total of 108 (54 in-house + 54 commercial material) test specimens were tested. Test specimens printed for Edge-45, Upright, Upright-45 orientation showed worse tensile load carrying capacity.

The paper [8] presents the results of an experiment conducted on PLA material. Seven parameters were selected: infill pattern, layer height, infill density, printing velocity, raster orientation, outline overlap, and extruder temperature and also their interactions. Their influence on Young's modulus and yield strength was also shown. The parameters with the greatest influence are infill density, infill pattern, printing velocity and printing orientation. Other parameters did not show significance on Young's modulus and yield strength.

3. Methodology

3.1. Test specimens

It is necessary to conduct a tensile test on the tensile test machine, during which the force and elongation of the test specimen are measured, and the force-elongation diagram (Hooke's diagram) is generated based on these data. The test specimens on which the test was carried out were made according to the ISO 527-2 standard for the test specimen type 1A, which is shown in Figure 1. The dimensions of the used test specimen are shown in the Table 1.

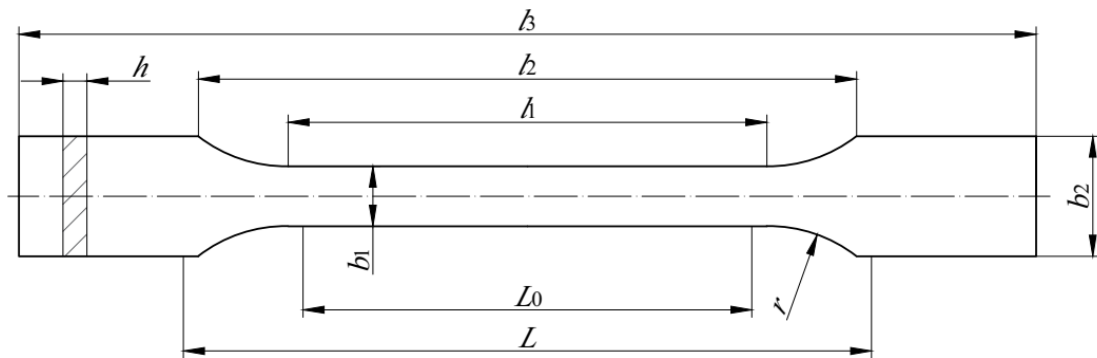


Figure 1. Test specimen type 1A according ISO 527-2 standard

Table 1. Dimensions of type 1A test specimen in millimetres, according to ISO 527-2 standard [9]

<i>Specimen type 1A, dimension in millimetres</i>		
l_3	Overall length ^a	170
l_1	Length of narrow parallel-sided portion	80 ± 2
r	Radius	24 ± 1
l_2	Distance between broad parallel-sided portions ^b	$109,3 \pm 3,2$
b_2	Width at ends	$20,0 \pm 0,2$
b_1	Width at narrow portion	$10,0 \pm 0,2$
h	Preferred thickness	$4,0 \pm 0,2$
L_0	Gauge length (preffered)	$75,0 \pm 0,5$
	Gauge length (acceptable if required for quality control or when specified)	$50,0 \pm 0,5$
L	Initial distance between grips	115 ± 1

3.2. Material

The test specimens were made of HI-PLA material, trade name PLA Strongman™ TDS manufactured by AzureFilm. The diameter of the filament used for 3D printing is 1.75 mm. Recommended printing temperature is 200 - 230 °C, heated bed temperature (which is not required) in range 50 - 60 °C and printing speed 40 - 50 mm/min. The test specimens were printed on a Prusa 13 3D printer.

AzureFilm HI-PLA is a filament with high performance designed for applications that require high impact toughness. HI-PLA filament has high beauty of 3D printed details, simple processability such as PLA filament (there is no warping, and no harmful smells) and also high impact toughness such as ABS filament [10].

Figure 2 shows a comparison of the mechanical properties (stiffness, strength, impact toughness, elongation, temperature resistance) and printing recommendations of PLA, ABS and HI-PLA according to the test data of the material manufacturer.

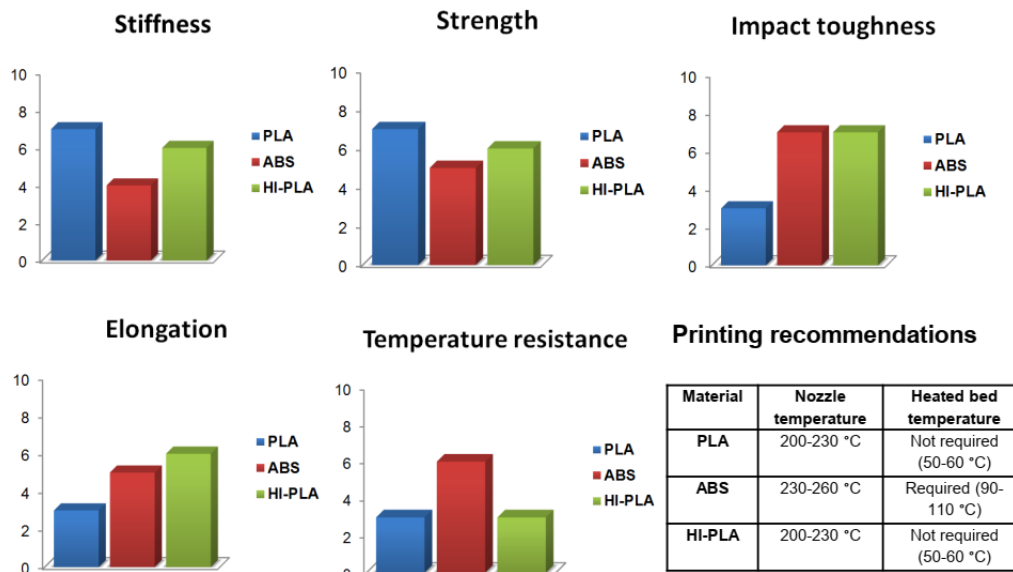


Figure 2. Material comparison for PLA, ABS and HI-PLA [10]

From the diagram in Figure 2, it can be seen that the stiffness and strength are slightly lower for HI-PLA compared to PLA, while the impact toughness and elongation are significantly higher for HI-PLA compared to PLA. The impact toughness of HI-PLA is equal to the values for ABS, while the elongation values achieved with HI-PLA are slightly higher compared to ABS material. Temperature resistance is significantly higher for ABS material compared to PLA and HI-PLA, whose values are at the same level.

3.3. Tensile test in –house machine

The tensile test was conducted on a tensile test in-house machine that was made for the master thesis [11] at the University Department for Professional Studies of the University of Split. The tensile test machine is designed for loads up to 6 kN. The tensile test machine is driven by two stepper motors, and each of the motors should produce a force of 3000N. The weight of the tensile test machine is 57 kg, and the dimensions are 431 mm x 722 mm x 711 mm. The distance between the grippers is from 0 to 150 mm, the travel speed of the movable gripper is from 1 to 20 mm/min, the force accuracy is $\pm 0,1$ N and for displacement measurement accuracy is 0,01 mm. The construction of the tensile test machine is shown in Figure 3.

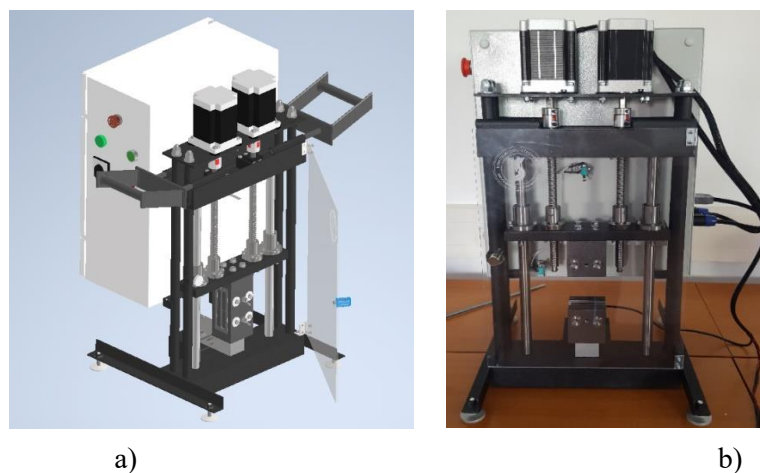


Figure 3. In-house performance of tensile test machine [11]

4. Experimental study

The selected type of test specimen 1A according to the ISO 527-2 standard was drawn in the Autodesk AutoCAD program, after which the file was converted into the appropriate format for 3D printing (.stl). For the selected 3D printer, all parameters required for printing are defined in the appropriate program and G-code is generated, which is transferred to the 3D printer using an SD card. This was followed by the printing of all the 11 states of the test specimens. During the printing test specimens made of HI-PLA material, the medium temperature 215 °C of the print nozzle was selected, while the heated bed temperature was 60 °C. The printing speed is set automatically to the printer and is 45 mm/min and the straight line structure of the print was used.

Figure 4 shows the selected parameters on the basis for which tests were performed (material infill 100%, and layer thickness 0,3 mm) for the test specimen 1.9 according to Table 2, that achieved the highest tensile strength.

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 ($N_0 = 3$) in the center, so the total number of measurement will be $N = 2^k + 2k + N_0 = 2^2 + 2 \cdot 2 + 3 = 11$ states of the experiment. The main goal of the experiment is to determine the influence of independent variables, in this case material infill percentage (%) and layer thickness (mm) on tensile strength (MPa).

The central composite design enables obtaining the response surface within defined limits for the purpose of obtaining optimal parameters, i.e. the largest amount of information is enabled with the implementation of the smallest number of test conditions (in this case 11) compared to a factorial experimental design. 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 performed in accordance with the ISO 527-1 [12] standard under appropriate conditions (the preferred atmosphere is 23 ± 2 °C). The tensile test was performed at a test speed of 5 mm/min.

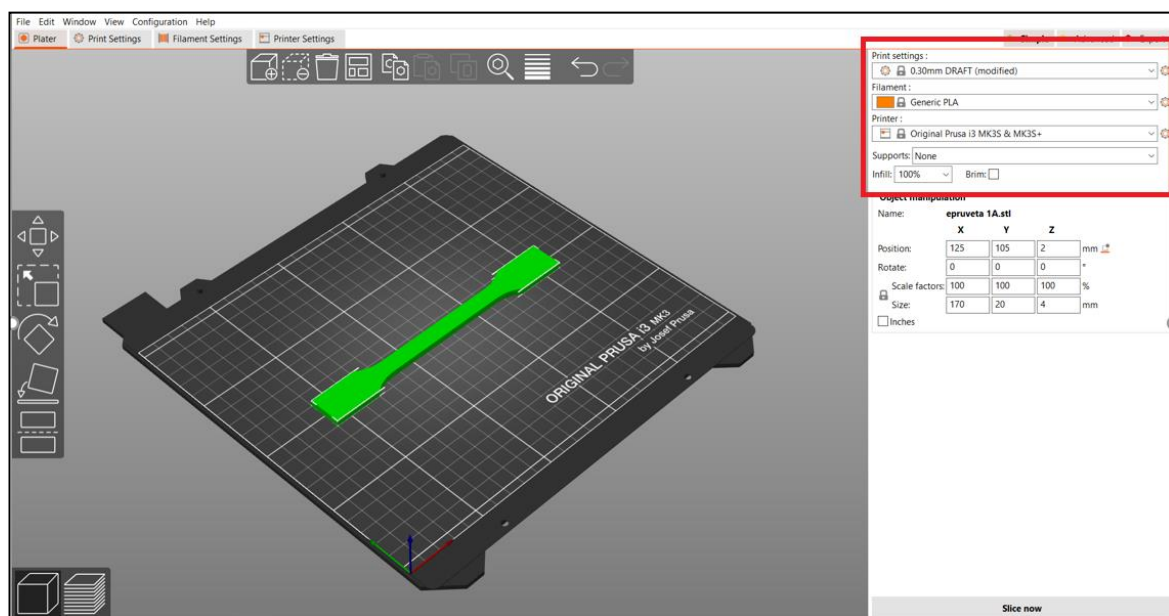


Figure 4. Parameter selection for the test specimen which achieved the highest value of tensile strength

Table 2 shows the dimensions of the test specimens which are measured before the tensile test experiment and the measured values of the achieved force and the calculated values of the tensile strength after the tensile test experiment.

Table 2. Dimensions of the test specimens with the achieved values of force and tensile strength

Test specimen	b_1 (mm)	h (mm)	A (mm)	F_m (N)	R_m (N/mm ²)
1.1	10,12	3,83	38,76	1579,67	40,76
1.2	9,97	3,84	38,28	1549,29	40,47
1.3	9,90	3,86	38,21	1106,04	28,94
1.4	9,93	3,83	38,03	1132,35	29,78
1.5	9,83	3,82	37,55	1021,64	27,20
1.6	9,92	3,80	37,70	962,08	25,52
1.7	9,90	3,80	37,91	1113,78	29,38
1.8	9,90	3,83	37,91	1111,25	29,31
1.9	9,80	3,84	37,63	1602,84	42,59 (max.)
1.10	9,92	3,85	38,20	927,69	24,29 (min.)
1.11	9,94	3,85	38,27	1130,45	29,54

Before the experiment, it is necessary to mark each test specimen on both ends. Figure 5 shows the test specimens before and after the tensile test.

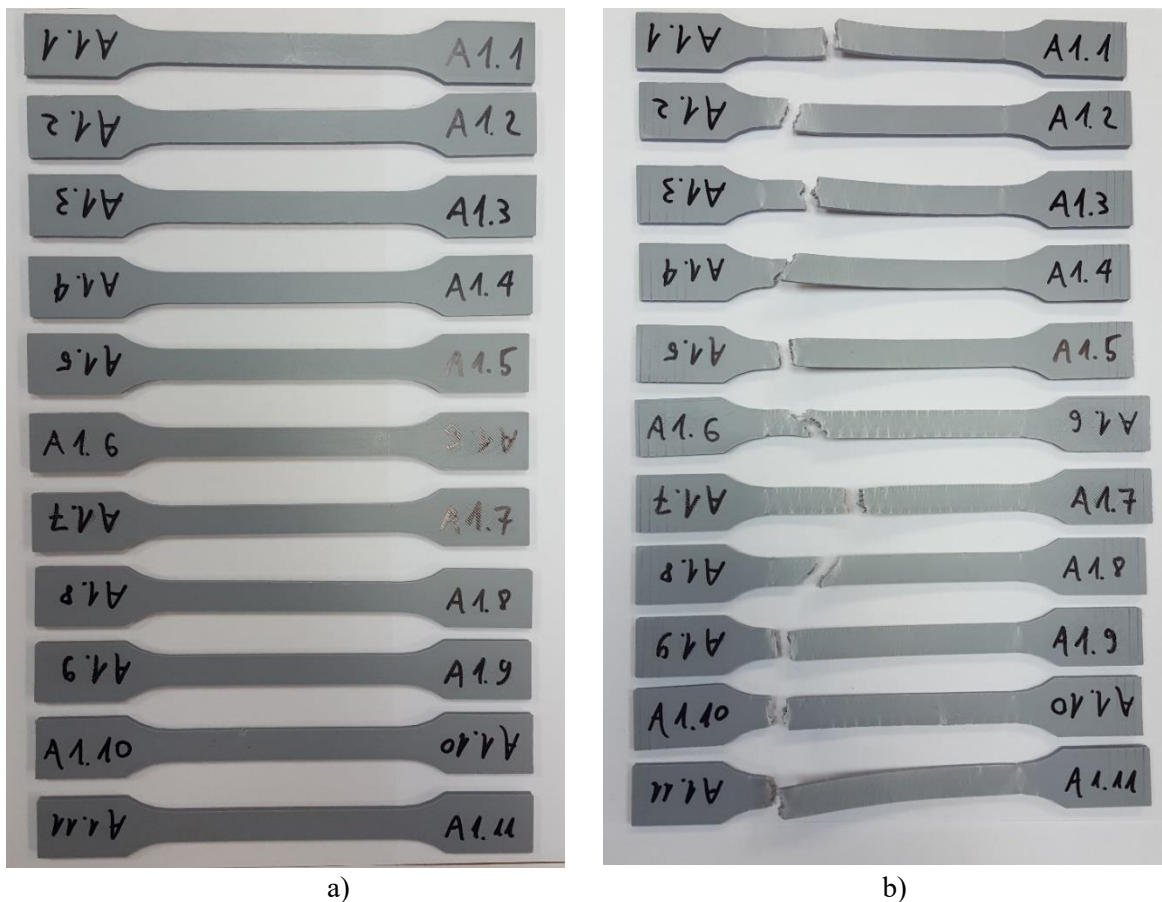


Figure 5. Tensile test specimens before a) and after b) tensile test performance

5. Results

The tensile test gives the force-elongation diagram as output results for all tested specimens. Figure 6 shows the results only for the test specimen that achieved the highest tensile strength (test specimen 1.9 according to Table 2). The maximum force F_m was achieved in the amount of 1602,84 N, while the maximum elongation was approximately 5 mm. Based on the maximum force and the cross-sectional area of the selected test specimen, the tensile strength R_m was calculated and its value is 42,59 N/mm². The obtained tensile strength value for HI-PLA is between the values for ABS and PLA (higher than ABS and lower than PLA), which corresponds to the test values of the material manufacturer shown in Figure 2.

Table 3 shows the obtained tensile strength values for used different values of layer thickness and infill percentage of the material, i.e. the resulting matrix with responses for the tested specimens. The table 3 was generated using Design Expert software. The results of tensile strength measurements were statistically processed and a mathematical model was created based on the entered values.

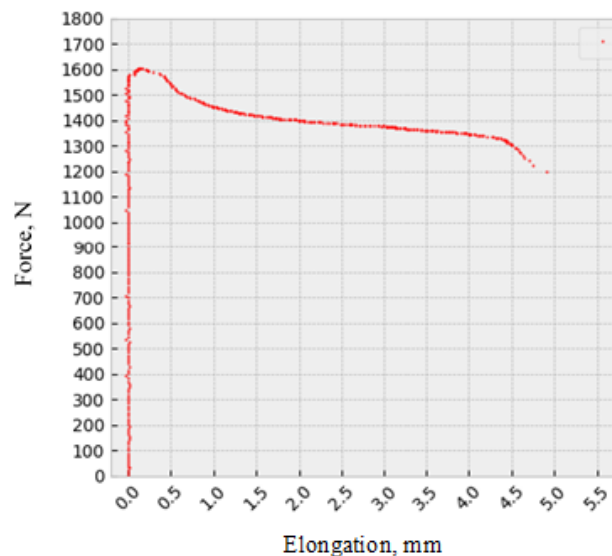


Figure 6. Force-elongation diagram for the test specimen which achieved the highest tensile strength

Table 3. Resultant matrix with response

Std	Run	Factor 1	Factor 2	Response
		A: Infill %	B: Layer thickness mm	Tensile strength MPa
2	1	100	0,1	40,76
6	2	94,1667	0,2	40,47
7	3	65	0,116667	28,94
10	4	65	0,2	29,78
5	5	35,8333	0,2	27,2
3	6	30	0,3	25,52
8	7	65	0,283333	29,38
11	8	65	0,2	29,31

4	9	100	0,3	42,59
1	10	30	0,1	24,29
9	11	65	0,2	29,54

Table 4 represents the results of ANOVA for Quadratic model for *Tensile strength* response. The *Model F-value* of 266,14 implies the model is significant. There is only a 0,01% chance that an *F-value* this large could occur due to noise.

The *Lack of Fit F-value* of 8,77 implies the *Lack of Fit* is not significant relative to the pure error. There is a 10,40% chance that a *Lack of Fit F-value* this large could occur due to noise, which indicating a well-fitted model.

Table 4. Results of analysis of variance (ANOVA) for Quadratic model for *Tensile strength* response

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	416,36	5	83,27	266,14	< 0,0001	significant
<i>A-Infill</i>	369,09	1	369,09	1179,63	< 0,0001	
<i>B-Layer thickness</i>	2,18	1	2,18	6,96	0,0460	
<i>AB</i>	0,0900	1	0,0900	0,2876	0,6147	
<i>A²</i>	40,36	1	40,36	129,00	< 0,0001	
<i>B²</i>	3,88	1	3,88	12,41	0,0169	
<i>Residual</i>	1,56	5	0,3129			
Lack of Fit	1,45	3	0,4847	8,77	0,1040	not significant
<i>Pure Error</i>	0,1105	2	0,0552			
<i>Cor Total</i>	417,93	10				

Figure 7 shows a three-dimensional representation of the response surface for tensile strength expressed in MPa for HI-PLA material as a function of material infill expressed in % and layer thickness expressed in mm.

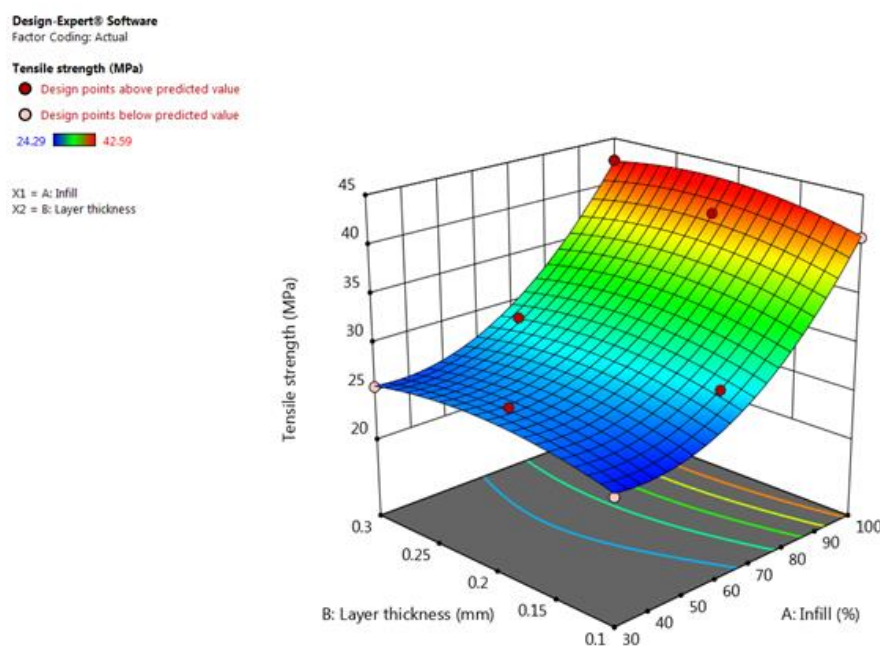


Figure 7. 3D representation of the response surface

Considering the results according to Table 3 and Figure 7, it can be concluded that the infill material percentage has a significantly greater importance on the tensile strength compared to the thickness of the layer. By increasing the infill material percentage, the tensile strength of the polymer material HI-PLA increases. The highest tensile strength value was achieved at a layer thickness of 0,3 mm. The lowest tensile strength value was achieved at a layer thickness of 0,1 mm.

The highest value of tensile strength was achieved at the 100% material infill, which could be expected because specimens that do not have 100% material infill have a hollow structure. Considering the specificity of the applied manufacturing process, the tensile strength results obtained for a material infill percentage with less than 100% are probably not the most relevant values, considering the appearance of the interior structure (between the first and last layer) of the test specimen. Of course, on the final values also affect the printing method (the stacking layers) and orientation of the fibers.

6. Conclusion

Analyzing the results according to Table 3, it can be seen that the specimen with the highest tensile strength of 42,59 MPa (achieved force 1602,84 N) is the specimen with a layer thickness of 0,3 mm and a material infill percentage 100%. The lowest tensile strength achieved is 24,29 MPa (realized force 927,69 N), with a specimen with a layer thickness of 0,1 mm and a material infill percentage 30%. However, the remaining specimen with material infill percentage 100% and a layer thickness of 0,1 gives only a slightly lower tensile strength value compared to a layer thickness of 0,3 with a material fill 100%. The specimen with an infill material percentage 94,166% and a layer thickness of 0,2 also gives a slightly lower tensile strength value compared to a layer thickness of 0,3 with an infill material percentage 100%.

Therefore, it can be concluded that the most important role in increasing the tensile strength have the material infill percentage. When the material infill percentage is 100%, the material is the strongest. The thickness of the layer has a slightly smaller influence on the tensile strength, and it has been shown that when thickness layer increase, the tensile strength of the material also increases. The strength of the material is also affected by the printing speed, i.e. as it increases, the strength decreases. In this case, the speed is constant for all test specimens and it is 45 mm/s.

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