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Experimental Study of Tensile Strength for 3D Printed Specimens of PLA material

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ABSTRACT: *Considering the importance of the mechanical material properties in the process of the design elements construction, this paper compares the results of the tensile strength of PLA material for two types of infill pattern and different percentages of material infill on test samples made on a 3D printer. Test samples according to the EN ISO 527-2 standard were made by the FDM process of additive technology and tested on an in-house tensile test machine. A central composite design (CCD) experiment was created using Design-Expert software for the test samples. The samples are made as Line and Gyroid infill pattern with layer thickness in range from 0.1 – 0.3 mm and with material infill percentage in range from 30–100%. The test results showed that is optimal to make test samples with a medium layer thickness of 0.2 mm for the Line material infill, because relatively high tensile strength (R_m) values are achieved with reduced printing time, while with Gyroid pattern infill, by increasing the thickness of the layer, higher tensile strength values are achieved.*

KEYWORDS: *tensile strength, 3D print, infill pattern, PLA specimens*

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I. INTRODUCTION

Additive manufacturing is increasingly represented on the market due to the possibility of manufacturing products at significantly lower costs compared to the conventional processes. Additive technology makes it possible to create models with very complex geometries, and they are most often used to create prototypes and parts of molds and tools. Conventional processes have an advantage over additive technology when high accuracy and dimensional stability are required. Products obtained by the 3D printing process, as part of additive technology, are created directly from the 3D CAD model, and it is not necessary to plan the production process or make a mold, which significantly affects to the amount of total costs. Additive technology is still in development, in terms of the different procedures (FDM, SLS, SLA, PolyJet, etc.) that are applied [1-4] and the type of materials that are available today. The mentioned limitation (type of the material) is observed in relation to, for example, the widespread injection molding process.

Considering that, the procedures of additive technology, such as 3D printing, are relatively new procedures (taking into account the new materials appearing on the market) with different possibilities during 3D printing, there is a need for various experiments, especially the examination of mechanical properties (both, the materials and the construction parts). Various studies of the influence of 3D printing parameters on the mechanical properties of PLA materials have been conducted in the literature [5-10].

This paper presents the results of the conducted experiment, central composite design (CCD) with three repetitions in the center for PLA polymer material. During the 3D printing of test samples, the printing speed and temperature are used as constant, while parameters the layer thickness and the percentage of material infill were variable. The test samples were made according to the experimental plan created in the Design-Expert software for two different pattern material infills: *Line* and *Gyroid*. The test samples were conducted to the mechanical test of tensile strength on an in-house tensile test machine. The obtained results were compared and the conclusions presented in the paper.

Different pattern infill geometries are used for different purposes (Table 1) according to [11]. Available geometries are determined by the software (slicer) used for a particular 3D printer.

II. MATERIAL AND METHODS

The test samples are made according to the EN ISO 527-2 standard for the test sample type 1A (Fig. 1). The test samples are made of PLA material on a 3D printer manufactured by Ender3Pro. PLA material is a material of high stiffness and strength, low breaking elongation and low impact toughness [12]. The diameter of the filament used is 1.75 mm. Recommended printing temperature is 200-230 °C, heated substrate temperature (not required) is in the range 50-60 °C and printing speed 40-50 mm/min. A nozzle temperature in the amount of 215 °C, a working surface temperature of 60 °C and a printing speed of 45 mm/s were selected for printing all test samples. The used software (slicer) is Ultimaker Cura, which is used to define the desired print parameters and generate G code.

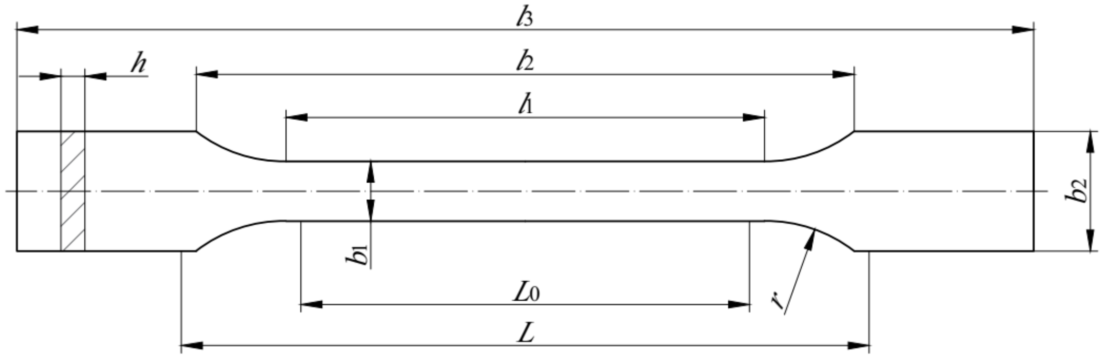
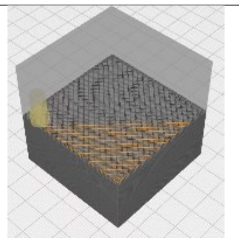
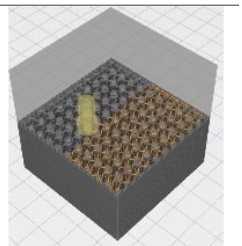


Figure 1: Test specimen type 1A according EN ISO 527-2 standard

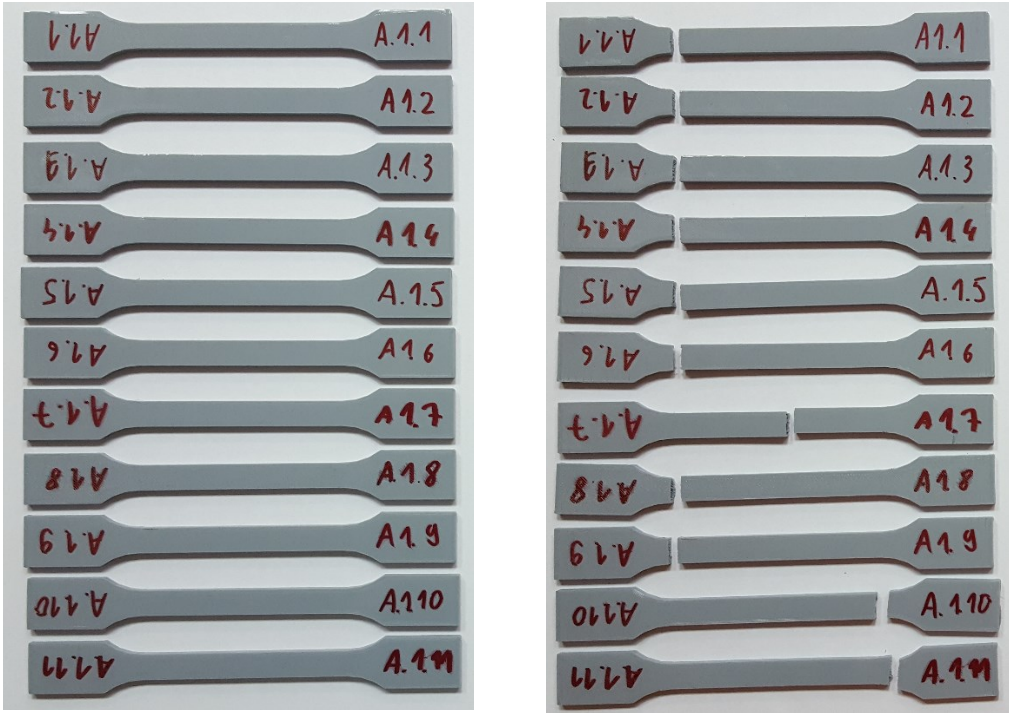
The purpose of the experiment was to determine the influence of the type of the pattern infill (according to the Table 1) on the tensile strength of the material.

***Table 1.* Selected types of 3D pattern infill geometry for experiment implementation**

Infill pattern type	Purpose	Pattern infill geometry
Line	It consists of several parallel lines per layer, with each layer passing over the previous one at an angle of 90°. The samples do not overlap each other on the same layer→reinforcement in two dimensions. Relatively fast printing.	
Gyroid	Alternating wavy print lines. It enables almost isotropic mechanical properties. Weaker along the Z axis, resistant to shear along the X and Y axes. Suitable for flexible materials. Printing a sample takes a little longer than other prints.	

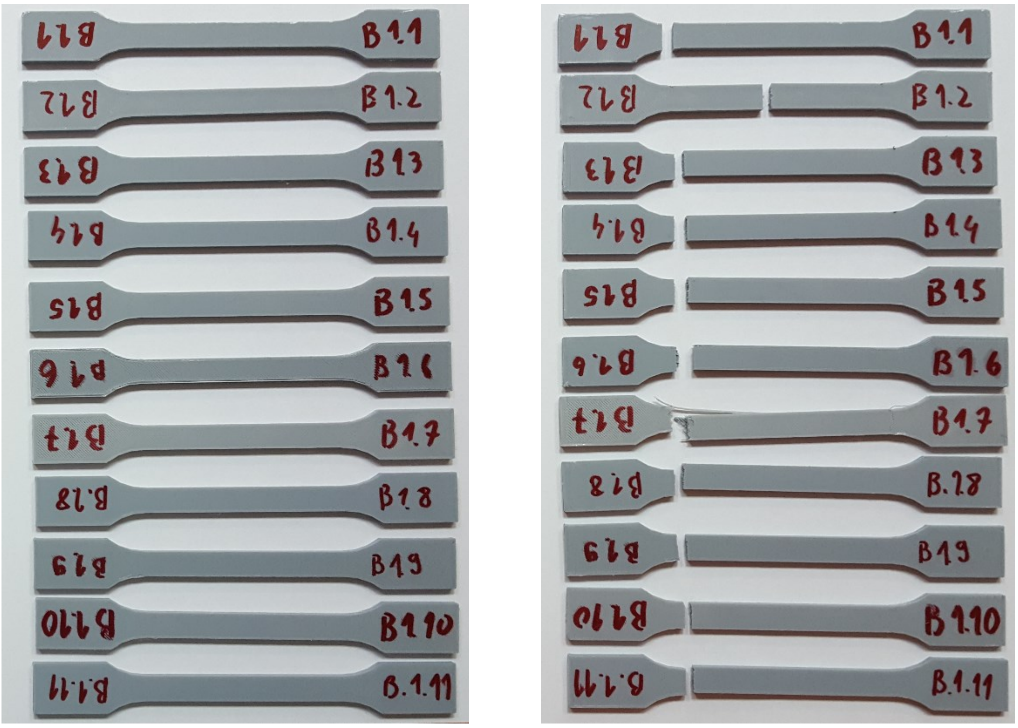
According to the experimental design plan, the test samples were made with different infill percentages and different layer thicknesses for *Line* and *Gyroid* type of infill pattern. The 11 test samples for *Line* infill pattern (group A indicated in the following text) and 11 test samples for *Gyroid* infill pattern (group B indicated in the following text) were made.

Before the experiment, it is necessary to mark each test sample on both ends. Fig. 2 and Fig. 3 shows the test samples [13] before and after the tensile test for *Line* ad *Gyroid* infill patterns.



a) b)

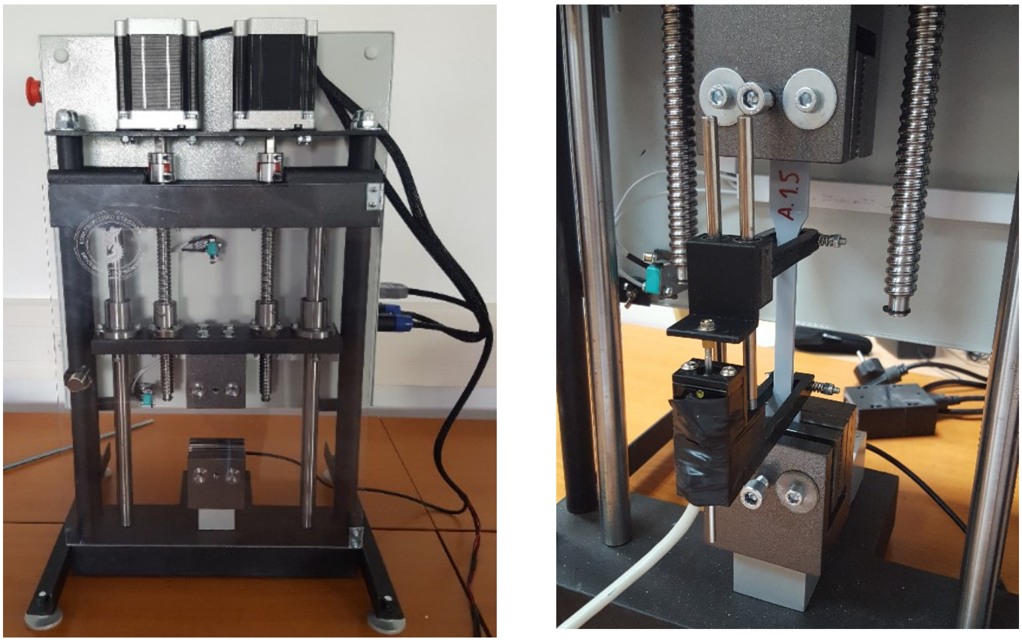
Figure 2: Tensile test "A" specimens before a) and after b) tensile test performance



a) b)

Figure 3: Tensile test "B" specimens before a) and after b) tensile test performance

A tensile strength test was conducted on in-house tensile test machine for polymer materials testing. The tensile test machine is designed for a load up to 6 kN. It is driven by two servomotors, while each of these can produce a force of 3000 N. The tensile test machine [12] and also the method of the experiment conduction is shown on Fig. 4.



a) In-house tensile test machine

b) Conduction of tensile test experiment for A 1.5 specimen

Figure 4: Tensile test experiment

Table 2 shows the dimensions of the test samples which are measured before the tensile test experiment and the measured values (during the tensile test experiment) of the achieved force, and also the calculated values of the tensile strength after the tensile test experiment.

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

Line **infill pattern**

A - test samples	b_1 (mm)	h (mm)	A (mm)	Fm (N)	Rm (N/mm²)
A 1.1	10.05	3.95	39.697	1706.26	**42.98**
A 1.2	10.1	3.95	39.895	1637.51	41.05
A 1.3	10.1	4	40.4	1071.51	26.52
A 1.4	10.1	3.95	39.895	1091.06	27.52
A 1.5	10.15	3.95	40.092	1268.32	31.63
A 1.6	10.2	4	40.8	891.54	21.85
A 1.7	10.15	3.9	39.58	923.19	23.32
A 1.8	10.1	3.95	39.895	1011.60	25.35
A 1.9	10.1	4.05	40.90	1473.59	36.02
A 1.10	10.1	3.95	39.895	1038.13	26.02
A 1.11	10.1	3.9	39.39	1008.51	25.60

Gyroid **infill pattern**

B -test samples	b_1 (mm)	h (mm)	A (mm)	Fm (N)	Rm (N/mm²)
B 1.1	10.1	3.85	38.885	1548.41	39.82
B 1.2	10.1	3.85	38.885	1021.74	26.27
B 1.3	10.1	3.85	38.885	900.85	23.16
B 1.4	10.1	3.9	39.39	1004.99	25.51
B 1.5	10.15	3.85	39.077	797.44	20.40
B 1.6	10.05	3.85	38.692	1245.95	32.20
B 1.7	10	3.9	39	572.48	14.67
B 1.8	10.1	3.85	38.885	1071.34	27.55
B 1.9	10.2	3.9	39.78	1669.22	**41.96**
B 1.10	10.2	3.9	39.78	657.13	16.51
B 1.11	10.1	3.8	38.38	1170.70	30.50

III. RESULTS AND DISCUSSIONS

Table 3 shows the obtained tensile strength values for used different values of layer thickness and infill percentage of the material for *Line* and *Gyroid* infill patterns. The data from Table 3 were generated using the Design-Expert software. The results obtained from the experimental tests were statistically processed using the Design-Expert software, and models were created to describe the influence of input factors on the measured size. The appropriateness of the obtained models was determined using the *F*-test as well as using the maximum value of the coefficient of determination, i.e. the adjusted and predicted coefficient of determination. The significance of the model and response polynomial terms was determined by analysis of variance (ANOVA). In order to obtain a mathematical model for describing the influence of 3D printing parameters on the tensile strength of PLA polymer material, i.e. a model that, 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.

Table 3. **Resultant matrix with corresponding response**

Line infill		Factor 1	Factor 2	Response
Std	Run	Infill	Layer thickness	Tensile strength
		%	mm	MPa
2	**1**	**100**	**0.1**	**42.98 max**
6	2	94.1667	0.2	41.05
7	3	65	0.116667	26.52
10	4	65	0.2	27.52
5	5	35.8333	0.2	31.63
3	6	30	0.3	**21.85 min**
8	7	65	0.283333	23.32
11	8	65	0.2	25.35
4	9	100	0.3	36.02
1	10	30	0.1	26.02
9	11	65	0.2	25.60

Gyroid infill		Factor 1	Factor 2	Response
Std	Run	Infill	Layer thickness	Tensile strength
		%	mm	MPa
2	1	100	0.1	39.82
6	2	94.1667	0.2	26.27
7	3	65	0.116667	23.16
10	4	65	0.2	25.51
5	5	35.8333	0.2	20.40
3	6	30	0.3	32.20
8	7	65	0.283333	**14.67 min**
11	8	65	0.2	27.55
4	**9**	**100**	**0.3**	**41.96 max**
1	10	30	0.1	16.51
9	11	65	0.2	30.50

The analysis of variance indicates that the dependence of the tensile strength of the material on the parameters of 3D printing for the *Line* infill pattern of the material can best be described by a reduced quadratic mathematical model. The analysis of variance also indicates that the dependence of the tensile strength of the material on the 3D printing parameters for the *Gyroid* infill pattern of the material can best be described by a linear mathematical model. The aforementioned analysis of variance is shown in Tables 4 (*Line* infill pattern) and 5 (*Gyroid* infill pattern).

The Table 4 represents the results of analysis of variance (ANOVA) for "Quadratic model" for tensile strength response for *Line* infill patterns. The Model *F*-value of 20.85 implies the model is significant. There is only a 0.23% 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 this case A, B, A^2, B^2 are significant terms of the model. Analysis of variance also indicate a significant influence of factors A and A^2. This confirms the influence of material infill percentage on the tensile strength of the material.

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

Source	***Sum of Squares***	***df***	***Mean Square***	***F-value***	***p-value***	
Model	491.62	5	98.32	**20.85**	0.0023	significant
A-Infill	281.96	1	281.96	59.79	0.0006	significant
B-Layer thickness	35.32	1	35.32	7.49	0.0409	significant
AB	1.95	1	1.95	0.4127	0.5489	not significant
A²	172.07	1	172.07	36.49	0.0018	significant
B²	52.07	1	52.07	11.04	0.0209	significant
Residual	23.58	5	4.72			
Lack of Fit	20.76	3	6.92	**4.91**	0.1739	not significant
Pure Error	2.82	2	1.41			
Cor Total	515.19	10				

Values greater than 0.1 indicate that the model terms are not significant. The *Lack of Fit* F-value of 4.91 implies the Lack of Fit is not significant relative to the pure error. There is a 17.39% chance that a Lack of Fit *F*-value this large could occur due to noise, which indicating a well-fitted model.

The Table 5 represents the results of analysis of variance (ANOVA) for „Linear model“ for tensile strength response for *Gyroid* infill pattern. The Model *F*-value of 1.88 implies the model is not significant. There is a 25.32% chance that an *F*-value this large could occur due to noise.

The *Lack of Fit F*-value of 12.83 implies the *Lack of Fit* is not significant relative to the pure error. There is a 7.31% chance that a *Lack of Fit F*-value this large could occur due to noise, which indicating a non-well-fitted model and the reduction of model is needed.

For the *Line* infill pattern, the deviations from the *Lack of fit* model are higher than 0.05, while for the *Gyroid* infill pattern, a linear model is provided where the deviations from the *Lack of fit* model are lower than 0.05.

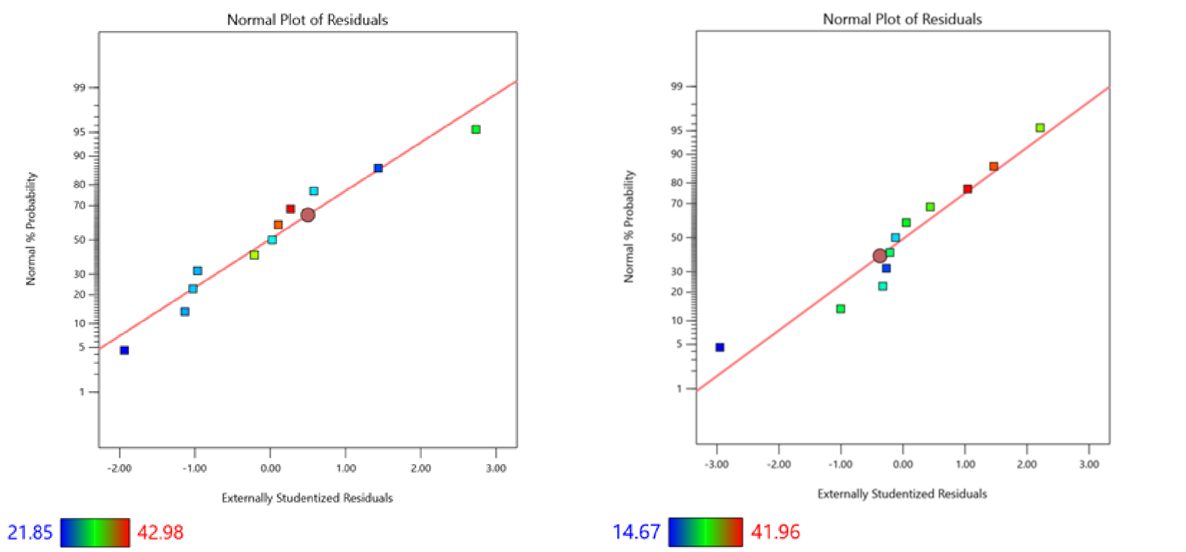
Table 5. **Results of analysis of variance for Linear model for *Tensile strength* response**

Source	*Sum of Squares*	*df*	*Mean Square*	*F-value*	*p-value*	
Model	478.31	5	95.66	**1.88**	0.2532	not significant
A-Infill	409.25	1	409.25	8.03	0.0365	significant
B-Layer thickness	0.5716	1	0.5716	0.0112	0.9198	not significant
AB	5.18	1	5.18	0.1015	0.7629	not significant
A²	48.28	1	48.28	0.9470	0.3752	not significant
B²	0.8489	1	0.8489	0.0166	0.9024	not significant
Residual	254.92	5	50.98			
Lack of Fit	242.33	3	80.78	**12.83**	0.0731	not significant
Pure Error	12.59	2	6.29			
Cor Total	733.23	10				

By model reducing, i.e. removing a large number of insignificant members from the model, it can be improved, which is determined by the values of the adjusted and predicted coefficient of determination. The adjusted value of the coefficient of determination defines the amount of variation around the mean value explained by the model, and takes into account the number of members in the mathematical model in relation to the number of states in the experimental plan. The predicted value of the coefficient of determination is a measure of the amount of variation in the new data explained in the model. The difference between these two values must be less than 0.2.

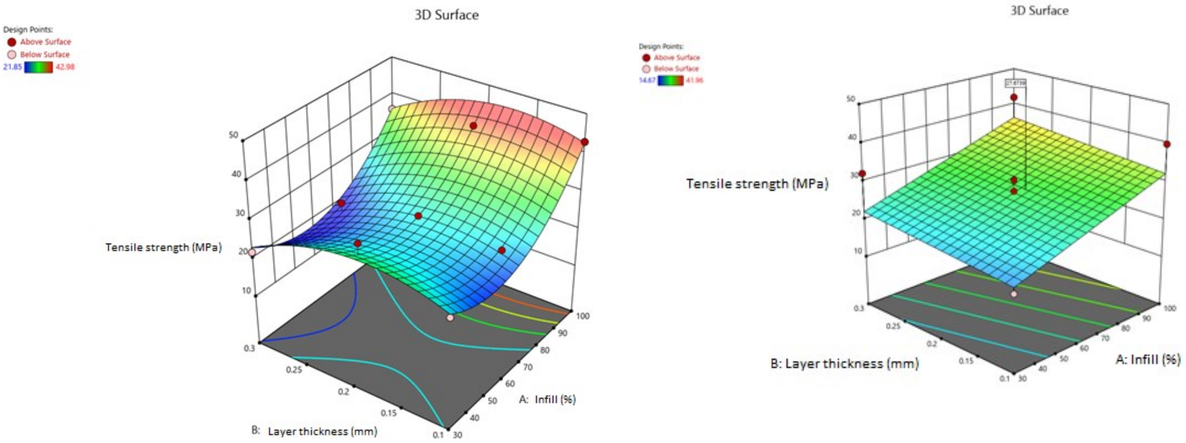
The normality of the measured values for individual conditions of the experiment is tested with the normalized residual probability paper. Fig. 5 shows the normal plot of residuals paper probability. We can see that residuals follow a normal distribution that represents a straight line. If the dots form the letter "S", it means that a transformation of the response is required in order to obtain a better analysis. For the case of *Line* infill pattern, we conclude that the dots do not form the letter "S", which means that the residuals follow a normal distribution, while for the *Gyroid* infill pattern, the dots indicate the shape of an "S", that is, the residuals do not follow a normal distribution.

Fig. 6 shows a three-dimensional representation of the response surface for tensile strength expressed in MPa for PLA material as a function of material infill expressed in percentage (%) and layer thickness expressed in milimeters (mm). From Fig. 6a and 6b, we can conclude that the highest values of tensile strength are achieved with the highest percentage of material infill and lower values of layer thickness, although the thickness of the layer has little influence with *Line* infill pattern. The thickness of the layer with *Gyroid* infill pattern has almost no effect on the tensile strength.



a) Tensile strength response for *Line* infill pattern b) Tensile strength response for *Gyroid* infill pattern

Figure 5: Tensile strength response for various pattern material infill



a) *Line* infill pattern b) *Gyroid* infill pattern

Figure 6: 3D representation of the response surface

IV. CONCLUSIONS AND RECOMMENDATIONS

The thickness of the layer significantly affects to the printing time, for example for a test sample with 100% infill (*Line* infill pattern) and layer thickness 0.1 mm, the printing time is 2 hours and 9 minutes, while for infill with 100% and layer thickness 0.3 mm, the time printing is 51 minutes. Also, for an infill of 65% and a layer thickness of 0.11 mm, the printing time is 1 hour and 33 minutes, and for the same infill of 65% with a layer thickness of 0.2833, the printing time is 52 minutes. The conclusion is that the thickness of the layer significantly affects the printing speed, which directly affects to the costs. The percentage (%) of the material infill also significantly affects to the printing speed. However, when we consider the strength of the material, it is unquestionable that for the elements under some kind of static tensile load, should be used the highest possible percentage of material infill.

Gyroid pattern infill material required twice as long printing time compared to *Line* pattern infill for the same parameters. The results of the tensile test showed that the *Gyroid* type of the infill does not achieve higher tensile strength values than samples printed with the *Line* type of infill pattern, which leads to the conclusion that the *Gyroid* type of the pattern infill is not cost-effective for application on the elements that are static tensile loaded.

For the *Line* type of the material pattern infill, it was determined experimentally that the tensile strength values increase with a decrease in the thickness of the layer, while in the case of the *Gyroid* pattern infill, it was shown that the thickness of the layer has no significant effect on the tensile strength.

For the static loaded elements, the highest possible percentage of infill (optimal 100%) is necessary, because the tensile test determined that the tensile strength values are significantly lower for infill values of 65% and also for 30%. The lower percentage of material infill is applicable for parts that are not under the load and for making a prototypes.

To obtain an additional conclusions regarding the type of pattern infill and its influence on the tensile strength of the material, it is necessary to carry out additional tests for different types of the infill patterns. The *Gyroid* infill pattern showed that it is weaker along the Z-axis (according to Table 1), and additional tests should be conducted to determine the strength of the material along the X and Y axes, which could certainly be a continuation of this research. Also, for additional test results non-brittle polymer materials should be considered.

REFERENCES

[1]. Acierno, D. and Patti, A. (2023). "Fused Deposition Modelling (FDM) of Thermoplastic-Based Filaments: Process and Rheological Properties-An Overview", Materials 16(24), 7664. https://doi.org/10.3390/ma16247664

[2]. Kulinowski, P., Piotr Malczewski, P., Pesta, E., Łaszcz, M., Mendyk, A., Polak, S., Dorożyński, P. (2021)."Selective laser sintering (SLS) technique for pharmaceutical applications-Development of high dose controlled release printlets", Additive Manufacturing, 38,101761.

[3]. Ma, X. L. (2013). "Research on Application of SLA Technology in the 3D Printing Technology". Applied Mechanics and Materials, 401–403, 938–941. https://doi.org/10.4028/www.scientific.net/amm.401-403.938.

[4]. Patel. D.B. (2017). "Polyjet – An Additive Manufacturing Process", IJSRD - International Journal for Scientific Research & Development|, 5(05), 2321-0613.

[5]. Hanon, M. M., Marczis, R. and Zsidai, L. (2021) "Influence of the 3D Printing Process Settings on Tensile Strength of PLA and HT-PLA", Periodica Polytechnica Mechanical Engineering, 65(1), 38–46. 10.3311/PPme.13683

[6]. Hanon, M.M., Dobos, J., Zsidai, L. (2021). "The influence of 3D printing process parameters on the mechanical performance of PLA polymer and its correlation with hardness", Procedia Manufacturing, 54,44-249, https://doi.org/10.1016/j.promfg.2021.07.038.

[7]. Auffray, L., Gouge, PA. & Hattali, L. (2022). "Design of experiment analysis on tensile properties of PLA samples produced by fused filament fabrication", Int J Adv Manuf Technol 118, 4123–4137, https://doi.org/10.1007/s00170-021-08216-7.

[8]. Chokshi, H., Patel, K., Shah, D., Patel, K. (2023). "Evaluation of Tensile Strength for 3D-Printed PLA Specimens", In: Dutta, K., Mallik, A., Kotadia, H.R., Das, S. (eds) Processing and Characterization of Materials. ACIEQ 2021. Springer Proceedings in Materials, vol 26. Springer, Singapore. https://doi.org/10.1007/978-981-99-5509-1_4

[9]. Hsueh M-H, Lai C-J, Chung C-F, Wang S-H, Huang W-C, Pan C-Y, Zeng Y-S, Hsieh C-H. (2021). "Effect of Printing Parameters on the Tensile Properties of 3D-Printed Polylactic Acid (PLA) Based on Fused Deposition Modeling. Polymers", 13(14):2387. https://doi.org/10.3390/polym13142387

[10]. M Rismalia et al. (2019). "Infill pattern and density effects on the tensile properties of 3D printed PLA material", J. Phys.: Conf. Ser. 1402 044041, doi 10.1088/1742-6596/1402/4/044041

[11]. UltiMaker Cura software help, available: https://ultimaker.com/software/ultimaker-cura/

[12]. Pezer, D., Vukas, F., & Butir, M. (2022). "Experimental study of tensile strength for 3D printed specimens of HI-PLA polymer material on in-house tensile test machine", Technium: Romanian Journal of Applied Sciences and Technology, 4(10), 197–206. https://doi.org/10.47577/technium.v4i10.7927

[13]. Giljanović, T. (2023). "Tensile test for polymer test specimens". University Department of Professional Studies, University of Split, Croatia. Master Thesis.