An investigation of the influence of 3d printing parameters on the tensile strength of PLA material

Materials Today: Proceedings

An investigation of the influence of 3d printing parameters on the tensile strength of PLA material

--Manuscript Draft--

Manuscript Number:	
Article Type:	SI:ICAMSE2022
Keywords:	3d printing; PLA; DOE; tensile strength; infill; Makerbot Replicator.
Corresponding Author:	Luca Fontana, M.D. Politecnico di Torino Torino, Italy ITALY
First Author:	Luca Fontana, M.D.
Order of Authors:	Luca Fontana, M.D.
	Luca Iuliano
	Paolo Minetola
	Serena Rifuggiato
	Mankirat Singh Khandpur
	Vito Stiuso
Abstract:	Fused Deposition Modelling (FDM), also known as 3d printing, is one of the most widespread Additive Manufacturing (AM) technologies based on the extrusion of a thermoplastic filament. This layerwise technology allows lightweight products to be built using different infill strategies and percentages. Furthermore, by varying other parameters, such as temperature, printing speed or layer thickness, it is possible to obtain components with different characteristics. Polylactic Acid (PLA) is one of the cheapest and most sustainable materials for 3d printing because it is a biobased and biodegradable plastic. Its use in 3D printing is widely spread among hobbyists and in the communities, such as the ones of Fablabs or the Makers movement. Nevertheless, to reduce the number of uncompliant parts that may fail into operation since they do not meet the expectations of the user, it is important to know in advance the mechanical performance that different 3d printing strategies can ensure for PLA parts. In this paper, Design of Experiment (DOE) is applied to investigate how main 3D printing parameters influence the tensile strength of PLA products. For this purpose, a 3x3 factorial plane with one replication was constructed and used for 3d printing tensile specimens of PLA Tough material using a Makerbot Replicator machine. The tensile test results show that the layer thickness is more significant than the infill percentage for the resistance of PLA products. A regression model is also proposed to allow the user to predict the ultimate tensile strength of PLA products depending on the values of those two parameters.

Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

materialstoday: PROCEEDINGS

[Name of the proceedings]

An investigation of the influence of 3d printing parameters on the tensile strength of PLA material

Luca Fontana*, Luca Iuliano, Paolo Minetola, Serena Rifuggiato, Mankirat Singh Khandpur, Vito Stiuso

Politecnico di Torino, Department of Management and Production Engineering (DIGEP), Corso Duca degli Abruzzi 24, 10129 Torino, Italy

Abstract

Fused Deposition Modelling (FDM), also known as 3d printing, is one of the most widespread Additive Manufacturing (AM) technologies based on the extrusion of a thermoplastic filament. This layerwise technology allows lightweight products to be built using different infill strategies and percentages. Furthermore, by varying other parameters, such as temperature, printing speed or layer thickness, it is possible to obtain components with different characteristics. Polylactic Acid (PLA) is one of the cheapest and most sustainable materials for 3d printing because it is a biobased and biodegradable plastic. Its use in 3D printing is widely spread among hobbyists and in the communities, such as the ones of Fablabs or the Makers movement.
Nevertheless, to reduce the number of uncompliant parts that may fail into operation since they do not meet the expectations of the user, it is important to know in advance the mechanical performance that different 3d printing strategies can ensure for PLA parts. In this paper, Design of Experiment (DOE) is applied to investigate how main 3D printing parameters influence the tensile strength of PLA products. For this purpose, a 3x3 factorial plane with one replication was constructed and used for 3d printing tensile specimens of PLA Tough material using a Makerbot Replicator machine. The tensile test results show that the layer thickness is more significant than the infill percentage for the resistance of PLA products. A regression model is also proposed to allow the user to predict the ultimate tensile strength of PLA products depending on the values of those two parameters.

Keywords: 3d printing; PLA; DOE; tensile strength; infill; Makerbot Replicator.

1. Main text

Among Additive Manufacturing technologies for polymeric materials, Fusion Deposition Modelling (FDM) technology, which is also widely named 3d printing, is the most widespread technique for many applications in various sectors. In this process, a thermoplastic filament is heated, extruded through a nozzle, and deposited layer by layer on the build plate of the 3D printer to fabricate the product [1]. Starting from the mathematical model of the part, designed in a 3d CAD software, and depending on the 3d printing strategy, a slicing software or slicer defines the amount of material to be deposed in each layer for creating the cross-sectional geometry of the product in the build direction. Through the slicing operation, the numerical control code corresponding to the print path is generated and then sent to the 3d printer for product fabrication.

Layerwise manufacturing brings numerous advantages. One of the most exploited benefits of AM is the possibility to fabricate lightweight products by optimization of the material distribution through topology optimization [2-4] or by designing internal porous structures, that reduce the density of the part and the infill ratio. An infill ratio of 100% corresponds to a fully dense part, whereas lower percentages of the infill define hollow areas in the cross-sectional

* Corresponding author. Tel.: +39-011-090-7295; fax: +39-011-090-7299.
E-mail address: luca.fontana@polito.it

geometry of each layer of the product depending on the infill path for material deposition. Before printing and within the slicing settings the user should define the layer height, the infill percentage, and the infill path among other printing parameters. Different infill strategies directly influence the mechanical performance of a 3d printed component [5-8]. Therefore, it is of paramount importance for the user to know in advance how the choice of slicing parameters will influence the part resistance.

An experimental approach by Design of experiments (DOE) is often applied for the optimization of the 3d printing parameters [9-10]. An improper design of the printing strategy may result in a failure of the product once it will go into operation under real loads. This undesired outcome will jeopardize the potential offered by topological optimization that allows engineers to combine part resistance with considerable material savings. From the point of view of sustainability, in order to reduce the number of uncompliant products and failures, the knowledge of the influence of the 3d printing settings on part strength is a key factor. As concerns 3d printing materials, Polylactic Acid (PLA) is often used by hobbyists and in the communities, such as the ones of the Makers movement or Fablab. PLA is a cheap and sustainable 3d printing material because it is a biobased and biodegradable plastic [11]. However, the amount of 3d printed to PLA to be recycled can be reduced by preventing undesired part failures resulting from inadequate product design and insufficient mechanical strength.

Therefore, this study aims to investigate how different 3d printing strategies affect the tensile strength of PLA material. Design of experiment with 2 factors and 3 levels is applied for thorough planning of the tests and analysis of the experimental results. Using experimental data, a regression model is proposed to the user to predict the ultimate tensile strength of PLA products. The study is applied to a Makerbot Replicator 5th generation 3d printer and Makerbot proprietary PLA Tough material.

2. Materials and methods

2.1. Design of experiments

In this study, it was investigated how the 3d printing layer height (LH) and the infill percentage (I) affect the mechanical properties of tensile specimens made of Makerbot PLA Tough material of Stone White colour. Referring to the ASTM D638 guideline for tensile testing of polymers [12], type IV specimens were produced using the Makerbot Replicator 5th generation printer of the Integrated Additive Manufacturing Center (IAM@PoliTO) of the Politecnico di Torino (Fig. 1a).

The experimental plan was defined with three levels for both LH and I factors to be set in the Makerbot Print slicer. The 3^2 factorial plan was defined with a single replication for each test to increase the robustness and reliability of the study. Consequently, a total of 18 tensile samples were produced and tested. The two factors were varied over three equally spaced levels: 0.1 mm, 0.2 mm and 0.3 mm for the layer thickness or height (LH) and 0.2 (20%), 0.5 (50%) and 0.8 (80%) for the infill percentage (I). A linear infill pattern was chosen for the deposition of the extruded material with alternating crossing directions of 0 degrees and 90 degrees between two consecutive layers. Other 3d printing parameters for the PLA Tough material were kept constant and set to the default values in the Makerbot Print software for slicing (Table 1).

a b

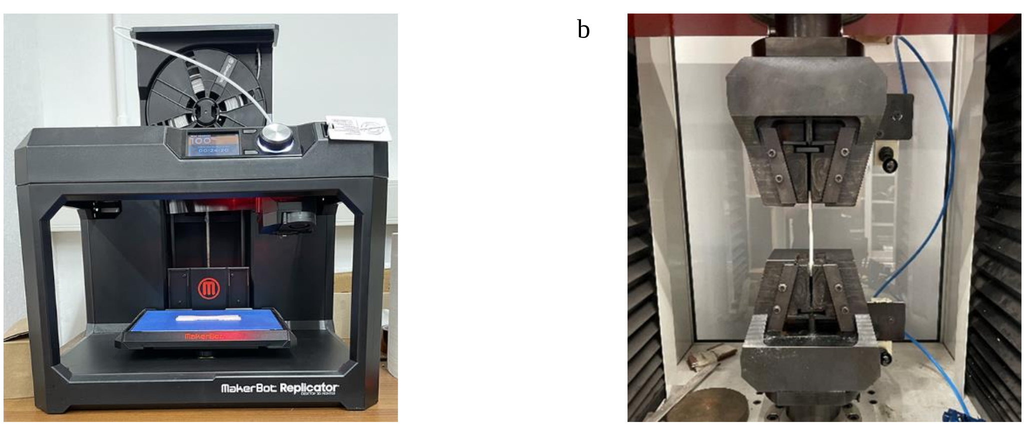

Fig. 1. (a) Makerbot Replicator with one printed tensile specimen of PLA Tough; (b) tensile test of a 3d printed specimen.

Table 1. Main 3d printing parameters for specimen fabrication.

Printing Parameter	Value
Temperature	215 °C
Travel speed along x-y directions	150 mm/s
Travel speed along the z direction	23 mm/s
Layer height (LH)	0.1 mm, 0.2 mm, 0.3 mm
Infill pattern	Linear, crossing 0 and 90 degrees
Infill percentage (I)	0.2, 0.5, 0.8
Infill print speed	90 mm/s
First layer print speed	30 mm/s
Speed for outlines	20 mm/s

In FDM, the build time is influenced by the layer thickness (LH) and the infill percentage (I): the higher the filling percentage, the longer the production time, vice versa for the layer thickness. Therefore, depending on the availability of the Makerbot Replicator machine, samples were fabricated sequentially with preference given to the build time over complete randomization of the factorial plan. The data in Table 2 shows layer height (LH) and the infill percentage (I) of the specimens in the order they were produced.

To consider the physical degradation of the PLA material over time due to its biobased organic nature [13-15], after 3d printing and before tensile testing, the specimens were kept in the laboratory environment of the Integrated Additive Manufacturing Center at about 21 °C and 55% humidity for different days (Table 2).

Tensile tests were carried out according to ASTM D638 guidelines [12] using an Aura 10T machine by Easydur. The value of the Ultimate Tensile Strength (UTS) was assumed as an estimator of the mechanical properties of the PLA Tough material (Table 2).

Table 2. Specimen data of the experimental campaign.

Run order	Layer height – LH (mm)	Infill percentage – I	Time passed before testing (days)	UTS (MPa)
1	0.3	0.5	0	9.34
2	0.3	0.8	0	24.58
3	0.1	0.8	4	24.86
4	0.1	0.2	10	16.96
5	0.1	0.5	10	24.29
6	0.2	0.2	8	18.40
7	0.2	0.5	8	22.71
8	0.2	0.8	9	19.83
9	0.3	0.2	1	7.90
10	0.3	0.5	1	19.69
11	0.3	0.8	1	13.80
12	0.1	0.8	2	12.22
13	0.1	0.5	2	27.31
14	0.1	0.2	2	21.99
15	0.2	0.2	0	20.41
16	0.2	0.5	0	18.25
17	0.2	0.8	1	23.43
18	0.3	0.2	0	8.19

3. Data analysis and results

Before proceeding with an in-depth analysis of the experimental results, an exploratory data analysis was carried out using Minitab® software (version 17.1.0) to investigate the main characteristics of the UTS variable. The descriptive statistics of the UTS variable are reported in Table 3, where the number of values is N and StDev is the standard deviation. Q1 and Q3 are the first quartile and third quartile, that is the value Q1 under which 25% of data points are found and the value Q3 under which 75% of data points are found when arranged in increasing order.

Table 3. Descriptive statistics of the UTS variable.

Variable	N	Mean (MPa)	StDev (MPa)	Minimum (MPa)	Q1 (MPa)	Median (MPa)	Q3 (MPa)	Maximum (MPa)
UTS	18	18,56	6,02	7,90	13,41	19,76	23,64	27,31

As the sample size is smaller than 30, the normal probability plot is used for checking whether the UTS data belongs to a normal distribution. In the normal probability plot (Fig. 2), all experimental values fit within the confidence intervals, therefore it is reasonable to assume that the UTS variable is normally distributed.

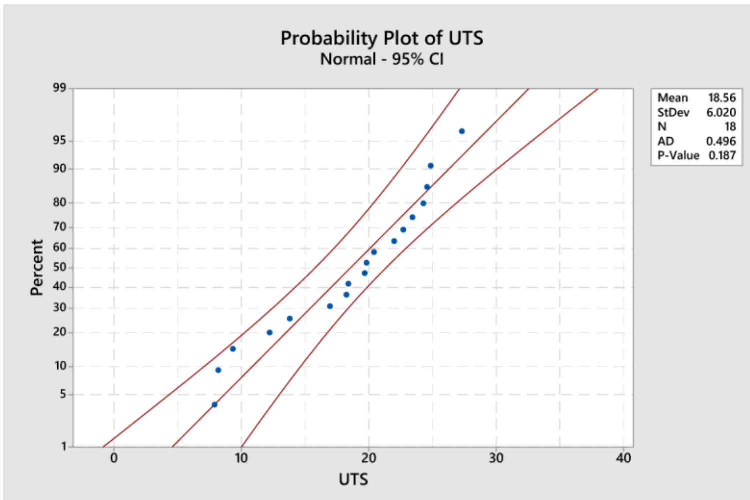

Fig. 2. Normal probability plot of the UTS variable.

3.1. Factor analysis and linear regression

The factor analysis was carried out to understand how the individual factors affect the UTS output. In the general factorial regression, the linear relationship for the layer height (LH) and infill percentage (I) factors was considered together with their interaction. The results of the analysis of variance (ANOVA) are reported in Table 4, including the degrees of freedom (DF), the adjusted sums of squares (Adj SS) and the adjusted mean squares (Adj MS).

Table 4. Analysis of variance of general factor regression.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	388,81	48,60	1,92	0,174
Linear	4	273,75	68,44	2,71	0,099
LH	2	196,18	98,09	3,88	0,061
I	2	77,57	38,79	1,54	0,267
2-Way Interactions	4	115,06	28,76	1,14	0,398
LH*I	4	115,06	28,76	1,14	0,398
Error	9	227,25	25,25		
Total	17	616,06			

Table 5 reports the standard error (S) of the regression and the coefficient of determination (R^2), where the standard error S has the same measurement unit of the UTS variable and describes the standard distance of data values from the regression line. The percentage of variation of the observed response values that the predictors explain is indicated by the value R2. This value is modified and adjusted (adj) for the number of terms of the regression model in the third column of Table 4.

Table 5. Statistics associated with the general regression model.

S	R^2	R^2 (adj)
5,02492	63,11%	30,32%

A low p-value of 0.061 was observed for the LH factor. This means that this factor is significant in the general regression model at the 93.9% level. On the other hand, the infill percentage (I) and the factor interaction (LH*I) have a higher p-value, indicating a low significance of these parameters. For the linear regression model, the coefficient of determination R^2 (Table 5) has a low value of approximately 63%.

The main effects plot in Fig. 3 shows the qualitative trend of the UTS variable with respect to the individual factors LH and I. A quadratic trend of the UTS variable is distinguished in the main effects plot.

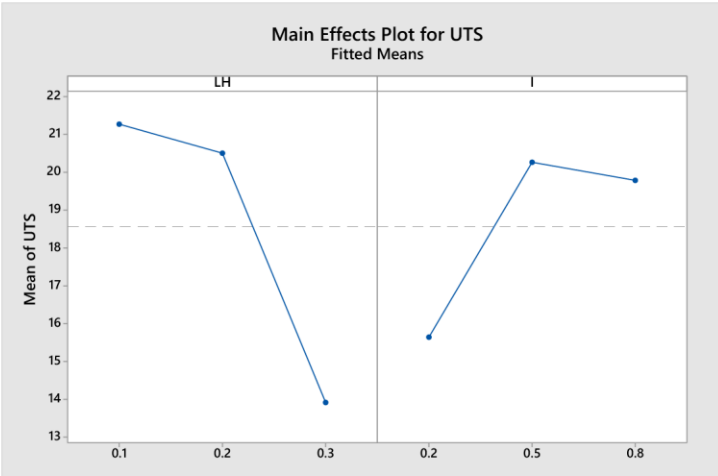

Fig. 3 – Main effects plot for the UTS variable in the general factorial regression.

In the interaction plot of Fig. 4, the factors interact when the lines are not parallel, meaning that the variability of one factor affects the variability of the other. In the case under study, there is evidence of interaction between the factors for low levels of the layer thickness (LH), while for higher levels there is little interaction.

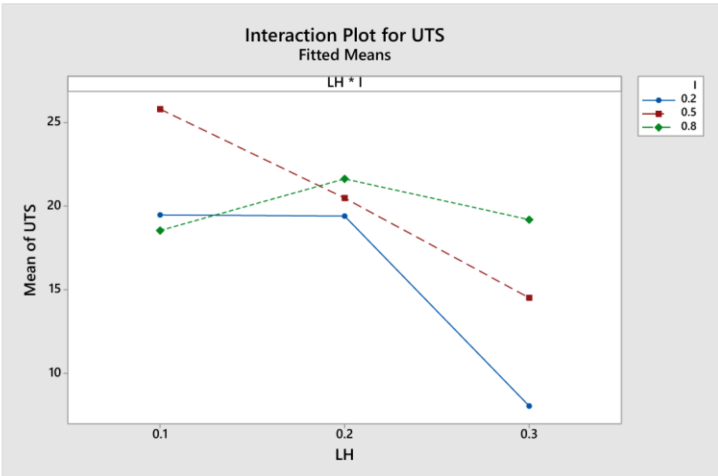

Fig. 4 – Interaction plot of the general factorial regression.

A particular variation is seen for 80% of the infill percentage (I). However, this interaction can only be observed graphically, as it is not significant in the ANOVA analysis (Table 4).

To consider the influence of the physical degradation of the PLA material, the time passed in days between the specimen fabrication and the tensile test was introduced as a covariate in the regression model and the analysis of variance was repeated.

Table 6. Analysis of variance considering the time passed as a covariate.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	392,486	43,61	1,56	0,271
Covariates	1	3,677	3,677	0,13	0,726
Time passed	1	3,677	3,677	0,13	0,726
Linear	4	244,383	61,096	2,19	0,161
LH	2	162,774	81,387	2,91	0,112
I	2	76,014	38,007	1,36	0,31
2-Way Interactions	4	118,731	29,683	1,06	0,434
LH*I	4	118,731	29,683	1,06	0,434
Error	8	223,572	27,946		
Total	17	616,058			

The results of the ANOVA analysis (Table 6) shows that the time passed has a very high p-value of 0.726, which means that it has a low significance in explaining the variation of the UTS for the PLA Tough specimens. For this reason, the statistics of the regression model (Table 7) do not differ significantly from those of the general regression model in Table 5.

Table 7. Statistics associated with the regression model considering the covariate of time passed.

S	R^2	R^2 (adj)
5,28644	63,71%	22,88%

3.2. Quadratic regression model

Since the main effects plot in Fig. 3 suggested a quadratic trend of the UTS variable, a non-linear regression model was considered and analysed. Table 8 reports the results of the analysis of variance for the quadratic regression model.

Table 8. Analysis of variance of the quadratic regression.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	346,71	69,34	3,09	0,051
Linear	2	213,83	106,92	4,76	0,03
LH	1	162,29	162,29	7,23	0,02
I	1	51,54	51,54	2,30	0,156
Square	2	59,92	29,96	1,33	0,30
LH*LH	1	33,89	33,89	1,51	0,243
I*I	1	26,03	26,03	1,16	0,303
2-Way Interaction	1	72,96	72,96	3,25	0,097
LH*I	1	72,96	72,96	3,25	0,097
Error	12	269,34	22,45		
Lack-of-Fit	3	42,10	14,03	0,56	0,657
Pure Error	9	227,25	25,25		
Total	17	616,06			

The analysis of variance for the non-linear regression model confirms that the LH factor is highly significant with a p-value of 0.020. On the other hand, the interaction between the layer height and the infill percentage is less significant with a p-value of 0.097.

In the case of the quadratic regression, a low value of the coefficient of determination R^2 is confirmed (Table 9), but the standard error (S) of the regression is reduced if compared to the one of the linear regression (Table 4).

Table 9. Statistics associated with the quadratic regression model.

S	R^2	R^2 (adj)
4,73766	56,28%	38,06%

The main effect plot in Fig. 5 confirms the quadratic trend of the UTS variable with respect to the individual factors.

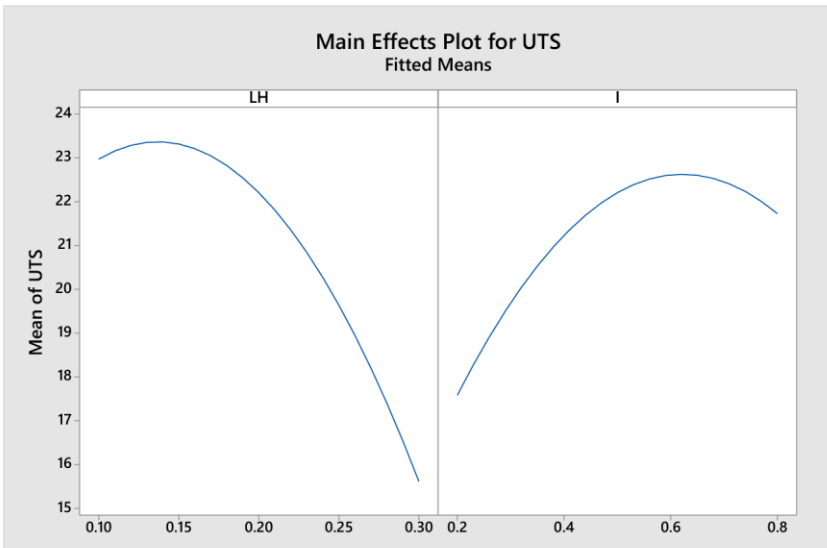

Fig. 5 – Main effect plot of the UTS variable for the quadratic regression.

The interaction plot in Fig. 6 confirms that for low levels of the layer thickness (LH) the factors LH and I interact, while for high values of LH they do not.

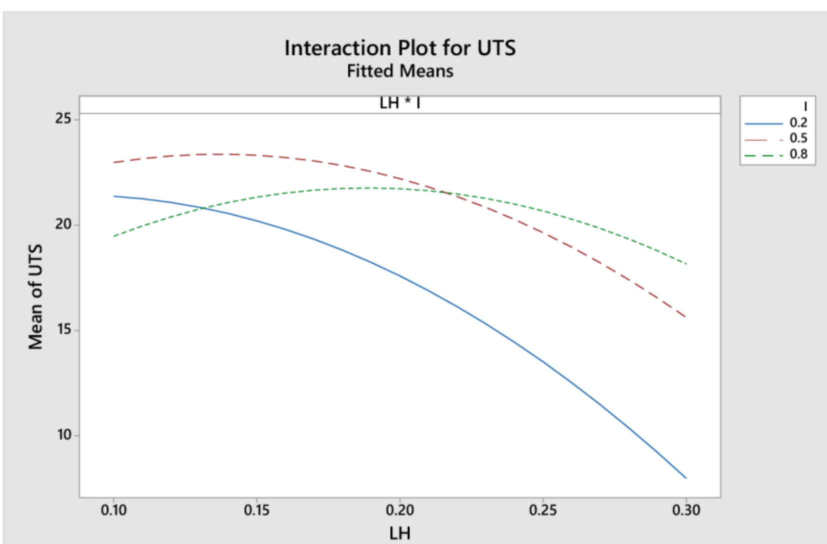

Fig. 6 – Interaction plot of factors for the quadratic regression.

To allow the user to predict the ultimate tensile strength of PLA products depending on the values of the two parameters LH and I, a response surface (Fig. 7) is determined from the quadratic regression model of Equation 1.

$$UTS = 17{,}4 + 29{,}3\ LH + 15{,}1\ I - 291\ LH \cdot LH - 28{,}3\ I \cdot I + 100{,}7\ LH \cdot I \qquad (1)$$

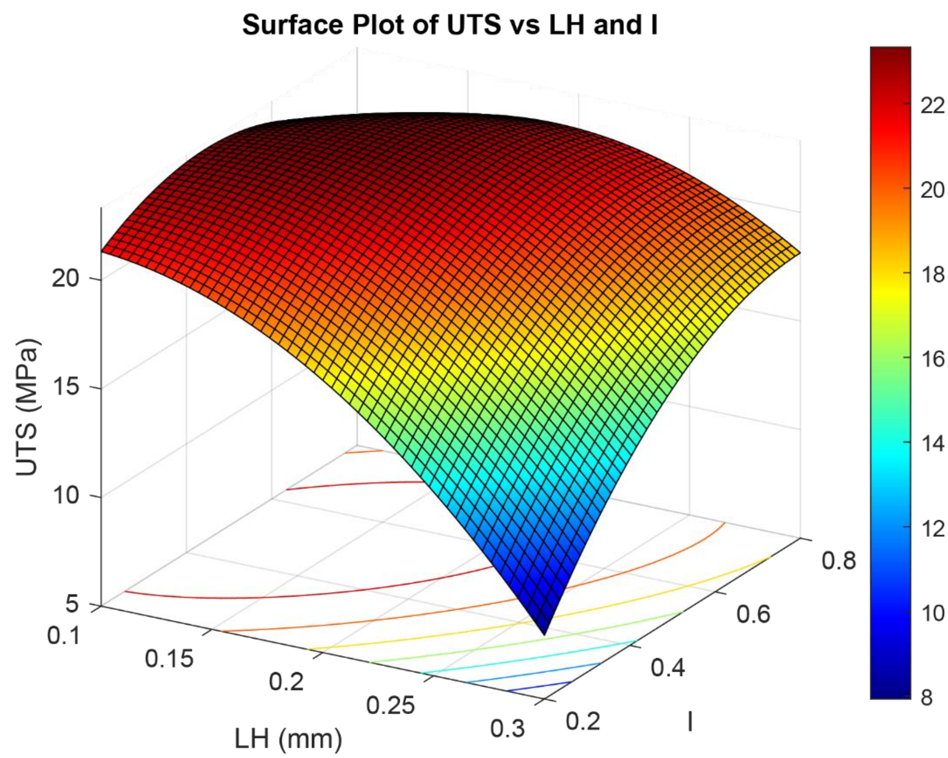

Fig. 7. Response surface with contour plot for the quadratic regression model for the UTS variable as a function of LH and I.

When searching for the maximum and minimum values of the UTS function in Equation 1, the minimum value of 7.97 MPa (Fig. 8a) is obtained for the higher layer height (LH) of 0.3 mm and the lowest infill percentage (I) of 0.20 (20%) as also the lowest point of the blue area of the response surface in Fig. 7 shows. The maximum UTS value of 23.37 MPa (Fig. 8b) can be obtained for LH equal to 0.14 mm and I equal to 0.51 (51%).

a

b

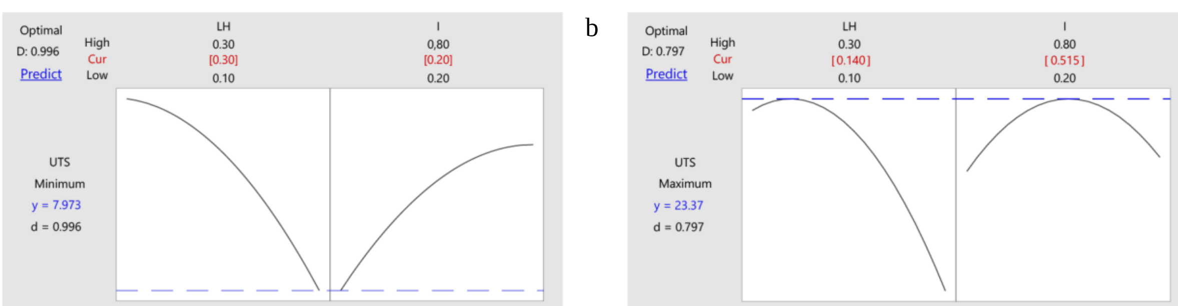

Fig. 8. Searching for the minimum (a) and maximum (b) values of the UTS versus the factors LH and I.

Conclusions

In this work, how layer height (LH) and filling percentage (I) affect the UTS value of 3d printed tensile specimens of Makerbot PLA Tough material was analysed. A 3x3 factorial plan was design by varying the values of the factors on 3 equally spaced levels. Experimental data analysis by ANOVA showed that the layer thickness parameter has higher importance than the infill percentage on the mechanical strength of the PLA Tough. Physical degradation of the PLA material for conservation at room temperature and 50% of humidity up to 10 days showed no significant effect on the UTS value.

In the factor analysis, there was evidence of interaction between the factors for low levels of layer height (LH), while for higher levels the interaction is negligible. A quadratic relationship between the UTS variable and both factors was observed, and the corresponding regression model was defined. From the response surface, it was determined that the highest UTS value for the PLA Tough material can be obtained for a 3d printing layer height of 0.15 mm and an infill percentage of 50% to be set as parameters in the slicing software of the Makerbot Replicator machine.

Acknowledgements

The authors would like to thank Prof. Gianfranco Genta for valuable discussions regarding the methodology and the data analysis during the lectures of his PhD course titled "Design of industrial experiments".

References

[1] Calignano F, Manfredi D, Ambrosio EP, Biamino S, Lombardi M, Atzeni E, Salmi A, Minetola P, Iuliano L, Fino P. Overview on additive manufacturing technologies, Proc. IEEE 105(4) (2017) 593-612.

[2] Liu J, Gaynor AT, Chen S, Kang Z, Suresh K, Takezawa A, Li L, Kato J, Tang J, Wang CC, Cheng L. Current and future trends in topology optimization for additive manufacturing. SMO. 2018;57(6): pp 2457-83.

[3] Brackett D, Ashcroft I, Hague R. Topology optimization for additive manufacturing. In 2011 International Solid Freeform Fabrication Symposium 2011 Aug 17. University of Texas at Austin.

[4] Zhu J, Zhou H, Wang C, Zhou L, Yuan S, Zhang W. A review of topology optimization for additive manufacturing: Status and challenges. Chinese Journal of Aeronautics (CJA). 2020.

[5] Dobrescu T, Pascu NE, Jiga G, Simion I, Adir V, Enciu G, Tudose DI. Tensile behavior of PLA and PLA composite materials under different printing parameters. Materiale Plastice (MP). 2019;56(4):783.

[6] Cho EE, Hein HH, Lynn Z, Hla SJ, Tran T. Investigation on influence of infill pattern and layer thickness on mechanical strength of PLA material in 3D printing technology. J. Eng. Sci. Res. 2019;3(2):27-37.

[7] Calignano F, Lorusso M, Roppolo I, Minetola P. Investigation of the Mechanical Properties of a Carbon Fibre-Reinforced Nylon Filament for 3D Printing. Machines, 8. 2020.

[8] Hsueh MH, Lai CJ, Liu KY, Chung CF, Wang SH, Pan CY, Huang WC, Hsieh CH, Zeng YS. Effects of Printing Temperature and Filling Percentage on the Mechanical Behavior of Fused Deposition Molding Technology Components for 3D Printing. Polymers. 2021;13(17):2910.

[9] Spoerk M, Arbeiter F, Cajner H, Sapkota J, Holzer C. Parametric optimization of intra‐ and inter‐layer strengths in parts produced by extrusion‐based additive manufacturing of poly (lactic acid). Journal of applied polymer science (JAPS). 2017;134(41):45401.

[10] Qattawi A, Alrawi B, Guzman A. Experimental optimization of fused deposition modelling processing parameters: a design-for-manufacturing approach. Procedia Manufacturing (PM). 2017 Jan 1;10:791-803.

[11] Pakkanen J, Manfredi D, Minetola P, Iuliano L. About the use of recycled or biodegradable filaments for sustainability of 3D printing. InInternational Conference on Sustainable Design and Manufacturing 2017 (pp. 776-785). Springer, Cham.

[12] ASTM International. ASTM D638-14 - Standard Test Method for Tensile Properties of Plastics. 2017.

[13] Kakanuru P, Pochiraju K. Moisture ingress and degradation of additively manufactured PLA, ABS and PLA/SiC composite parts. Additive Manufacturing (AM). 2020;36:101529.

[14] Teixeira S, Eblagon KM, Miranda FR, Pereira MF, Figueiredo JL. Towards Controlled Degradation of Poly(lactic) Acid in Technical Applications. C 2021, 7, 42.

[15] Moreno Nieto D, Alonso-García M, Pardo-Vicente MA, Rodríguez-Parada L. Product Design by Additive Manufacturing for Water Environments: Study of Degradation and Absorption Behavior of PLA and PETG. Polymers. 2021;13(7):1036.