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Influence of 3D Printing Parameters on Mechanical Properties of the PLA Parts made by FDM Additive Manufacturing Process

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Abstract. Paper presents the results of factorial experiments made to establish the influence of technological parameters of 3D printing using the Fused Deposition Modeling (FDM) Technology, on the mechanical properties of the material deposited with ULTRA PLA filaments. By planning the experiments and the statistical processing of the results, mathematical relations were established regarding the dependence between the objective functions, the controllable factors and their interactions. To obtain high tensile strengths of the components made by 3D printing, regimes are required to allow the deposition of layers as thin as possible (h = 0.1 mm) and temperatures as high as possible, close to 300°C. The choice of inappropriate values of these process parameters can lead to a significant decrease in tensile strength, reaching even up to 30-40% of the maximum possible value to be reached. The experiments reveal that the printing speed does not have a major influence on the mechanical properties. Practical, the printing speed is limited by the technical characteristics of the printer used. The results of the experimental research obtained on a number of 30 process variants led to the establishment of optimal 3D printing variants that correspond to the requirements imposed on the objectively analysed functions (tensile strength, dimensional accuracy, speed of execution, surface quality).

1. Introduction

Fused Deposition Modeling (FDM) additive manufacturing technology is constantly evolving. New printing possibilities is implemented, high-performance prints have been made and new materials have appeared. However, although it has been used for many years, the PLA (PolyLactic Acid) filament has not lost ground to the new materials, being one of the most used filaments in 3D printing with thermoplastic materials due to the fact that it behaves properly in the printing process. It combines mechanical characteristics with those of plasticity at an acceptable level, it is a biodegradable material, its decomposition being achieved at temperatures above 60 °C in certain humidity conditions and in the presence of microorganisms that accelerate the process. The technological process of 3D printing is a complex technological system, being characterized by a relatively large number of independent variables, which requires their optimization in order to obtain high productivity and quality of products. A modern variant of industrial process optimization is the use of factorial experiments that consider the analysis of the influence of certain controllable factors on the outputs, as response functions. In this way, the necessary resources and workload can be considerably reduced, by resorting to the statistical processing of experimental results and establishing relationships of dependence between objective functions, controllable factors and their interactions.

The effect of printing parameters on the mechanical properties of parts fabricated by 3D printing is a topic of interest for specialists in the field, being known a series of previous studies [1 - 6]. It has been found that 3D printing by FDM is a complex phenomenon and the mechanical properties of the printed parts are strongly depending on the 3D printing process parameters and on the filament material composition. On the other hand, since FDM deposits material directionally, the result is a layered parts with anisotropic behaviour. Also, normally distributed errors were achieved between the predicted and experimental values. The experiments have shown [3] that the pre-processing technologies such as vacuum-assisted FDM and laser or infrared heating could be used to improve the quality of the 3D printed parts due to positive impact on bonding between the layers. Also, the part cooling rate, environmental conditions and post-processing need to be considered as well since they have a significant effect on characteristics of the 3D printed components. Thus, research must be done to find optimal solutions [7-11] for the combinations of parameters to adapt them based on the application (since various optimal parameters could be obtained based on dimensional accuracy, printing time, flexural, impact or tensile strength as well as surface roughness).

In this paper, in order to establish the influence of technological parameters on the mechanical properties of the material deposited by printing using ULTRA PLA filament, the Design of Experiments approach (DOE) has been used [12]. Thus, a factorial experiment was designed and implemented aiming the following 5 objective functions: tensile strength, roughness of the printed surface, test piece thickness a, test piece width b and printing duration. The main factors (technological parameters) that significantly influence the results obtained are: print temperature, print speed (speed of movement of the print head relative to the printed component) and the height of the layer deposited at each pass (determined by the distance between the print head and component).

2. Experimental Work

2.1 Material and methods

ULTRA filaments (PLA) were used in the experimental program on the influence of technological parameters on the mechanical properties of the material deposited by 3D printing. Table 1 shows the main characteristics of this material, according to the manufacturer's specification (Roboze).

Table 1: Main characteristics of the ULTRA (PLA)

ULTRA (PLA)		
Properties	Value	STANDARD
Tensile strength	52 MPa	ISO 527
Elongation	20%	ISO 527
Flexural strength	85 MPa	ISO 178
Impact strength	22 kJ/m^2	ISO 180
HDT @1.80 MPa	65 °C	ISO 75
Density	1,25 g/cm^3	ISO 1183
Description	Material designed to make high-definition parts, ideal for prototypes and small series that require both precision and mechanical rigidity.	

In order to determine the limits of variation of the parameters specific to the 3D printing process and to design the factorial experiments, preliminary tests were performed in a first stage of the research. It was taken into account that these parameters influence the mechanical strength characteristics and the dimensions of the printed specimen, thus there is a need to establish optimal variants of 3D printing regimes depending on the different requirements for the practical applications.

Preliminary tests have established the ranges in which the main parameters called controllable factors of the 3D printing process can vary so that the process runs smoothly. The ranges of values obtained based on the results of the preliminary research carried out, are presented in Table 2.

Table 2: Controllable factors and their ranges of variation

No. Crt.	Technological parameter	Symbol	U.M.	Ranges
1	Temperature	T	[º C]	200 – 300
2	Printing speed	v	[mm/s]	60 – 80
3	Layer height	h	[mm]	0.1 – 0.3

Simplify3D software was used to design and simulate the printing of test specimens for the experiment program. An example of a simulation is shown in Fig. 1.

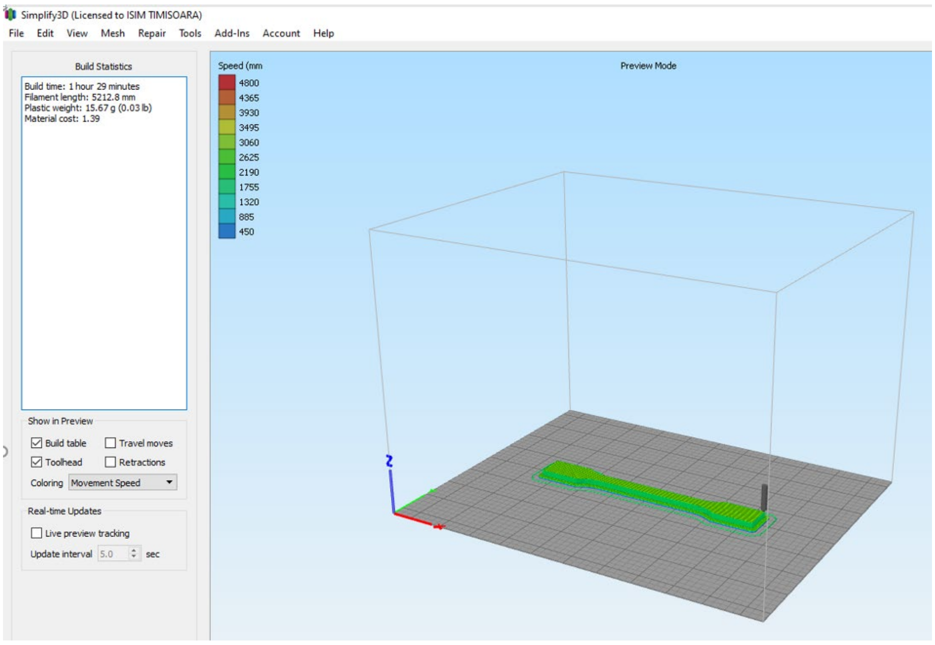


Figure 1: Design and simulation of specimen printing, using Simplify3D software

The software allows to load from a database the 3D drawing of the component to be printed and the selection of process parameters: extrusion temperature, printing speed, layer height, how is made the "shell" of the component and selecting the mode of " filling” of the component. Also, the software can estimate the printing time of the component, the length of the filament consumed when making it, the weight of the component, as well as the cost of the material. The printing of the specimens was made with Roboze one printer (Fig. 2).

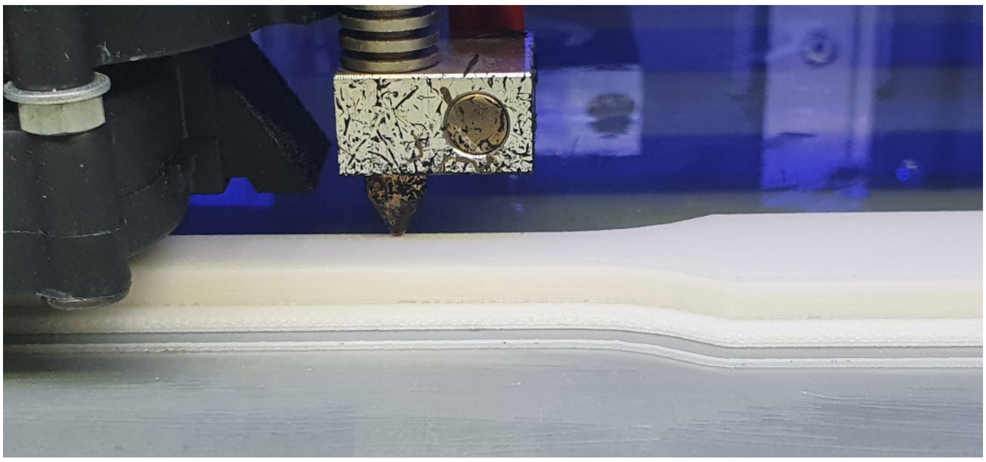


Figure 2: Printing of tensile test specimens

To evaluate the surface quality of 3D printed components, roughness measurements were performed using a Mitutoyo SJ - 201P device, Fig. 3.

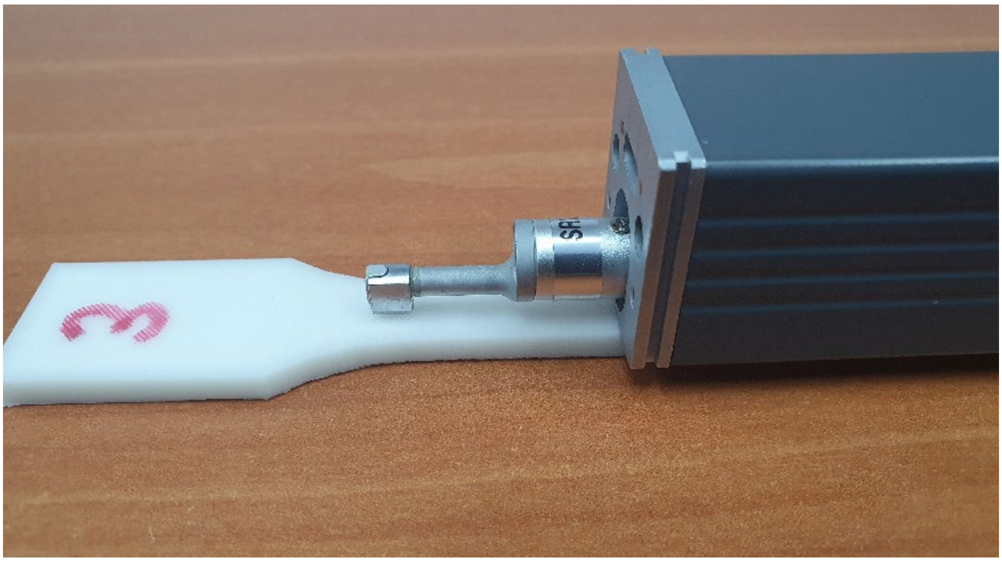


Figure 3: Roughness measurements

2.2 Experimental testing program

Within the experimental program, specimens for tensile tests according to [13] were printed. The experimental program consisted in designing and implementing a 1st order factorial experiment on 30 test pieces with 3 controllable factors with 2 levels, 3 replicas for each combination of controllable factors and 6 replicas in the central point. The following five objective functions were taken into consideration to be analysed: tensile strength R_m [N/mm^2], surface roughness R_a [µm], specimen thickness a [mm], specimen width b [mm] and printing time t_p [min]. Based on the data obtained in the preliminary experiments, the central point of the experiment was determined, after which the process parameters for the experimental program, presented in Fig. 4 and Table 3, were established.

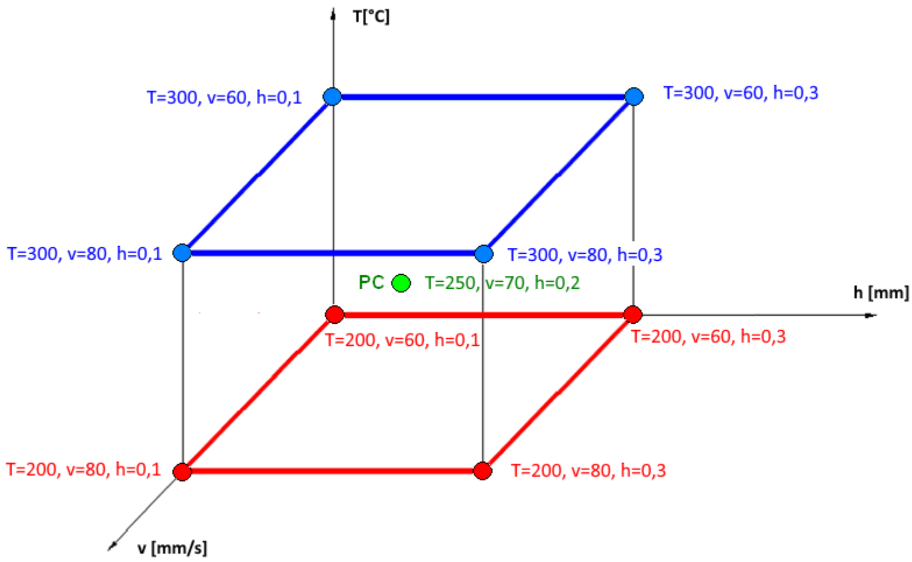


Figure 4: Establishing the technological parameters for the factorial experiment

Table 3: Factorial experiment - printing variants

Experiment no./ sample identification	Temperature T [ºC]	Printing speed v [mm/s]	Layer heigh h [mm]
1, 1’, 1’’	-1	-1	-1
2, 2’, 2’’	1	-1	-1
3, 3’,3’’	-1	1	-1
4, 4’, 4’’	1	1	-1
5, 5’, 5’’	-1	-1	1
6, 6’, 6’’	1	-1	1
7, 7’, 7’’	-1	1	1
8, 8’, 8’’	1	1	1
9, 10, 9’, 10’, 9’’, 10’’	0	0	0

where: 1, 0 and -1 represent the values of the upper and lower limits and respectively the average values of the analysed process parameters (Table 4).

Table 4: Parameters of the 3D printing process

Value	Temperature T [ºC]	Printing speed v [mm/s]	Layer heigh h [mm]
Maximal (1)	300	80	0.1
Average (0)	250	70	0.2
Minimum (-1)	200	60	0.3

Next, samples for the experimental program were printed using the parameters presented above. Before being tested, the specimens were conditioned at a temperature of 23 °C ± 1 °C and a relative humidity of 50% for 8 hours, after which they were subjected to a mechanical tensile test using Zwick equipment with maximum load of 5 kN.

3. Results and Discussion

The aspect of the 3D printed specimens, after the tensile tests, is shown in Fig. 5.

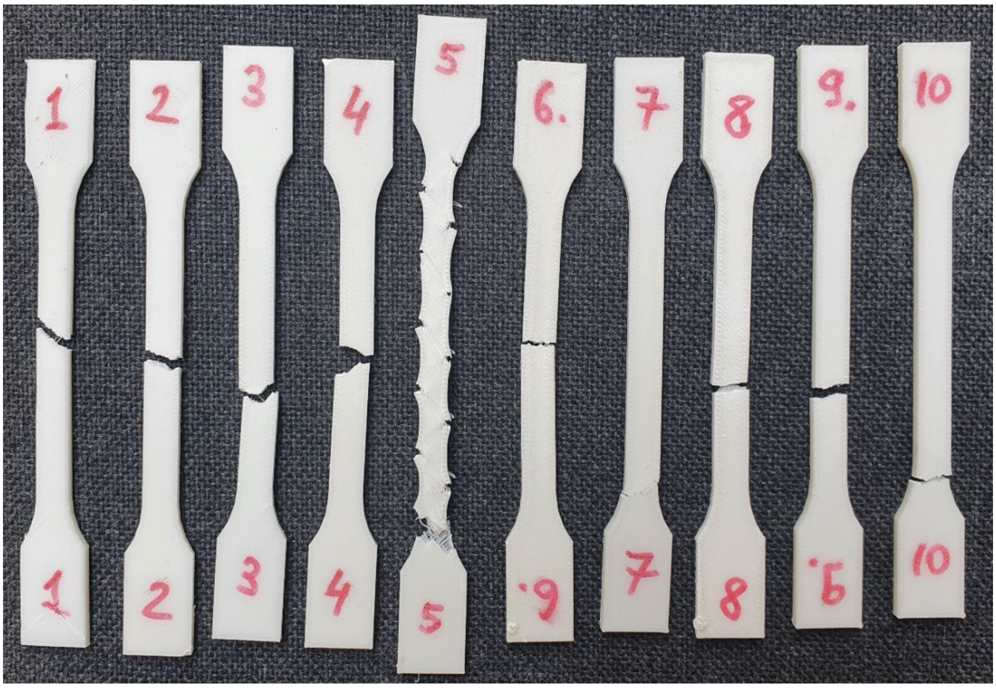


Figure 5: The appearance of 3D printed specimens, after the tensile test

It is found that both the failure mode and the appearance of the fracture surfaces are related to the 3D printing parameters used to make the specimens. Thus, specimens 1, 3 and 5 show a ductile fracture with a partial or complete tearing of the printed structure (Fig. 6). The other specimens show a brittle fracture, specimen 4 presenting the most brittle behaviour the since the failure occurred suddenly with the detachment of a portion from the specimen (Fig. 7).

a) Specimen 1 b) Specimen 3 c) Specimen 5

Figure 6: Details of the failure mode and the appearance of the fracture surface (ductile fractures)

a) Specimen 8 b) Specimen 4

Figure 7: Details of the failure mode and the appearance of the fracture surface (brittle fractures)

Fig. 8 shows the Pareto diagram regarding the influence of T, v and h parameters of the 3D printing process on the tensile strength (R_m). It can be observed that the temperature (T) and the layer heigh (h), and their interaction have a significant influence on the objective function.

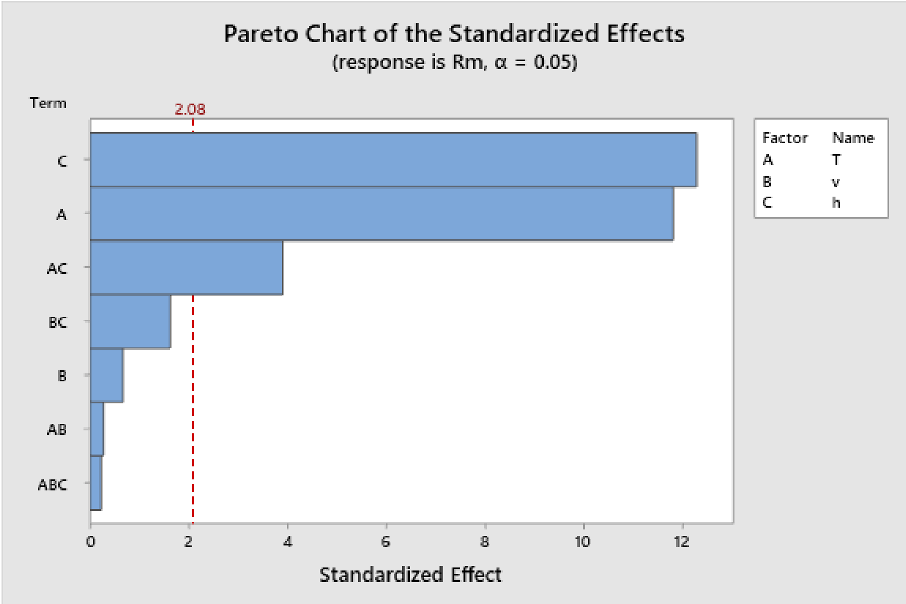


Figure 8: Pareto diagram - the influence of the process parameters T, v and h on the tensile strength (R_m)

Eq.1 describes the variation of the objective function - tensile strength (R_m) with the process parameters and their interactions:

$$R_m = 20.2 + 0.067\ T + 0.040\ v - 128\ h - 0.00054\ T \cdot v + 0.167\ T \cdot h + 0.17\ v \cdot h + 0.00168\ T \cdot v \cdot h + 1.231\ Ct\ Pt \quad (1)$$

Fig. 9a and Fig. 9b presents the response surfaces regarding to the influence of printing process parameters on tensile strength (R_m). Fig. 9a shows that in order to obtain the highest values of tensile strength of the printed components, it is favourable to be selected a temperature as close as possible to 300°C, correlated with the use of speeds close to the extreme values, (printing speed of 80 mm/s).

Fig. 9b shows the need to select the highest possible values of temperature (T), close to 300°C and a thickness of the layer heigh (h) as small as possible, of 0.1 mm, to obtain high tensile strengths exceeding 25 N/mm^2. It is also observed that in the case of lower temperature values, towards the minimum limit of 200°C and if a layer heigh close to 0.3 mm are used, a significant decrease of the tensile strength, up to 10 N/mm^2 can occur.

From the graphs shown in Fig. 9c and Fig. 9d, data can be obtained that confirm the information previously presented in the surface graphs. Thus, to obtain the highest possible values of tensile strength (R_m), the highest possible values of the printing temperature, close to 300°C, the layers heigh as thin as possible and the printing speeds close to the extreme values should be selected.

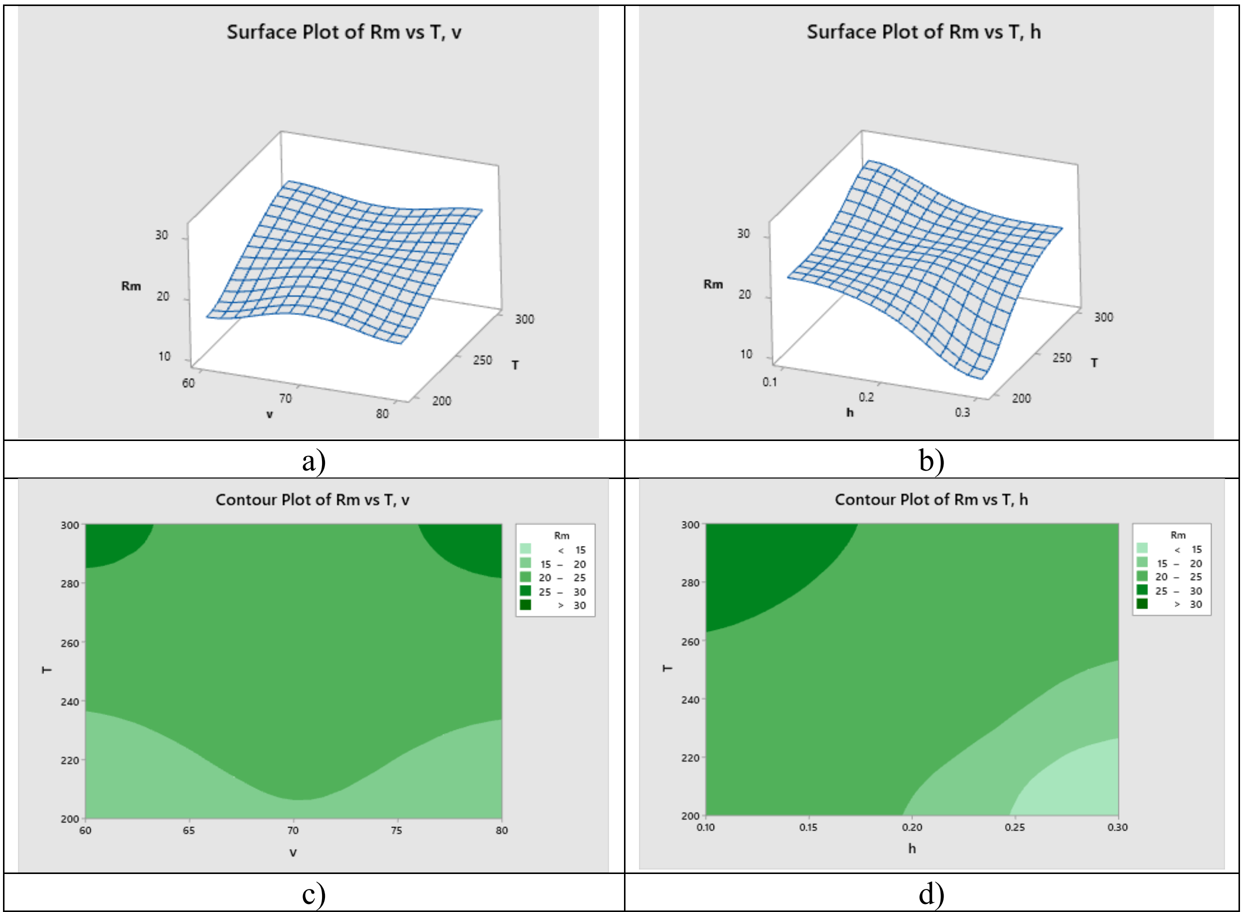


Figure 9: Correlations between the main parameters of the 3D printing process (T, v and h) on the tensile strength (R_m)

Eq. 2 describes the variation of the objective function – surface roughness (R_a) with the process parameters and their interactions:

$$R_a = 19.7 - 0.091\ T - 0.026\ v - 66\ h + 0.00069\ T \cdot v + 0.699\ T \cdot h + \\ + 2.19\ v \cdot h - 0.0122\ T \cdot v \cdot h + 3.25\ Ct\ Pt \quad (2)$$

Fig. 10 shows the Pareto diagram on the influence of the parameters T, v and h of the 3D printing process on the tensile strength (R_a). It can be observed that the temperature (T). It is observed that the layer heigh (h) and the temperature (T) have a significant influence on this objective function.

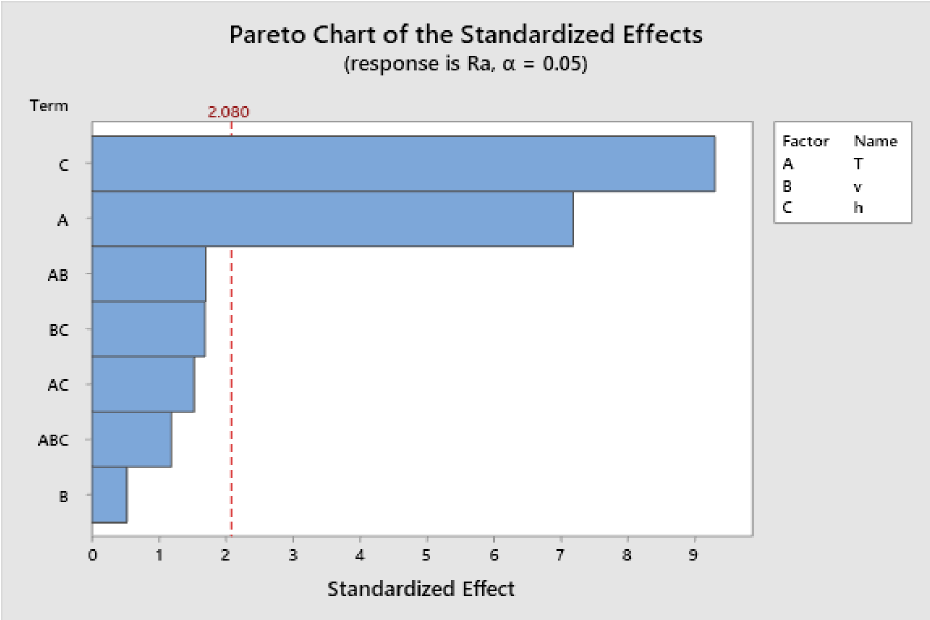


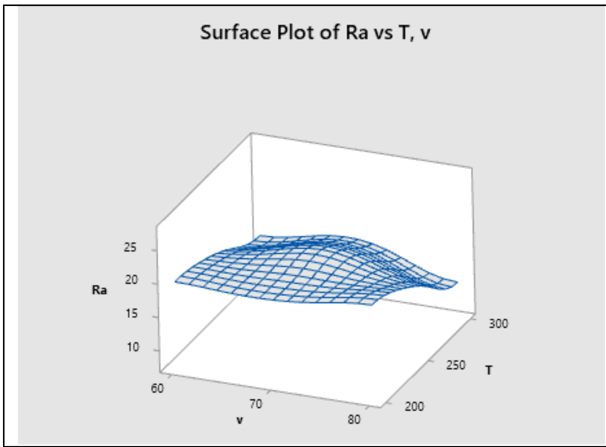
Figure 10: Pareto diagram - the influence of the process parameters T, v and h on the surface roughness (R_a)

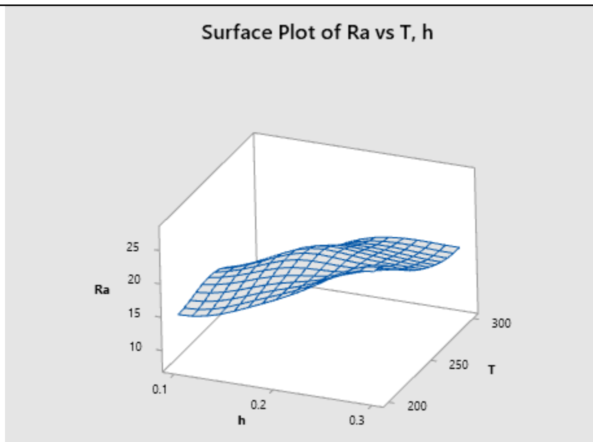
Fig. 11a and Fig. 11b presents the response surfaces regarding to the influence of the printing process parameters on the surface roughness of the specimen (R_a).

To obtain the lowest possible values of surface roughness, it is recommended to choose temperatures as close as possible to 300°C, layers heigh as thin as possible, of 0.1 mm and printing speeds close to 60 mm/s or 80 mm/s.

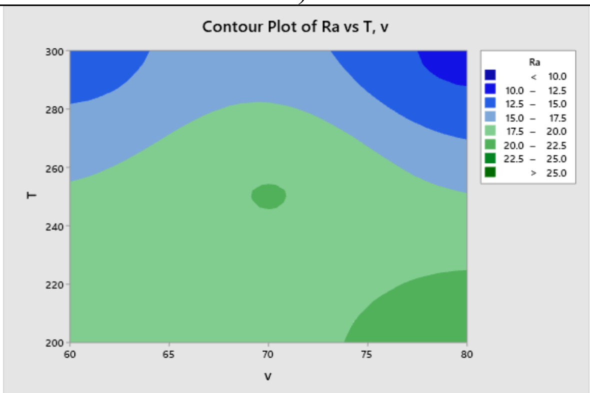
From the graphs in the form of contour plots, shown in Fig. 11c and Fig. 11d, more accurate additional information can be obtained regarding to the selection of appropriate values of the process parameters, when it is desired to obtain a surface roughness as low as possible.

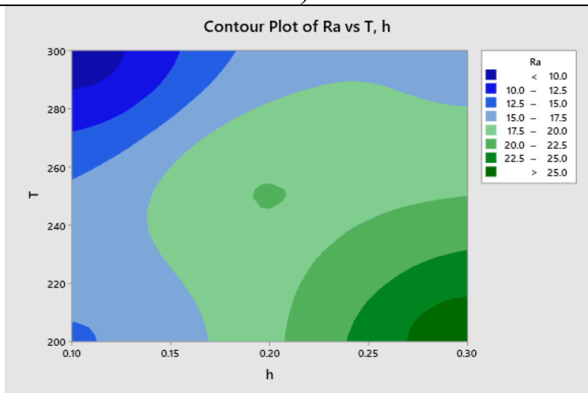
Thus, e.g., if the value of R_a is to be between 10 to 12.5 µm, it is recommended that the printing temperature be higher than 270°C and the layer height be selected less than 0.15 mm. (Fig. 11d).





a)	b)





c)	d)

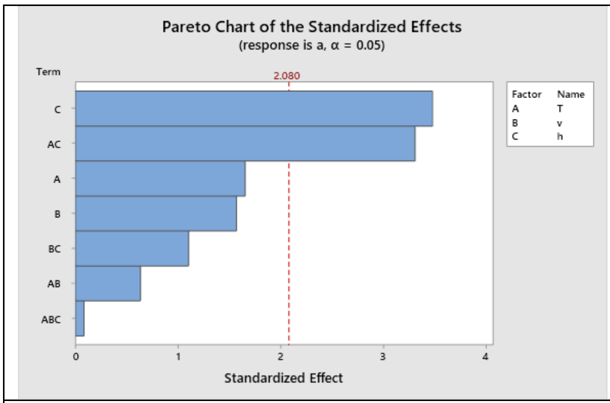
Figure 11: Correlations between the main parameters of the 3D printing process (T, v and h) on the surface roughness (R_a)

Eq. 3 describes the variation of the objective function - the thickness of the test piece (a) with the process parameters and their interactions and Eq. 4 describes the variation of the objective function - the width of the test piece (b) with the process parameters and their interactions:

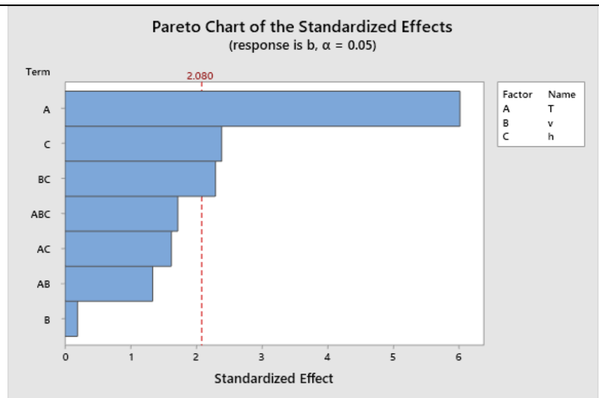
$$a = 5.24 - 0.00417\,T - 0.0092\,v - 4.67\,h + 0.000032\,T\cdot v + 0.0153\,T\cdot h + 0.030\,v\cdot h - 0.000033\,T\cdot v\cdot h + 0.0458\,Ct\,Pt \quad (3)$$

$$b = 9.518 + 0.00305\,T + 0.00533\,v + 3.35\,h - 0.000037\,T\cdot v - 0.0182\,T\cdot h - 0.0550\,v\cdot h + 0.000300\,T\cdot v\cdot h - 0.0458\,Ct\,Pt \quad (4)$$

Fig. 12 shows the Pareto diagram regarding the influence of T, v and h parameters of the 3D printing process on the specimen dimensions (a and b). It is observed that the layer heigh (h) and its interaction with the temperature (T) have a significant influence on this objective functions.



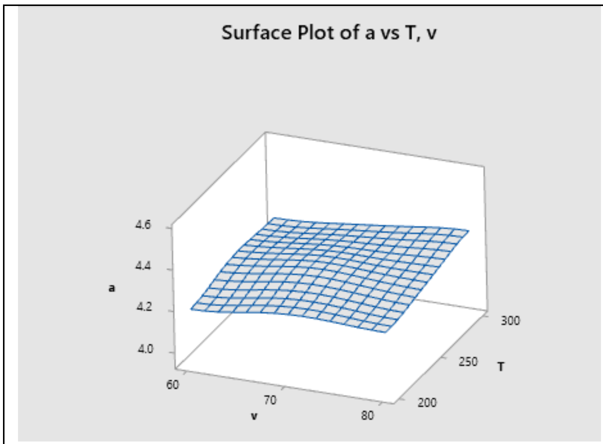
a)



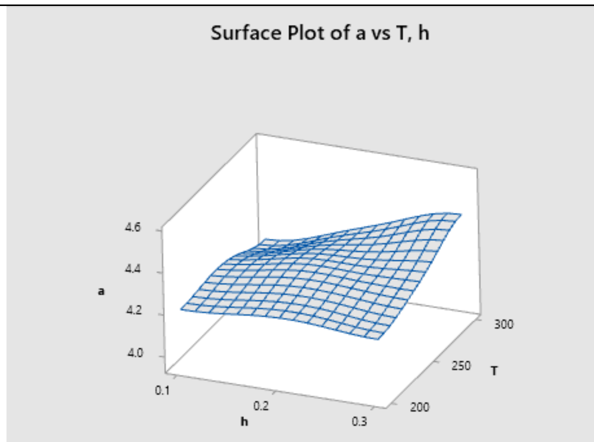
b)

Figure 11: Pareto diagrams - the influence of the process parameters T, v and h on the specimen dimensions a) and b).

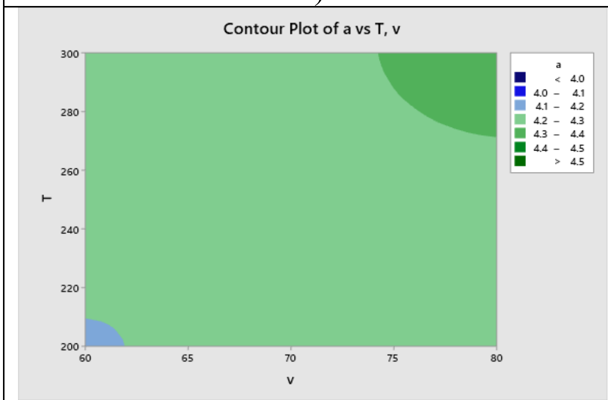
In the similar way Fig. 12 and Fig. 13 presents the response surfaces and the contour plots regarding to the influence of the printing process parameters on the dimensions of the specimen (a and b).



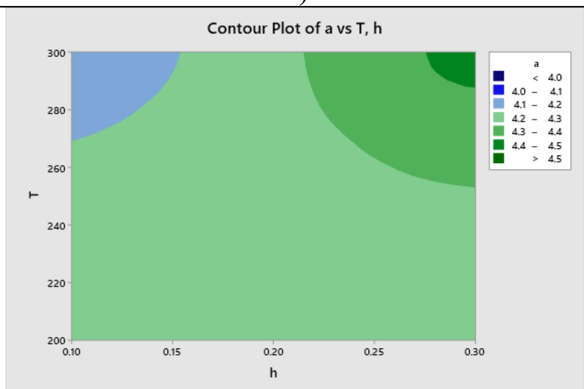
a)



b)



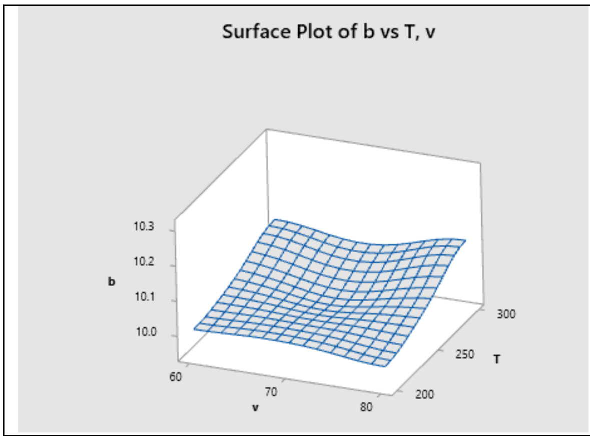
c)



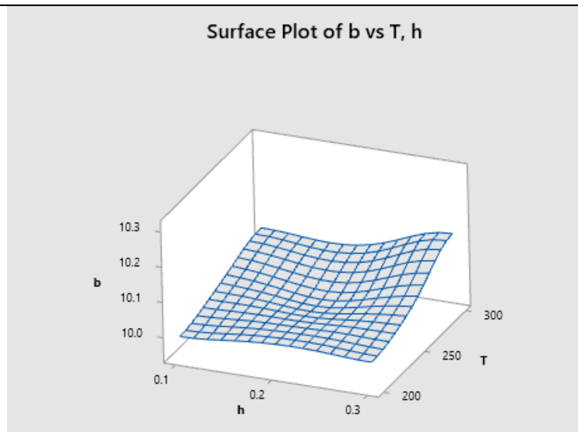
d)

Figure 12: Correlations between the main parameters of the 3D printing process (T, v and h) on the sample thickness (a)

It is revealed that obtaining values of the thickness of the test piece located in the range of 4.1 to 4.2 mm, requires the use of high temperature values, higher than 270°C and a thickness of the deposited layer less than 0.15 mm.



a)



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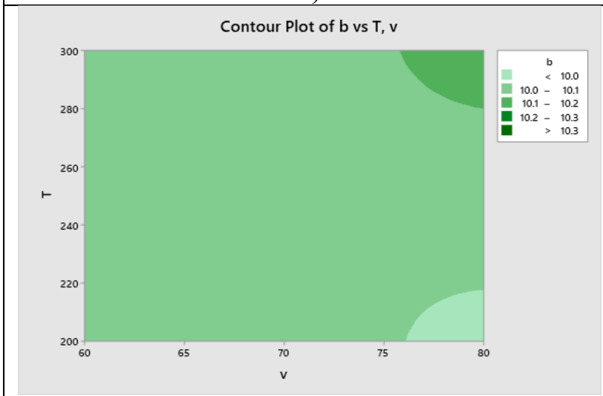
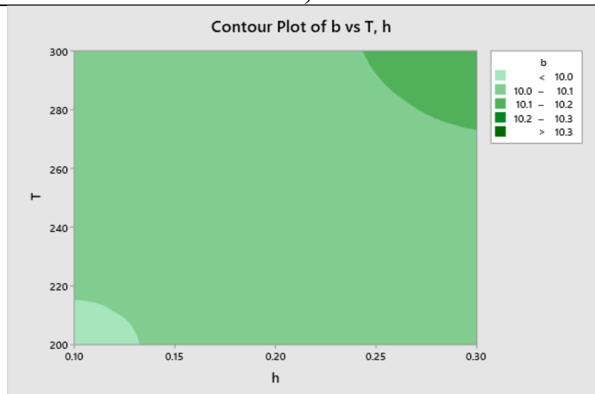


c)



d)

Figure 13: Correlations between the main parameters of the 3D printing process (T, v and h) on the sample width (b)

Eq. 5 describes the variation of the objective function - printing time (t_p) with the process parameters and their interactions:

$$t_p = 182 - 1.175\ v - 360\ h + 2.25\ v \cdot h - 11.25\ C_t\ Pt \qquad (5)$$

In this case, there is an influence on the objective function (t_p) only from a smaller number of controllable factors and their interactions, in particular it can be seen that there is a decrease in printing time with increasing of printing speed and layer height.

Given that this size of the specimen needs to be as close as possible to a standardized value, in this case 10 mm, it is recommended to select as much as possible a set of parameters with lower values for temperature and layer thickness, speed printing has a relatively small influence on this objective function. In order to obtain values of the test piece width (b) in the range 10.0-10.1 mm, it is shown that the process parameters can vary between relatively wide limits.

The optimization of the process as a whole was performed based on the mathematical models obtained for each objective function. In order to optimize the process, the following criteria have been established for each objective function:

- tensile strength by R_m - maximum value
- surface roughness R_a - minimum value
- the test piece thickness a - target value of 4 mm
- the test piece width b - target value of 10 mm
- printing time t^p - minimum value

The optimal values of the printing process parameters for the different combinations of objective functions considered are presented in Table 5. Given some requirements that may arise in industrial practice, based on the results obtained in the experimental four other optimal variants of the printing process parameters were established as following:

a) Component quality (dimensional accuracy and superior mechanical characteristics) - optimization with four objective functions (Rm, R_a, a, b);

b) Execution speed - optimization with three objective functions (t_p, a, b);

c) Component strength - optimization with an objective function (R_m);

d) Degree of surface finish - optimization with an objective function (Ra).

Table 5: Optimal parameters

Optimal variant	**Temperature** T [°C]	**Printing speed** v [mm/s]	**Layer heigh** h [mm]
Optimum 1: with 5 objective functions (R_m, R_a, a, b, t_p)	300	80	0.1
Optimum 2: with 4 objective functions (R_m, R_a, a, b)	300	60	0.1
Optimum 3: with 3 objective functions (t_p, a, b)	200	80	0.3
Optimum 4: with one objective function (R_m)	300	60	0.1
Optimum 5: with one objective function (R_a)	300	60	0.1

4. Conclusions

A 1^{st} order factorial experiment was conducted on 30 test pieces taking into consideration the main process parameters of 3D printing process using 3 controllable factors (T, v and h) with 2 levels, 3 replicas for each combination of controllable factors and 6 replicas in the central point.

Based on the experimental results obtained, regression models for correlation between the 3D printing process parameters and objective functions: tensile strength, surface roughness and component dimension (a and b) were obtained. Regression models can be used to select the appropriate process parameters to obtain required characteristics of 3D printed components, depending on the loading and operation conditions.

Experimentally, optimal variants of parameters were determined that correspond to minimum printing speeds, maximum tensile strength, high surface quality or high dimensional accuracy.

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