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Optimizing 3D printing parameters to improve hardness and surface roughness

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Abstract. **The purpose of this paper is to study the factors affecting roughness and hardness of 3D printed models. Two parameters are analyzed- 3D printing speed and layer thickness. The main disadvantage of 3D printed models is their higher roughness, which depends on the printing parameters. In order to obtain parts with smoother surfaces, it is necessary to study these parameters. Based on the obtained experimental results, a regression dependence was built describing the relationship between roughness and hardness with the investigated printing parameters.**
Keywords: 3D printing, hardness, surface roughness

I. INTRODUCTION

In recent years, 3D printing has become more and more popular in some industries, such as architecture, automotive, mechanical engineering, medicine etc [1], [2]. In order to meet the great demand for this technology. If at the beginning of this century, 3D models of souvenirs and irresponsible details were mainly made, nowadays more and more emphasis is placed on the possibility of achieving high mechanical and physical properties.

Real surfaces have micro-uniformities, which are a consequence of technological operations [3]. Surface roughness is an important characteristic for operational qualities of parts, especially in assembled units, because it affects the quality of the assembly[4]. High values of roughness also reduce the fatigue limit of materials. High roughness values also reduce fatigue limit of materials.

Hardness is an important mechanical characteristic in 3D printing, as it represents both the wear resistance and behavior of the parts in general - the type of failure, plasticity, etc., an important advantage of the hardness test is that it is non-destructive test [5].

In general, 3D printed parts have weaker mechanical properties compared to other manufacturing technologies, so their properties are determined by the weakest layer. Their application is growing especially in the automotive industry. Precisely for these reasons, testing the hardness of 3D printed parts is very relevant.

This article looks at one of the most common applications of 3D technology, namely the printing of various parts with a wide variety of openings.[6] Through the methods of statistical analysis, it is shown how the roughness and hardness of the model may be determined on the basis of a certain sample of experimental models. Mainly for printing 3D models used in mechanical engineering and automotive industry, polymers with better physical and mechanical properties are used.

In the article, the printed models are from the ABS polymer Acrylonitrile-Butadiene-Styrene[7]. It is also possible to use other polymers such as PETG, polypropylene, polyethylene, but they have higher requirements for the 3D printer, most often a higher extrusion temperature. The printer we use is a Flashforge Creator 3, it allows a maximum extrusion temperature of 250°C and a maximum substrate temperature of 120°C

Factors that can be changed are polymer extrusion temperature, print speed, layer height and substrate temperature [8],[9]. The two technological invoices, the extrusion temperature and the temperature of the base, we assume to be constant because they can deteriorate the

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quality of the print itself. Optimizing of 3d parameters to improve parameters is very current [10].

The extrusion temperature for ABS is in the range of 235-240°C, when the temperature decreases, we do not have good thinness, and this leads to problems with clogging the nozzle of the 3d printer and interrupting the printing process. At extrusion temperatures above 240 °C, the material begins to boil and pit the nozzle walls, and the high temperature can cause material to flow freely and uncontrollably from the extruder.

At a high temperature of the printer base above 110°C, the pattern is difficult to peel off and may break at the base. At temperatures below 100°C, the pattern peels off during printing and the process has to be started from the beginning.

II. MATERIALS AND METHODS

ABS is an amorphous polymer that is obtained by emulsion or bulk polymerization of acrylonitrile and styrene in the presence of polybutadiene. The most important properties of ABS are its good impact resistance and strength

Investigated parameters of 3D printing are speed and height of layer, because they affect properties of parts. The 3D printer parameters that are constant for all trials, ie. are constant: nozzle diameter 0.4mm; flow 100%; retreat 1mm; bed temperature 110°C.

Hardness was measured according to the standardized Shore D method according to DIN 53505 [11].This method is the most popular for plastics. The measuring device is calibrated and its range is according to the theoretical hardness of the material. In order to reduce the measurement error, the firings were made at a distance of more than 2 times the diameter of the pin from the final contour of the specimen, as well as a distance of more than 3 times the diameter of the needle between individual impressions [12].

For greater precision, 5 tests were made on each sample, fig. 1.

Each of the test specimens was measured at three locations using a Surface Roughness Tester Surftest 4, fig2, Mitutoyo brand. The measurements are presented in tabular form table 1, [13].

Fig. 1. Hardness measurement

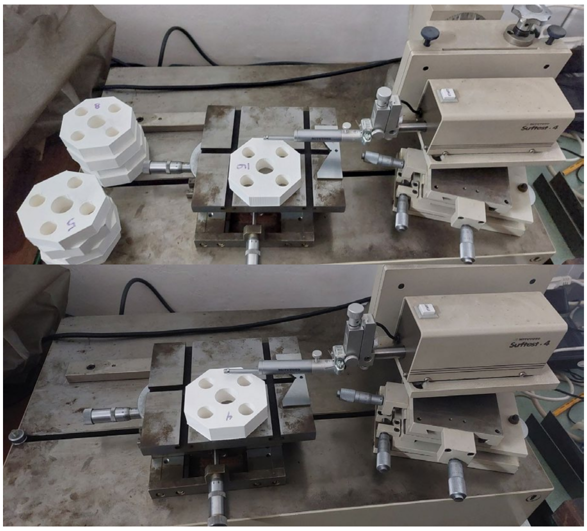

Fig. 2. Surface Roughness Tester Surftest 4

III. RESULTS AND DISCUSSION

TABLE 1 EXPERIMENTAL RESULTS OF SURFACE FINISH

Layer [mm]	Speed [m/min]	Roughness of tested 3 countours [Ra]			Average [Ra]
		1	2	3	
0.1	10	1.24	1.46	1.39	1.36
0.1	45	1.26	1.15	1.76	1.39
0.1	80	1.32	1.24	0.96	1.17
0.25	10	5.89	4.68	6.43	5.67
0.25	45	4.27	3.11	5.01	4.13
0.25	80	2.48	2.97	4.2	3.22
0.4	10	1.99	2.98	3.5	2.82
0.4	45	3.01	3.47	2.8	3.09

The data from Table 1 on the roughness were processed and the following regression model was obtained:

$$Avr\ Ra = -5.722 + 88.19\ layer + 0.0566\ Speed - 166.6\ layer*layer - 0.744\ layer*Speed + 1.512\ layer*layer*Speed \quad (1)$$

Results are shown in tables 2 and 3

TABLE 2 MODEL SUMMARY

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
0.195021	99.33%	98.20%	1.54035	90.90%	112.23	1.61

The coefficient of determination R-sq = 99.33% was calculated, and the adjusted coefficient of determination has the value R-sq(adj) = 98.2%, which satisfies the requirement of being above 95%[14]. The P-value must be below 0.05, this condition is not met only for the layer*speed variable, table 11. For the same variable, the F-value condition is not met, but the influence is insignificant and is therefore ignored. On the Pareto diagram[15], Fig. 3, it is also seen that the component AB is insignificant and the others are significant.

TABLE 3 ANALYSIS OF VARIANCE

Source	DF	Seq SS	Contribution	Adj SS	Seq MS	F-Value	P-Value
Regression	5	16.8052	99.33%	16.8052	3.36104	88.37	0.002
layer	1	3.9474	23.33%	8.7895	3.94741	103.79	0.002
Speed	1	1.1151	6.59%	0.9340	1.11514	29.32	0.012
layer*layer	1	9.8371	58.14%	8.0779	9.83708	258.64	0.001
layer*Speed	1	0.0148	0.09%	1.7799	0.01480	0.39	0.577
layer*layer*Speed	1	1.8908	11.18%	1.8908	1.89078	49.71	0.006
Error	3	0.1141	0.67%	0.1141	0.03803		
Total	8	16.9193	100.00%				

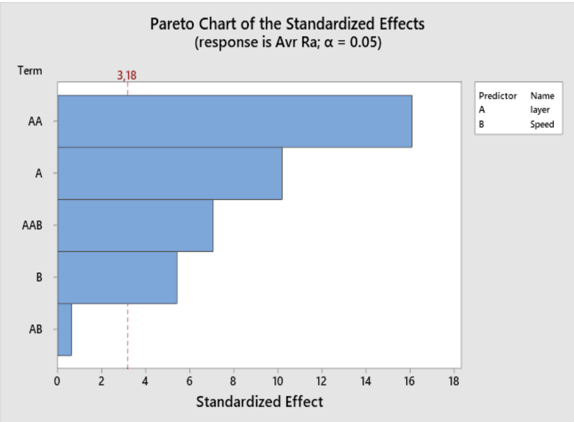

Fig. 3. Pareto chart

The value of the standardized residuals is in range of -2;+2, Fig. 4.

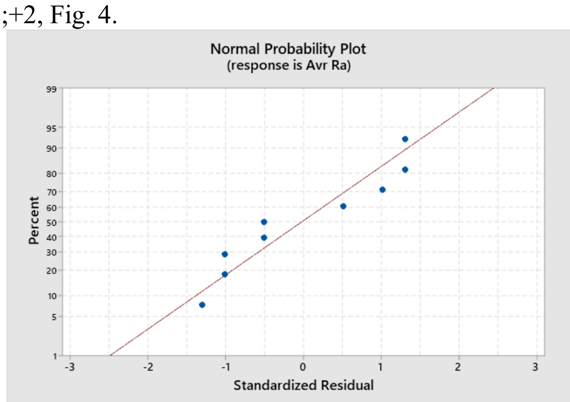

Fig. 4. Normal probability plot

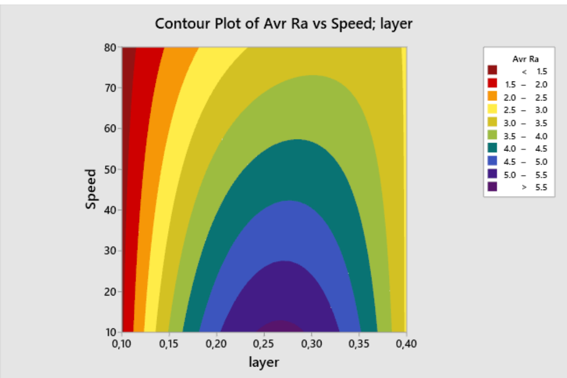

Fig. 5. Contour Plot

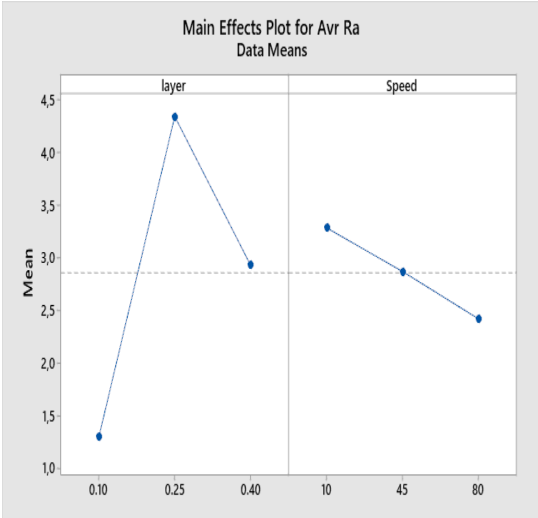

Fig. 6. Main effect

It was also analyzed how the influence of layer and speed on the roughness, fig. 5-6.

The obtained experimental results for hardness are presented in Table 4. The data from the table were processed and the following regression model was obtained:

$$Avr = -12.45 + 552.1\ layer + 0.0779\ Speed - 960\ layer*layer \quad (2)$$

TABLE 4 EXPERIMENTAL RESULTS HARDNESS SHORE D

Sample	Layer [mm]	Speed [m/min]	Probe position [Shore D]					Average Shore D
			1	2	3	4	5	
1	0.10	10	33.8	38.8	31.3	37.1	39.6	36.1
2	0.10	45	37.2	39.8	31.0	33.3	42.3	36.7
3	0.10	80	43.0	29.5	36.0	30.8	46.5	37.2
4	0.25	10	69.9	73.5	67.4	71.8	69.0	70.3
5	0.25	45	69.5	68.1	68.2	67.1	72.9	69.2
6	0.25	80	71.1	64.4	65.9	68.8	68.4	67.7
7	0.40	10	47.5	48.5	51.2	51.8	54.0	50.6
8	0.40	45	49.1	53.6	56.0	60.2	59.3	55.6
9	0.40	80	63.7	66.6	71.0	69.8	71.5	68.5

TABLE 5 MODEL SUMMARY

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
5.10171	92.80%	88.48%	508.577	71.86%	79.58	60.57

TABLE 6 ANALYSIS OF VARIANCE

Source	DF	Seq SS	Contribution	Adj SS	Seq MS	F-Value	P-Value
Regression	3	1677.28	92.80%	1677.28	559.09	21.48	0.003
layer	1	698.98	38.67%	1198.56	698.98	26.86	0.004
Speed	1	44.61	2.47%	44.61	44.61	1.71	0.247
layer*layer	1	933.70	51.66%	933.70	933.70	35.87	0.002
Error	5	130.14	7.20%	130.14	26.03		
Total	8	1807.42	100.00%				

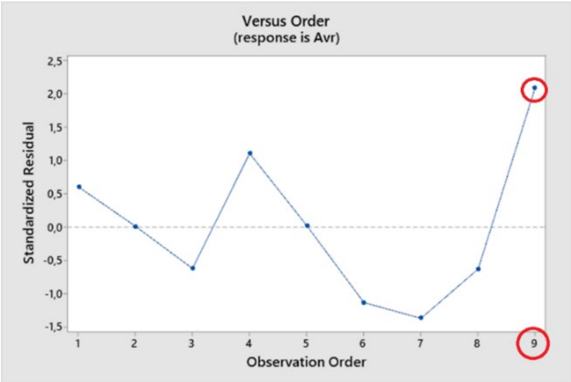

Fig. 7. Versus Order

Fig. 7 clearly shows the presence of 1 error: - observation #9, the value of the standardized residual should be within the limits of -2;+2. This gives us reason to remove the observation and process the data again.

After reprocessing the results we get the following Regression Equation:

$$Avr = -12.01 + 591.2\ layer + 0.0061\ Speed - 1072.0\ layer*layer \quad (3)$$

TABLE 7 MODEL SUMMARY

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
2.02695	98.97%	98.19%	83.1653	94.77%	68.46	38.86

TABLE 8 ANALYSIS OF VARIANCE

Source	DF	Seq SS	Contribution	Adj SS	Seq MS	F-Value	P-Value
Regression	3	1574.94	98.97%	1574.94	524.98	127.78	0.000
layer	1	495.94	31.16%	1305.32	495.94	120.71	0.000
Speed	1	31.81	2.00%	0.20	31.81	7.74	0.050
layer*layer	1	1047.19	65.80%	1047.19	1047.19	254.88	0.000
Error	4	16.43	1.03%	16.43	4.11		
Total	7	1591.38	100.00%				

The coefficient of determination R-sq = 98.97% was calculated, and the adjusted coefficient of determination has the value R-sq(adj) = 98.19%, which satisfies the requirement of being above 95%. The P-value for all variables is below 0.05, table 8. The Pareto diagram, fig.8 also shows that the components are significant [16].

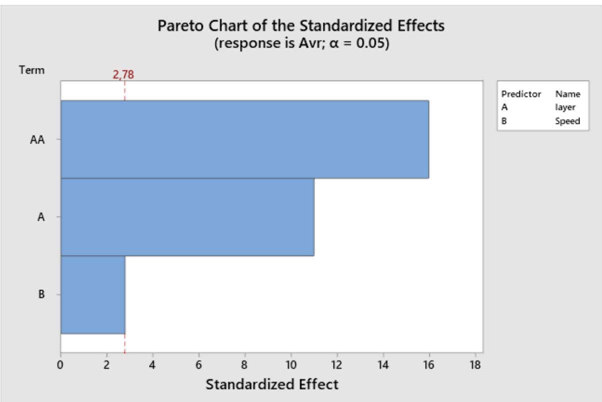

Fig. 8. Pareto chart

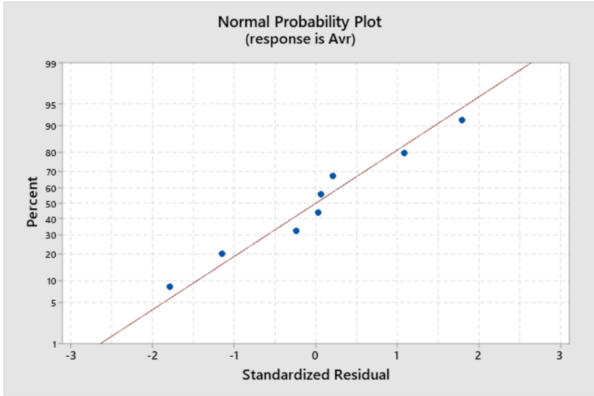

Fig. 9. Standartized residual

The value of the standardized residuals is in range of -2;+2 [17], Fig. 9-10.

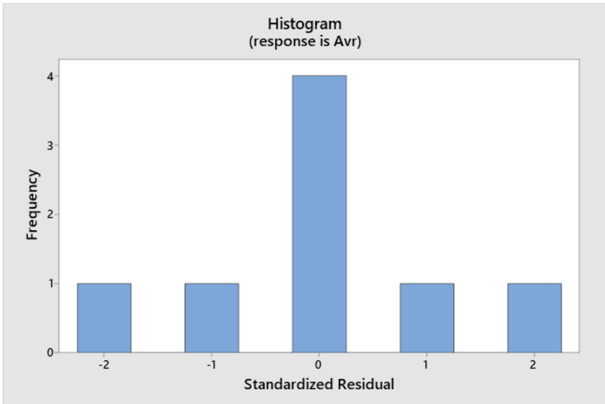

Fig. 10. Histograma for hardness

It was also analyzed how the influence of layer and speed on the hardness, fig. 11-13

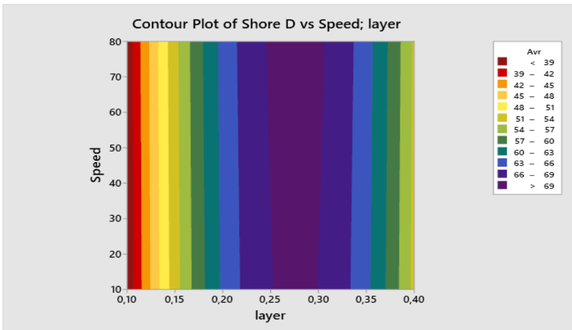

Fig. 11. Contour plot

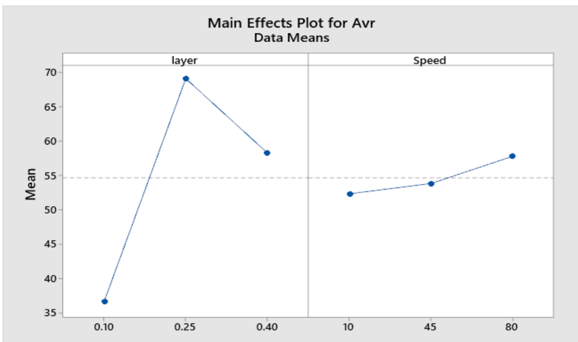

Fig. 12. Main effect

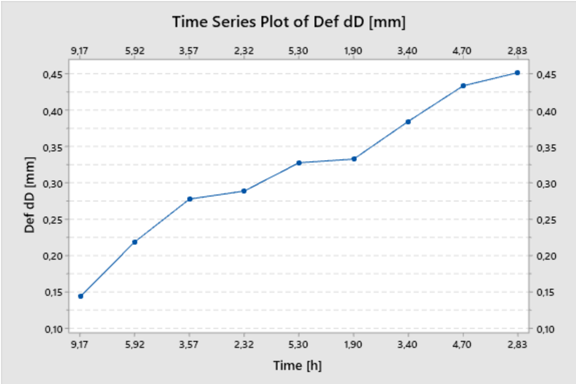

Fig. 13. Time series plot

The relationship between the deviation from the size and the time for printing the part was established, fig.13. It can be seen that the smaller the size deviation, the longer the printing time.

IV. CONCLUSIONS

For execution of the experiments is selected central composition plan to reduce the number of experiments. It allows optimal distribution of variables for correct statistical analyze. The studied polymer material ABS, one of the current polymers, is used for the production of technical details.

After literature review and according the abilities of the 3D printer are defined the important parameters of the process-printing speed from 10 m/min to 80 m/min, thickness of the layer from 1mm- 0,4 mm. The rest 3D printing parameters are constant. The statistical proceed was done, that shows 95% influence of thickness layer on roughness and hardness.

V. ACKNOWLEDGMENTS

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