Modeling and Optimization of Tensile Strength of ABS Parts Manufactured by the Fused Deposition Modeling Process

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Abstract: In the last two decades additive manufacturing (AM) technology has been emerged as a powerful fabrication method to obtain fnished components within a short span of time, without any tooling requirement and minimal human interface. Fused Deposition Modeling (FDM) is one of the most used AM techniques. It has an ability to produce a complex functional geometries with a good properties. Properties mainly depend on process parameters and can be improved by setting parameters at appropriate levels. In this paper, mathematical models for prediction of ultimate tensile strength (UTS) and cost were developed. Process parameters whose influence was analyzed are top and bottom surface layers, fill spacing and layer resolution. Experiments were conducted on specimens manufactured from Acrylonitrile butadiene styrene (ABS) material. Design Expert software and ANOVA analysis were used for mathematical modelling and optimization and based on that process parameters that lead to maximal tensile strength and minimal cost were defined. Thus obtained results will have practical meaning for users involved in FDM additive manufacturing process.

Izvorni znanstveni rad

Sažetak: U posljednja dva desteljeća tehnologija aditivne proizvodnje (AM) se istaknula kao moćna metoda izrade za dobivanje gotovih komponenata u kratkom vremenu, bez potrebnih alata i uz minimalno učešće čovjeka. Taložno očvršćivanje materijala (FDM) je jedan od najčešće korištenih postupaka aditivne proizvodnje. Uz pomoć njega se mogu proizvesti kompleksni funkcionalni geometrijski oblici s dobrim svojstvima. Svojstva uglavnom ovise o parametrima samog procesa i mogu biti poboljšana postavljanjem parametera na odgovarajuće nivoe. U ovome radu razvijeni su matematički modeli za predviđanje vlačne čvrstoće (UTS) i troškova. Parametri procesa čiji utjecaj je analiziran su broj nanesenih gornjih i donjih slojeva materijala, razmak između slojeva i rezolucija slojeva. Eksperimenti su provedeni na uzorcima izrađenim iz akrilonitril-butadien stirel (ABS) materijala. Za matematičko modeliranje su primjenjeni Design Expert softver i ANOVA analiza i temeljem toga su definirani parametera procesa kojima se postiže maksimalna vlačna čvrstoća i minimalni trošak. Tako dobiveni rezultati će imati praktičan značaj za korisnike uključene u FDM postupak aditivne proizvodnje.

1. Introduction

Additive manufacturing (AM) is relatively new technology used to fabricate three dimensional computer aided designed (CAD) component by building it in layers of material. Today on the global market exist several different AM processes. These processes differ mainly according to the type of material used in production process and a manner in which the layers of material apply and join together. Among all available AM processes the Fused Deposition Modeling (FDM) is one of the most popular due to its lower production costs, simple manipulation and higher strength of fabricated components. In FDM process parts are built by applying polymer wire material in a molten state to the moveable platform according to computer controlled paths (x-y plane). Extruded material quickly solidifies at a room temperature and thereby generates the first layer of component. After generating the first layer the building platform moves down by the thickness of the new layer (z axis) and furtherly next layer applies. Building process is repeated until a complete part is generated. If some complex geometric parts should be created then it is required a supporting material structure. Once the model is built a supporting structure can be easily removed by melting in water of fracturing. Also built parts can be further processed by conventional machining operations such as turning, milling or grinding. Materials that are mainly used in this process are plastics as ABS, PLA, PC, PP, PE-HD, PE-LD etc.[1][2][3]. Parameters of FDM process differently affect the properties of build parts. To analyze their effects and to find values that lead to optimal responses many authors conducted a comprehensive researches. Sood et al. [4] made an extensive study to understand the effect of five important FDM parameters such as layer thickness, part build orientation, raster angle, raster width and air gap on the compressive stress of test specimens. They also developed a statistically validated predictive equations using artificial neural network approach and regression analysis and found optimal parameter settings through quantum-behaved particle swarm optimization (QPSO). Raut et al. [5] investigated the effect of the built-up orientation on the mechanical properties and total cost of the FDM parts. Considered responses were mechanical and bending strength . The specimens were prepared at three different orientations (0°, 45°, 90°) and in three different axes with the axis of rotation parallel to the larger length of the specimen and perpendicular to the other two sides. Onwubolu et al. [6] analyzed the influence of layer thickness, part orientation, raster angle, raster width and air gap on tensile strength of test specimens. Mathematical models relating the response with the process parameters were developed using group method of data handling (GMDH). Optimal process parameters that lead to maximized tensile strength were defined through application of differential evolution (DE) algorithm. Panda et al. [7] performed experiments to analyze the impact of layer thickness, orientation, raster angle, raster width and air gap on tensile, flexural and impact strength. Response surface methodology (RSM) was used for mathematical modeling and bacterial foraging optimization algorithm (BFOA) for finding optimal process parameters settings. Mohamed et al. [8] studied the influence of layer thickness, air gap, raster angle, build orientation, road width and number of contours using Q-optimal response surface methodology. Their effects on build time, feedstock material consumption and dynamic flexural modulus were critically examined. Mathematical models were formulated to describe a functional relationship between the processing conditions and the process quality characteristics. ANOVA technique was employed to check the adequacy and significance of mathematical models and furtherly optimal setting of process parameters were determined. Nidagundi et al. (9) performed parametric optimization of ultimate tensile strength, surface roughness, dimensional accuracy and manufacturing time using Taguchi method and ANOVA. Input process parameters that were considered were layer thickness, orientation angle and fill angle. Validation of optimal conditions was conducted by making verification experiment. Panda et al. [10] carried out performance modelling of FDM parts using two soft computing (SC) methods such as multi-gene genetic programming (MGGP) and general regression neural network (GRNN). Proposed SC models predict compressive strength of fabricated specimens in terms of input process parameters, layer thickness, orientation and raster angle. The predictions of compressive strength by mathematical models were evaluated against the data generated in experimental study. Liu et al. [11] considered three responses that characterize the mechanical properties of FDM parts, tensile strength, flexural strength and impact strength. As significant factors that contrbute to the strength of a FDM product were identified deposition orientation, layer thickness, deposition style, raster width and raster gap. The influences of input parameters on responses were analyzed by the use of ANOVA analysis. Finally, based on the gray relational analysis, process parameters values that optimize mechanical properties of built parts were obtained. Except these mentioned, there is also a large number of other research papers dealing with modeling and optimization of FDM parts properties related with various input process parameters.

In present article experiments were conducted on samples fabricated from ABS material. ABS parts are sufficiently resistant to heat, chemicals and moisture and that enables FDM parts to be used for prototyping, functional testing and installation. It was analyzed the influence of input process parameters, top and bottom surface layers, fill spacing and layer resolution on ultimate tensile strength and cost. Mathematical modelling and optimization were performed using regression analysis (RA) and Design Expert software.

2. Experimental procedure

In order to optimize FDM process and develop mathematical models design of experiments (DOE) method was utilized. Usually, DOE method is followed by analysis of variance (ANOVA) and regression analysis (RA). These mathematical models should be able to predict process output responses based on some influential input parameters. In this paper, DOE was prepared using D-Optimal response surface design [12]. D-optimal design is very often used because offers the possibility of process optimization. Furthermore, selection of both numerical and categorical factors are possible. In order to optimize FDM process, influence of fill spacing, layer resolution and number of top and bottom surface layers on built samples maximal tensile strength and material cost are investigated. Numerical

factors, in this case, are top and bottom surface layers in range from 3 to 15 and fill spacing in range from 2 mm to 15 mm. The categorical factor is layer resolution and it is varied on three levels, 70 µm, 200 µm and 300 µm. Main aim is to optimize process and to develop mathematical models which will be enabled to predict the cost of material for desired ultimate tensile strength (UTS) of built samples. The second goal is to find optimal parameters to produce FDM samples with good mechanical properties and lower cost. Utilizing DOE and D-Optimal design experimental plan is created by means of ''Design Expert'' software (Table 1). Fixed input parameters are: building material: ABS, print mode: custom, print strength: strong, print pattern: cross, outer walls: 1.

Table 1. Design of experiment and results

Tablica 1. Dizajn eksperimenata i rezultati

Simulation	Top and bottom surface layers	Fill spacing [mm]	Layer resolution [µm]	UTS [MPa]	Cost [€]
1	6	8.50	200	9.74	1.14
2	10	2.00	300	10.94	1.06
3	3	7.39	300	6.19	0.69
4	15	15.00	70	17.61	1.59
5	15	15.00	200	12.45	1.39
6	15	9.62	300	8.42	0.97
7	8	15.00	300	9.50	1.00
8	8	15.00	300	8.97	1.00
9	15	2.00	70	20.30	2.22
10	9	8.50	70	12.83	1.28
11	9	8.50	300	10.17	1.13
12	3	8.50	70	8.49	1.02
13	6	2.00	70	14.82	1.84
14	15	2.00	200	11.70	1.49
15	3	15.00	70	6.83	0.73
16	9	2.81	200	12.38	1.60
17	3	15.00	200	7.69	0.79
18	15	15.00	200	9.82	1.37
19	15	15.00	70	17.67	1.57
20	10	2.00	300	11.83	1.05
21	15	9.62	300	8.88	0.96
22	3	2.00	200	8.52	1.19

According to experimental plan, 22 experiments should be performed. As shown in Tab. 1, AM machine was set to build part with top and bottom surface layer number 3, 6, 8, 9, 10 and 15, values of fill spacing are 2 mm, 2.81 mm, 7.39 mm, 8.50 mm, 9.62 mm and 15 mm.

Finally, layer resolutions are 70 µm, 200 µm and 300 µm. Experimental work was conducted on a CubePro (3D Systems) additive manufacturing machine (Fig. 1a). Test specimens were generated according to standard HRN EN ISO 527:2012 (Fig. 1b). Building material was

applied in layers in z axis (Fig. 1c). Furthermore, ultimate tensile strength evaluation was performed on universal testing machine ''Instron 8801'' (Fig. 2a).
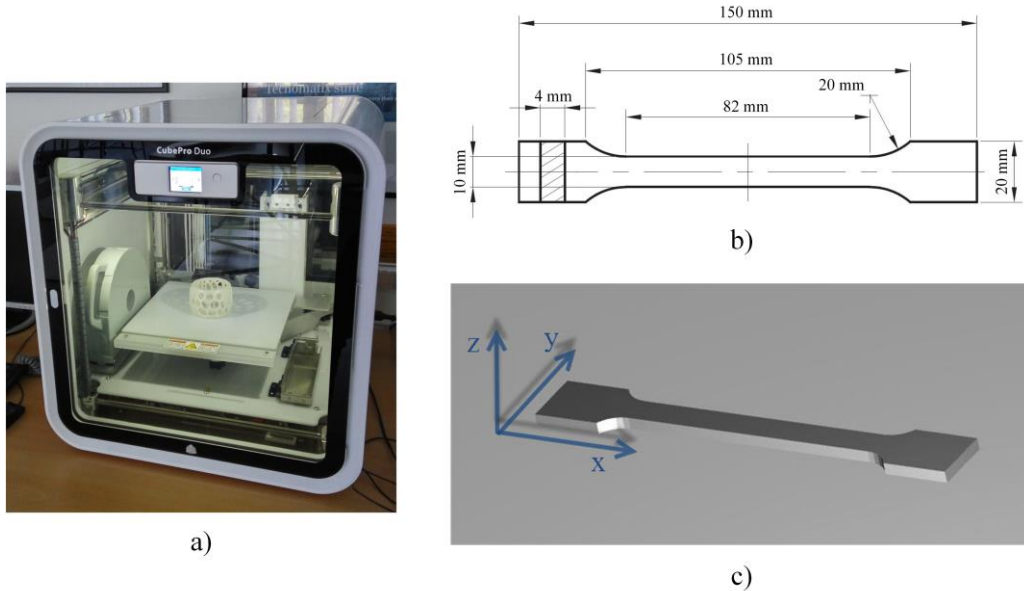

Figure 1. a) CubePro additive manufacturing machine, b) Test specimen dimensions, c) Building direction

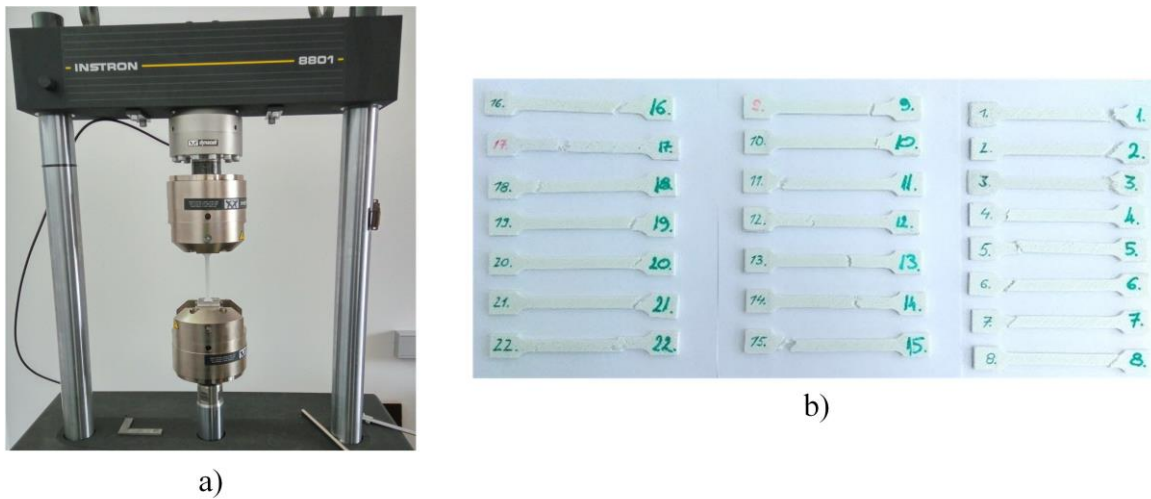**Slika 1.** a) CubePro uređaj za aditivnu proizvodnju, b) Dimenzije ispitnog uzorka, c) Smjer izrade

Figure 2. a) Universal tensile testining machine ''Instron 8801'', b) 22 samples after tensile testing

Slika 2. a) Univerzalna kidalica ''Instron 8801'', b) 22 uzorka nakon vlačnog testa

3. Results and analysis

After experiments, obtained results for the ultimate tensile strenght are in the range from 6.19 MPa to 20.30 MPa, while samples material cost is in the range from 0.69 € to 2.22 €. In order to create mathematical models, RA and ANOVA are performed by means of Design-Expert software. According to analysis three quadratic mathematical models were proposed, one for each categorical factor (Table 2). Also, ANOVA indicates that all three parameters have an influence on UTS. R-Squared, Adj R-Squared, Pred R-Squared and Adeq Precision in this case are 0.9371, 0.9056, 0.8139 and 18.455, respectively. Three mathematical models for each categorical factor predict UTS based on input fill spacing and surface layers are presented in Table 2. For further notice, surface layers will be denoted as A model term, while fill spacing will be denoted as B model term.

Table 2. Mathematical models for UTS

Tablica 2. Matematički modeli za vlačnu čvrstoću (UTS)

Layer resolution	Mathematical models	Eq.
70 µm	$UTS = 4.35429 + 1.82541 \cdot A - 0.14126 \cdot B - 0.053183 \cdot A^2$	(1)
200 µm	$UTS = 5.74949 + 1.26549 \cdot A - 0.14126 \cdot B - 0.053183 \cdot A^2$	(2)
300 µm	$UTS = 5.13681 + 1.15089 \cdot A - 0.14126 \cdot B - 0.053183 \cdot A^2$	(3)

Figure 3. in continuation is a graphical representation of the influence of top and bottom surface layers number and fill spacing value on UTS for each layer resolution (70 µm, 200 µm and 300 µm).

a) Layer resolution 70 µm

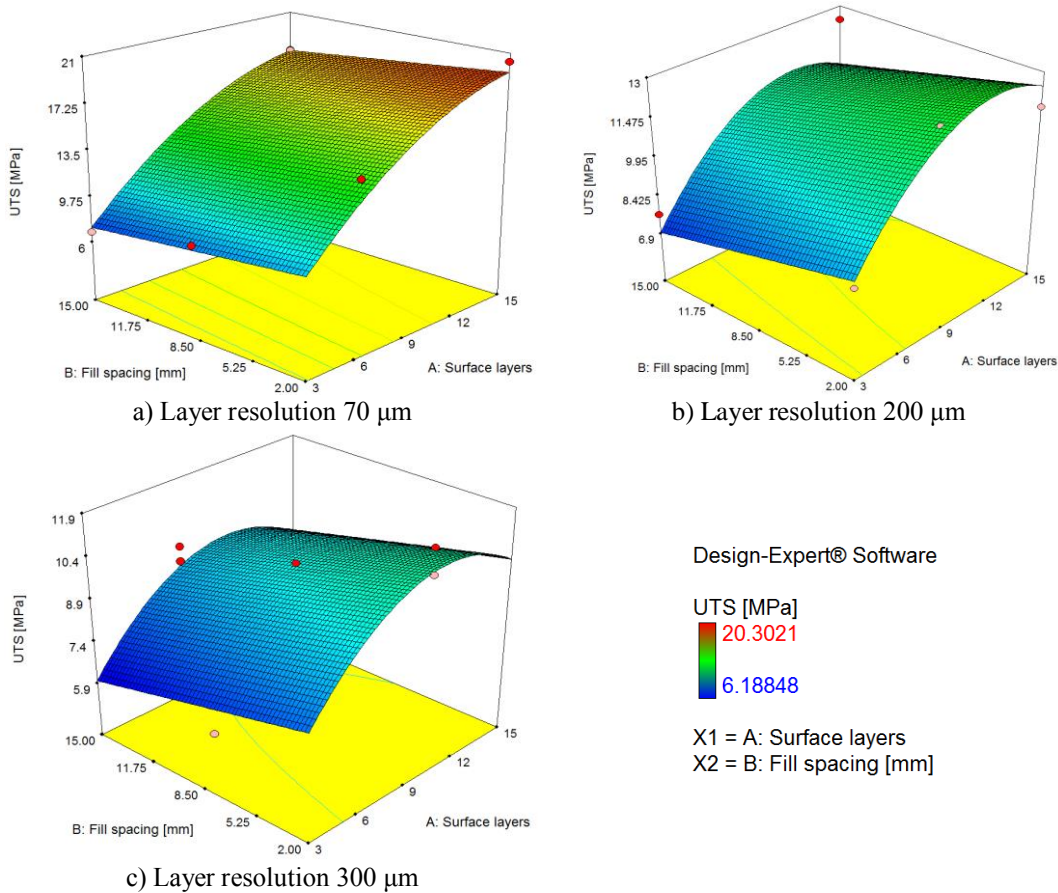b) Layer resolution 200 µm

c) Layer resolution 300 µm

Figure 3. Influence of fill spacing and top and bottom surface layers number on ultimate tensile strength for three different layers resolution (70 µm, 200 µm and 300 µm)

Slika 3. Utjecaj razmaka između slojeva i broja nanesenih gornjih i donjih slojeva materijala na vlačnu čvrstoću za tri različite rezolucije slojeva (70 µm, 200 µm and 300 µm)

Generally, the higher number of surface layers increase UTS, while the higher value of fill spacing decrease UTS, (Figure 3). For samples produced with layer resolution 70 µm influence of surface layers of the sample on UTS is more pronounced than the influence of fill spacing, (Figure 3a). However, the influence of fill spacing on UTS is more pronounced for samples produced with layer resolution 200 µm and 300 µm than for those with 70 µm layer resolution, (Figure 3b and 3c). However, for samples produced with layer resolution 200 µm and 300 µm and one choosen fill spacing in range from 2 mm to 15 mm, a number of surface layers between 12 and 15 provide similar results in UTS. Overall, lowest values of UTS are for layer resolution 300 µm, while highest are for layer resolution 70 µm.

Statistical analysis was also done and for material cost evaluation and also three quadratic mathematical models were proposed, one for each categorical factor, (Table 3). Also, ANOVA indicates that all three parameters have the influence on cost. R-Squared, Adj R-Squared, Pred R-Squared and Adeq Precision in this case are 0.9117, 0.8573, 0.7255 and 17.257, respectively. Three mathematical models for each categorical factor predict material cost based on input fill spacing and surface layers are presented in Table 3.

Table 3. Mathematical models for cost evaluation

Tablica 3. Matematički modeli za procjenu troška

Layer resolution	Mathematical models	Eq.
70 μm	$Cost = 1.36282 + 0.068244 \cdot A - 0.057569 \cdot B$	(4)
200 μm	$Cost = 1.12455 + 0.039034 \cdot A - 0.024704 \cdot B$	(5)
300 μm	$Cost = 0.85449 + 0.014560 \cdot A - 1.87306 \cdot 10^{-3} \cdot B$	(6)

Figure 4. in continuation is graphical representation of influence of top and bottom surface layers number and fill spacing value on cost of the specimens for each layer resolution.
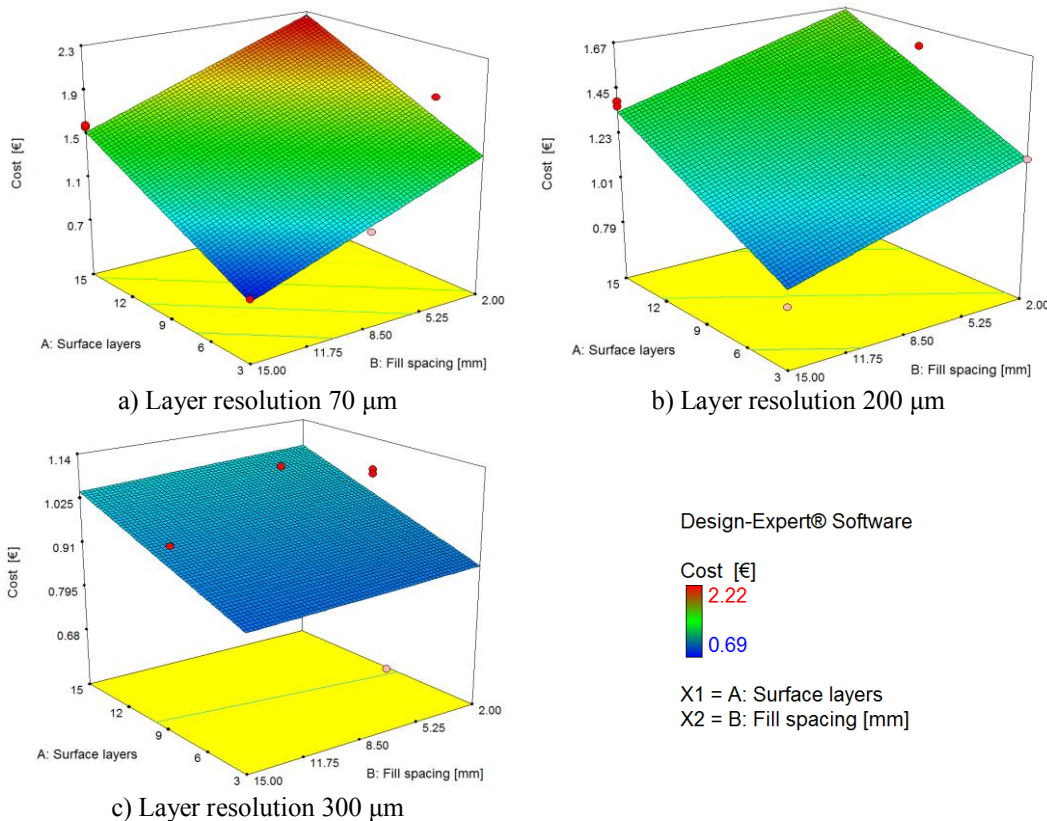

a) Layer resolution 70 μm

b) Layer resolution 200 μm

c) Layer resolution 300 μm

Design-Expert® Software

Cost [€]

2.22

0.69

X1 = A: Surface layers
X2 = B: Fill spacing [mm]

Figure 4. Influence of fill spacing and top and bottom surface layers number on material cost for three different layers resolution (70 μm, 200 μm and 300 μm)

Slika 4. Utjecaj razmaka između slojeva i broja nanesenih gornjih i donjih slojeva materijala na trošak materijala za tri različite rezolucije slojeva (70 μm, 200 μm and 300 μm)

According to the results for layer resolution 70 μm and 200 μm both fill spacing and number of surface layers have great influence on the material cost, (Figure 4a and 4b). Fill spacing decrement and surface layers number increment results with the material cost increase. However, for samples with layer resolution 300 μm, the influence of fill spacing on samples cost is not that pronounced as for samples with layer resolutions 70 μm

and 200 μm, (Figure 4c). As expected highest cost (2.22 €) have samples with layer resolution 70 μm, 15 surface layers and fill spacing 2 mm, but this samples also have higher UTS (20.30 MPa). On the other hand lowest cost (0.69 €) have sample produced with 300 μm layer resolution, 3 surface layers and 7.39 mm fill spacing. Furthermore, according to the results as already was mentioned highest values of UTS have samples with 70 μm layer resolution, while lowest have samples with 300 μm. Influence of fill spacing, for samples with 70 μm layer resolution, is much less pronounced on the UTS than on the material cost of the same samples.

Thus, authors of this work found that optimization of the process could be performed in order to find which parameters are better to produce samples with good mechanical properties, but also with reduced price. Utilizing Design-Expert software package and D-Optimal response surface methodology optimization of the process was performed. According to optimization results samples produced with 11 surface layers, fill

spacing 15 mm and layer resolution 70 μm will have UTS 15.79 MPa and their cost will be 1.24 €.

According to this results, it is possible to produce samples which have 77.8 % of maximal UTS (20.3 MPa) obtained in this research, but these samples also cost 45.9 % less than those with the maximal value of UTS (2.22 €).

4. Conclusion

In the present work an attempt has been made to study the effect of three processing parameters, layer resolution, fill spacing and surface layers on tensile strength and cost of FDM built parts. The experimental results were used to establish a mathematical relationship between tensile strength and cost (output) and process parameters. Mathematical models were validated by using statistical measures. Effect of factors and their interactions were explained using response surface plots. Also, the models were proven to be effective for further analysis to define the process parameters values that lead to optimal combination of tensile strength and cost. According to that, desirability analysis was performed and it was found out the process parameters settings that result in minimal cost and maximal tensile strength should be 11 surface layers, fill spacing 15 and layer resolution 70 μm. Future research will take into consideration other mechanical properties of FDM built parts and their modeling and optimization procedures.

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REFERENCES

[1] Peko, I., Bajić, D., Veža, I., (2015), *Selection of additive manufacturing process using the AHP method*, International Conference ''Mechanical Technologies and Structural Materials'', Split, Croatia

[2] Dandgaval, O., Bichkar, P., (2016), *Rapid prototyping technology-study of fused deposition modeling technique*, International Journal of Mechanical and Production Engineering, Vol. 4, Iss. 4, pp. 44-47.

[3] Novakova Marcincinova, L., Novak Marcincin, J., (2012), *Applications of rapid prototyping fused deposition modeling materials*, Annals of DAAM for 2012 and Proceedings of the 23rd International DAAM Symposium, Vol. 23, No.1, DAAM International, Vienna, Austria

[4] Sood, A. K., Ohdar, R. K., Mahapatra, S. S., (2012), *Experimental investigation and empirical modeling of FDM process for copmpressive strength improvement*, Journal of Advanced Research, Vol. 3, pp. 81-90.

[5] Raut, S., Jatti, V. S., Khedkar, N. K., Singh, T. P., (2014), *Investigation of the effect of built orientation on mechanical properties and total cost of FDM parts*, Procedia Matreials Science, Vol. 6, pp. 1625-1630.

[6] Onwubolu, G. C., Rayegani, F., (2014), *Characterization and Optimization of Mechanical Properties of ABS Parts Manufactured by the Fused Deposition Modelling Process*, International Journal of Manufacturing Engineering, Volume 2014, Article ID 598531

[7] Panda, S. K., Padheee, S., Sood, A. K., Mahapatra, S. S., (2009), *Optimization of fused deposition modelling (FDM) process parameters using bacterial foraging technique*, Intelligent Information Management, Vol. 1, pp. 89-97.

[8] Mohamed, O. A., Masood, S. H., Bhowmik, J. L., (2016), *Mathematical modeling and FDM process parameters optimization using response surface methodology based on Q-optimal design*, Applied Mathematical Modelling, Vol. 40, Iss. 23-24, pp. 10052-10073.

[9] Nidagundi, V. B., Keshavamurthy, R., Prakash, C. P. S., (2015), *Studies on Parametric Optimization for Fused Deposition Modelling Process*, Materialstoday: Proceedings, Vol. 2, Iss. 4-5, pp.1691-1699.

[10] Panda, B. N., Bahubalendruni Raju, M. V. A., Biswal, B. B., (2015), *A general regression neural network approach for the evaluation of compressive strength of FDM prototypes*, Neural Computing and Applicationa, Vol. 26, Iss. 5, pp. 1129-1136.

[11] Liu, X., Zhang, M., Li, S., Si, L., Peng, J., Hu, Y., (2017), *Mechanical property parametric appraisal of fused deposition modeling parts based on the gray Taguchi method*, The International Journal of Advanced Manufacturing Technology, Vol. 89, Iss. 5, pp. 2387-2397.

[12] Vinayagamoorthy, R., Rajeswari, N., Vijayshankar, S., Balasubramanian, K., (2014), *Drilling Performance Investigations on Hybrid Composites by Using D-Optimal Design*, International Review of Mechanical Engineering, Vol. 8, No. 5, pp. 952-961.