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EXPERIMENTAL INVESTIGATION OF EXTRUSION SPEED AND TEMPERATURE EFFECTS ON ARITHMETIC MEAN SURFACE ROUGHNESS IN FDM-BUILT SPECIMENS

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ABSTRACT

Surface roughness remains one of the soft spots of FDM technology in general, while the problem is specially pronounced in the domain of 3D printers for personal use. Extrusion speed and extrusion temperature are two controllable parameters which, other than layer thickness, have greatest impact on the surface quality of FDM-built parts. Analyzed in this paper is the influence of extrusion speed and temperature on the arithmetic average of the roughness profile (Ra) of FDM specimens. A 2^2 factorial experiment was used with two replicas and two center points. The results indicate a dominant, statistically significant influence of extrusion speed, as well as the pronounced nonlinearity of effects.
Key words: *3D printing*, *FDM, extrusion speed, temperature speed, surface roughness.*

1. INTRODUCTION

Today, Fused Deposition Modelling (FDM) is one of the most popular additive manufacturing technologies. It is used for rapid prototyping as well as for manufacture of an ever larger number of final products. Its popularity is due to several advantages, such as: simplicity and ease-of-use, choice of materials, easily replaced and non-toxic filament, as well as cost-effective maintenance. However, due to limitations which are primarily related to filament and extruder nozzle diameter, as well as some deficiencies which are intrinsic to the process of filament extrusion, FDM technology yields relatively low surface quality compared to traditional stereolithography (SLA) or PolyJet technology. For this reason, it is interesting, from the technological point of view, to investigate controllable factors which have dominant impact on surface quality, in order to achieve the best possible surface quality before post-processing.

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In a study on surface roughness in the domain of FDM technology, Perez [1] built surfaces at various angles of inclination (0-90^o) while testing their dimensional accuracy and surface roughness parameters, Ra i Rq.
Galantucci et al. [2] used factorial analysis to examine the influence of several technological parameters on Ra in FDM-built parts.
In a comparative study of five additive manufacturing technologies (SLS, FDM, DLP, 3DP and PolyJet), Ulbrich et al. [3] have investigated surface roughness as one of parameters, using ABS as material.
Mahesh et al. [4] have proposed a benchmark model composed of 3-D modules of various geometries, dimensions, locations and orientations. The authors have demonstrated that SLA produces highest surface quality and accuracy,followed by SLS, LOM and FDM. Upcraft and Fletcher [5] have also proposed a benchmark model for measuring surface qualitydepending on the angle of inclination, α, where α was varied from 0° to 90°. Based on their experiments a significant difference in surface quality has been observed based on applied technology, layer thickness and material, as well as the angle of inclination of the measured surface.
One common trait of these investigations is that they employed industrial-class machines, the price of which is usually on the 10^4 € order of magnitude. On the other hand, modern trends in development of additive technologies are oriented towards a newly emerged market of 3D printers for personal, desktop application, which are within the available price range and are often able to produce quality partswhich find application in various walks of life.
One of the most popular 3D printers in this class is the *Makerbot Replicator 2,* which is based on FDM technology and can work with 0.1, 0.2 and 0.3 layers, allowing user to vary a broad range of parameters. In this experiment, *Makerbot Replicator 2* was used to produce specimens of prismatic geometryin order to systematically investigate the influence of controllable technological factors on surface quality. Based on the literature [6], two influential factors were taken into consideration: extrusion speed and extrusion temperature. arithmetic mean surface roughness, Ra [µm], was adopted as output parameter, i.e., dependent variable in this experiment.Design of experiment (DoE) was used to allow systematic investigation of the influence of main factors and their interaction.

2. SELECTION OF INFLUENTIAL FACTORS

Literature dealing with the investigation of factors which influence surface roughness in FDM technology has been mostly focused on the following parameters:

- Layer thickness;
- Part orientation;
- Width of the deposited path;
- Spacing between the paths;
- Inclination of surface;
- Method of material deposition.

With this in mind, in this experiment the goal was to introduce two additional factors:

- Extrusion temperature and
- Extrusion speed,

with three previously listed factors: layer thickness, part orientation and angle of inclination of the measured surface. However, the experiments conducted with the variation of these parameters resulted in specimens which, for some extreme combinations of factors, could not pass even the visual inspection (Figure 1). Considering the fact that the primary goal of this study was to investigate the influence of extrusion temperature and speed, the rest of the parameters were eliminated from the plan of experiment and a two-factor experiment was conducted. Selected for the output variable was the arithmetic mean surface roughness, Ra [μm].

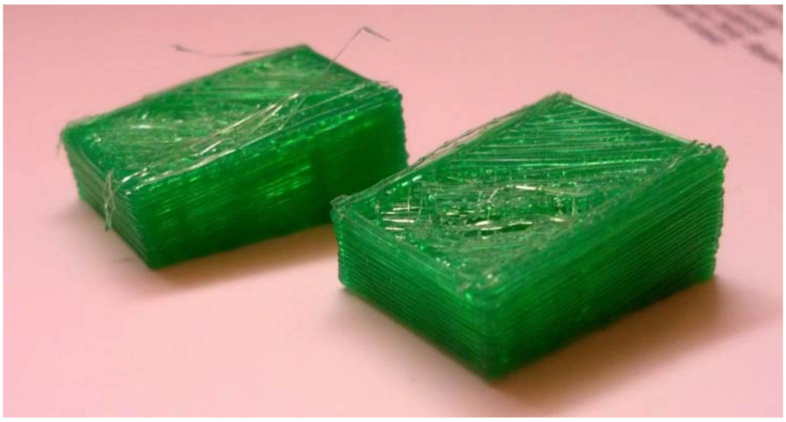

Fig.1 *- Specimens of inadequate surface quality and layer compactness, due to adverse combination of extreme values of parameters in the initial experiment*

3. DESIGN AND REALIZATION OF EXPERIMENT

3.1. Design of experiment

Experimental investigation was organized around a 2^2 factorial experiment with two replicates and two center points - in total, ten experiments. The center points were used to increase the number of degrees of freedom (*dof*), allow calculation of error and detect possible non-linearity of effects [7]. Chosen factors and their levels are shown in Table 1.

Table 1: Factors and levels used in the experiment

Factor	Unit	Low level (-1)	Cent. level (0)	Upper level (+1)
Extr. temp. (A)	[^{o}C]	225	230	235
Extr. speed (B)	[mm/s]	40	60	80

All experiments were conducted at the same layer thickness of 0.1 mm, with the specimens being centered on the build platform, and oriented with their dominant dimension along the *X* printer axis. The material was deposited in lanes at an angle of +45/-45^o, in alternative layers.

3.2. Preparation and building of specimen holder

Geometry of the specimens used in the experiment to test surface roughness was defined to accommodate the portable surface roughness device TR 200, while at the same time the goal was reduce build time as much as possible. The specimens are prismatically shaped, 25x10x3mm. In order to allow correct positioning of specimens during measurements, a simple specimen holder was designed and built on a 3D printer (Figure 2).Illustrated in Figure 3 is a correctly located specimen in the specimen holder, within the TR 200 carrier.

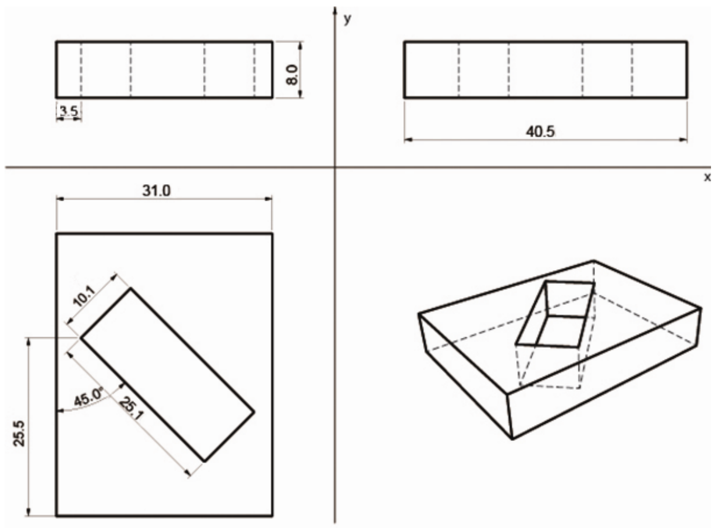

Fig.2 *- Geometry of the 3D-printed specimen holder*

Once the specimen holder was finished, *MakerbotReplicator 2* was used to print the ten specimens according to the design of experiment (Figure 4). PLA (*Polylactic Acid*) material was used in experiment. Technological parameters held constant during the experiment are shown in Table 2. Environment temperature was 27 ^{o}C.

Table 2: Technological parameters kept constant during the experiment

Parameter	Value	Comment
Infill [%]	15	Percentage of material in part volume
No. of shells	2	Number of paths deposited to define the outer contour in each layer
Raft	no	Weaved basic structure whose function is to anchor the part to the build plate and compensate for flatness errors
Layer thickness [mm]	0.1	-
Speed while travelling [mm/s]	100	Feed motion of extruder

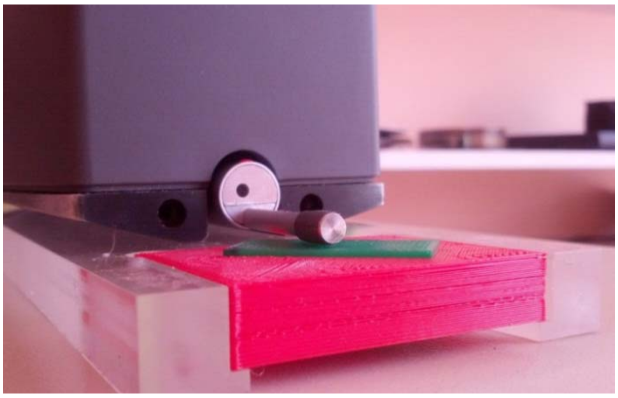

Fig.3 *- Specimen holder with a located specimen is correctly positioned within TR 200*

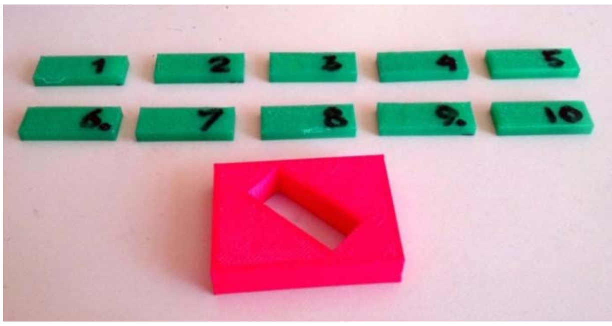

Fig.4 *- Specimen holder with the ten specimens built according to design of experiment*

3.3. Surface roughness measurement

As seen in Figure 4, the specimen holder features a diagonally oriented hole for the reception of specimens, which allows correct approach of stylus onto the surface roughness profile during measurement. Trajectory of stylus (Figure 5) was orthogonal relative to the lane along the melted material was deposited during specimen building process. The lanes were at an angle of 45^o relative to horizontal axis. Cut-off values of λ_C =0.8 and 1.2 mm were used to calculate R_a. On each of the ten specimens surface roughness was measured five times, which allowed calculation of mean value to be used in subsequent analysis.

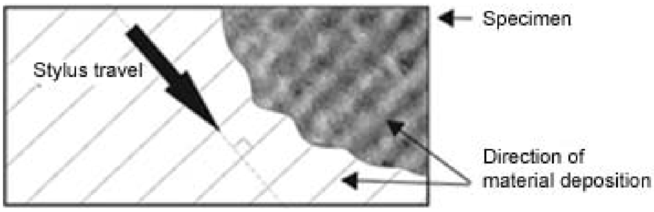

Fig.5 *- Direction of stylus during its travel along specimen top surface*

4. RESULTS

Generation of DoE table and analysis of results were performed in *Minitab v16*. Shown in Table 3 is the factorial experiment. First column of the table states the randomized order of experiment, while in the second column a standard order is shown as defined by the software. Shown in the last column is the mean R_a value calculated from the five measurements, as previously mentioned.

Table 3: Design of experiment

Practical order of experiment	Standard order of experiment	Extrusion temperature [°C]	Extrusion speed [mm/s]	Ra [µm]
1.	8.	235	80	7.3168
2.	4.	235	80	7.3436
3.	3.	225	80	8.0386
4.	2.	235	40	1.4180
5.	7.	225	80	7.8848
6.	1.	225	40	1.8690
7.	9.	230	60	6.8524
8.	5.	225	40	1.4684
9.	10.	230	60	6.2342
10.	6.	235	40	1.6842

Figure 6 displays the diagrams of various residual deviations which allow user to establish whether the basic requirements for the application of subsequent tests are satisfied. Diagram in Figure 6a shows that the residuals follow normal distribution. Random disposition of residuals about the zero in Figure 6b confirms the hypothesis of homogeneity of variance. Histogram (Figure 6c) shows that there skewness and kurtosis are within the normal, while there are no outliers, while the random scatter of residuals around the zero line indicates that, due to randomization of experiment, the order of observations does not effect the results (Figure 6d).Presented in Table 4 are the results of five measurements for each specimen, with the corresponding means. The last column shows standard deviations for each row. The results of ANOVA are given in Table 5. Statistical significance of the effects of extrusion speed and temperature and their interaction on R_a [µm] are shown on a half-normal plot in Figure 7, while the main effects diagram (Figure 8) illustrates the effects of extrusion speed and temperature on R_a and their relative strengths. Geometric interpretation of the factorial experiment is shown in Figure 9, with main factorial and center points.

Table 4 - Results of five measurements of Ra [μm] for each of the ten samples

Order of experiment	Measur. #1	Merasur. #2	Measur. #3	Measur. #4	Measur. #5	Ra [μm]	StDev
1.	7.204	7.114	6.992	7.006	8.268	7.3168	0.53868
2.	8.268	7.387	8.094	6.737	6.232	7.3436	0.86936
3.	8.853	8.599	6.963	8.423	7.355	8.0386	0.82905
4.	1.476	1.050	1.667	1.267	1.630	1.4180	0.25910
5.	6.511	9.572	8.591	7.303	7.447	7.8848	1.20030
6.	1.929	2.019	2.027	1.586	1.784	1.8690	0.18600
7.	7.481	6.993	6.458	6.769	6.561	6.8524	0.40692
8.	1.381	1.205	1.295	2.031	1.430	1.4684	0.32599
9.	5.752	6.358	6.990	5.190	6.881	6.2342	0.76285
10.	1.6842	1.280	1.567	2.014	1.918	1.642	0.29254

Table 5 - Analysis of variance for Ra [μm]

Source	DF	Seq SS	Adj MS	F	P
Main Effects	2	73.1484	36.5742	573.36	0.000
Extrusion temperature	1	0.2806	0.2806	4.40	0.090
Extrusion speed	1	72.8678	72.8678	1142.33	0.000
2-Way interactions	1	0.1320	0.1320	2.07	0.210
Extr.temp[^{o}C]*Extr.speed[mm/s]	1	0.1320	0.1320	2.07	0.210
Curvature	1	5.8699	5.8699	92.02	0.000
Residual Error	5	0.3189	0.0638		
Pure Error	5	0.3189	0.0638		
Total	9	79.4692			

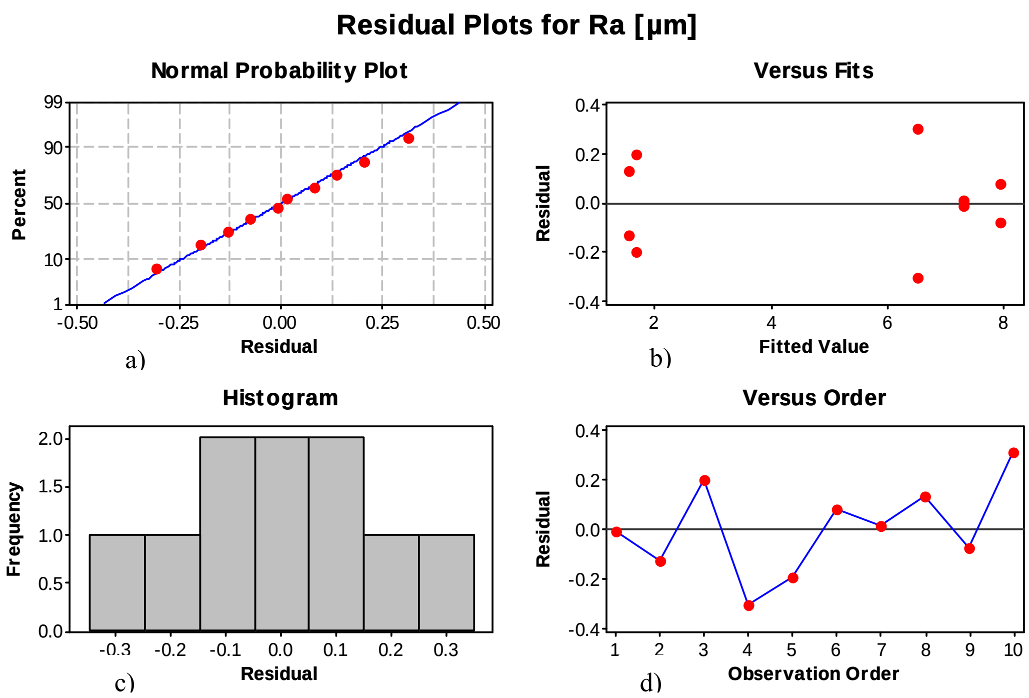

Fig.6 - *Diagrams of residuals for R_a*

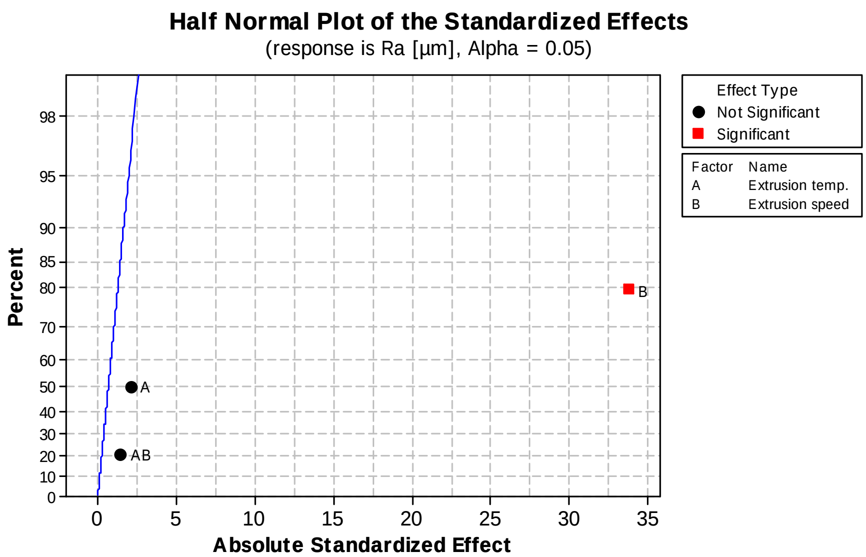

Fig.7 - *Half normal plot showing significance of factors*

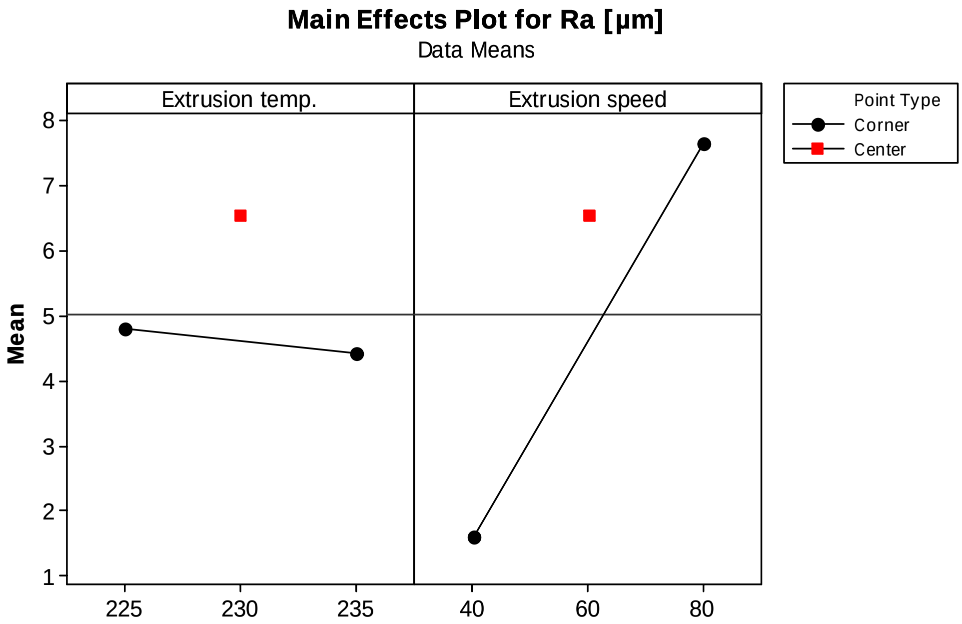

Fig.8 *- Influence of extrusion speed and temperature on surface roughness effects*

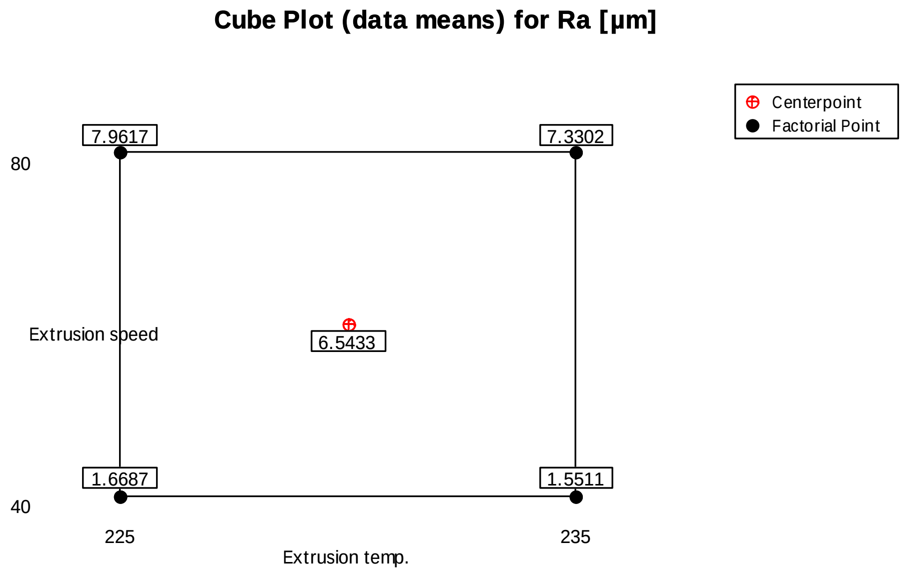

Fig.9 *- Geometric interpretation of the factorial experiment*

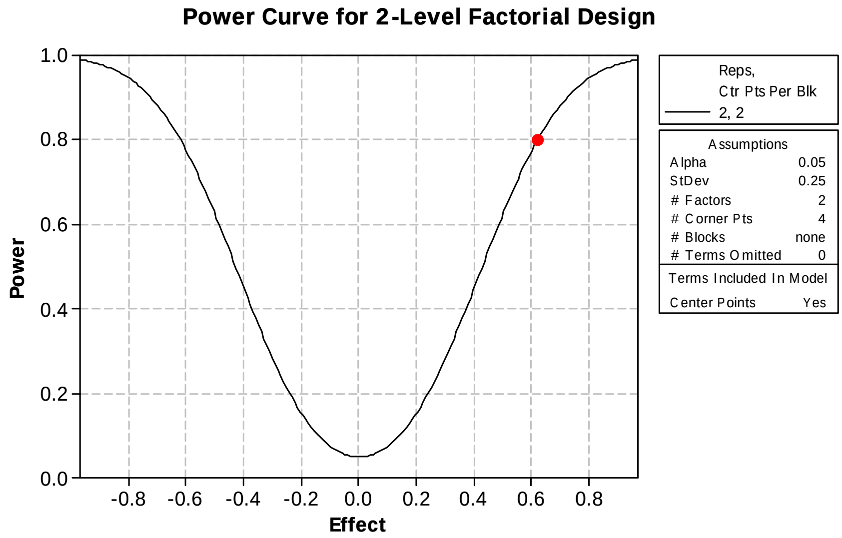

Fig.10 *- Computed test power curve*

5. ANALYSIS OF RESULTS

Analysis of variance for R_a (Table 5), showed a dominant, statistically significant effect of extrusion speed on surface roughness $F(1,9)=1142.33$, $p=0.00$. No significance was found for extrusion temperature and interaction ($p>0.05$). ANOVA also showed that curvature is statistically significant $F(1,9)=99.02$, $p=0.00$, which indicates non-linearity of effects and the need to include quadratic terms in the model. Significance of curvature is also visible in Figure 8, where the center points (red dots) visibly deviate from the factorial points.

Half-normal plot also confirms the significance of extrusion speed (Figure 7). It can also be observed that extrusion temperature (factor A) has a sort of marginal significance on R_a ($p=0.09$).

Main effects diagram (Figure 8) shows that higher extrusion temperature has mildly effect the reduction of R_a, while the increase of extrusion speed has a pronounced effect on the increase of R_a. Visible, in the same diagram, is the departure of the center points from the line which represents mean values of R_a and extreme values of extrusion speed and temperature, which confirms the effect of non-linearity.

Based on the geometric interpretation of factorial experiment (Figure 9) it can be concluded that the lowest surface roughness is yielded in the area of low extrusion speeds and high extrusion temperatures, where R_a equals 1.5511 μm.

6. CONCLUSIONS

Investigated in this paper was the influence of extrusion speed and temperature on arithmetic mean surface roughness (R_a) in FDM-built specimens. For the purpose of systematic investigation, a 2^2 design of experiment was conducted with two replicates and two center points. In this way, the ten experimental runs allowed us to investigate the main effects and their interaction on the dependent variable R_a.

The introduction of center points added replication, allowed calculation of error term and allowed us to check curvature. Significant presence of non-linear effects was established.
The results showed that speed of extrusion has a dominant, statistically significant effect on R_a, while the extrusion temperature and interaction were found insignificant.
Despite the fact that the *Makerbot Replicator 2* 3-D printer used in this experiment allows building with wider range of extrusion speeds and temperatures, our experiment kept those values within narrower limits. The reason for that lies in the fact that the combination of extreme factor values during specimen building, produce surface quality which cannot pass even visual inspection.
With this in mind, it should also be noted that the marginal influence of temperature extrusion could become statistically significant should a wider range of extrusion temperatures be used in the experiment. The analysis also included the size of effect our model was able to detect. Based on the number of runs (2) and center points (2), desired power of test (0.8) and sample standard deviation (S=0.25) the size of effect equaled 0.62 μm. Shown in Figure 10 is the computed test power curve, where the red dot indicates the effect size which could be detected at the chosen power of 0.8.
Finally, the introduction of center points in this experiment allowed the detection of statistically significant curvature effect, which indicates that the next experiment should be conducted at three levels (2^3). In this way it will be possible to exactly establish the values of quadratic terms in the model, as well as to perform optimization using Surface Response Analysis. based on this analysis it will be possible to establish the right combination of extrusion speed and temperature which, within the designated range of extrusion speed and temperature values yields minimal R_a.

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EKSPERIMENTALNO ISTRAŽIVANJE UTICAJA BRZINE I TEMPERATURE EKSTRUDIRANJA NA SREDNJU ARITMETIČKU HRAPAVOST DELOVA IZRAĐENIH U FDM TEHNOLOGIJI

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REZIME

Površinska hrapavost važi za jednu od ključnih slabosti tehnologije gradnje modela deponovanjem topljenog filamenta (FDM - Fused Deposition Modelling). Problem kvaliteta površine je posebno izražen u domenu 3D štampača personalne klase. Brzina i temperatura ekstrudiranja predstavljaju dva upravljiva parametra koja, ako se izuzme debljina sloja, imaju najveći uticaj na kvalitet površine kod delova izrađenih u FDM tehnologiji. U ovom radu je primenjen statistički zasnovan eksperiment u cilju sistematskog ispitivanja uticaja brzine i temperature ekstrudiranja na srednju aritmetičku hrapavost (Ra), uzoraka koji su izrađeni u FDM tehnologiji. Korišćen je faktorni eksperiment 2^2 *sa dve replike i dve centralne tačke. Na osnovu rezultata ustanovljen je dominantan, statistički značajan uticaj brzine ekstrudiranja, kao i izražena nelinearnost efekata.*
Ključne reči: *FDM, temperatura ekstrudiranja, brzina ekstrudiranja, hrapavost površine,*

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