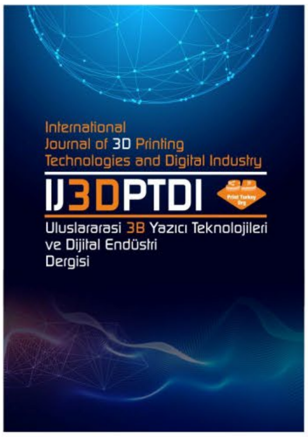

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OPTIMIZATION OF ACCURACY AND SURFACE ROUGHNESS OF 3D SLA PRINTED MATERIALS WITH RESPONSE SURFACE METHOD

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ABSTRACT
3D printers are used frequently for rapid prototyping and production. SLA (stereolithographic) printers, widely used in areas requiring precision production, form the final shape by solidifying the liquid resin with UV rays. In SLA printing, the final figure is created by changing many printing parameters. For this reason, surface integrity and precision of measurements vary. Dimensional accuracy (DA) and surface roughness (SR) outputs should be investigated for precise printing. Therefore, the effects on SR and DA output parameters were investigated by changing the layer height, exposure time, and lift input parameters with the Response Surface Method (RSM). The effective parameters for both outputs are layer height and lift. As the layer height and lift increased, the SR and DA values of the printed parts increased. The predicted results calculated with the regression equations and the experimental results were quite close. Optimum input parameters were found by multi-response optimization. Accordingly, the 8th experiment, 0.05mm-4s-1.5mm, was the best parameter. The difference between the predicted and experimental values for multi-response optimization was 4.28% for SR and 0.27% for DA. Thus, effective parameters for SR and DA have been determined for precision production in SLA printers.

Keywords: 3D Printing, SLA, Multi-Response Optimization, Surface Roughness, Accuracy, ANOVA.

1. INTRODUCTION
Rapidly developing technological applications necessitate the emergence of new production methods. The need for acceleration of production has caused 3D-aided manufacturing methods to gain more and more importance due to their advantages, such as rapid prototyping, dimensional accuracy, easy and low-cost production [1-3]. There are different types of 3D printing such as binder jetting, directed energy deposition, fused deposition modeling (FDM), materials jetting, powder bed fusion, sheet lamination and vat photopolymerization [4]. In vat polymerization printing, a photopolymer, or light-curable resin, is treated with visible or ultraviolet light while kept in a container during photopolymerization. The polymerization reaction is set off and triggered by the hardening light. It creates polymer chains or cross-links them to make a solid resin [5]. One of the most researched and frequently used vat photopolymerization method is stereolithographic (SLA) 3D printing method. SLA 3D printing is frequently used in areas requiring sensitive production, such as jewelry, dentistry, health, and defense industries. SLA method, which gives high surface quality, high-speed production, and excellent dimensional accuracy results depending on the production parameters, is the process of forming the desired shape of the layers that solidify on top of each other with the ultraviolet (UV) rays applied to the resin [6-7]. It allows the creation of thin-structured complex geometries due to adjustable accuracy values [8-9]. The SLA method, which has significant areas of use, is especially preferred because of its high surface quality and dimensional accuracy [10-11]. However, these properties are greatly affected by the process parameters. SLA printing is frequently preferred in the production of molds, especially in the fields of jewelry and dentistry.

[12-15]. Deformations that may occur in the mold as a result of not determining the printing parameters properly will also be reflected in the final product. In addition, shrinkage of the resin after printing also affects the dimensional accuracy of the final shape [16]. For this reason, optimization of 3D SLA process parameters in terms of surface quality and dimensional accuracy is of great importance to producing with desired properties. Many studies investigate the selection of printing parameters and output optimization of 3D SLA printers. The parameters that are thought to be effective in printing, layer height, exposure time, and lift, have been determined with the help of the literature [17-20]. Surface roughness, dimensional accuracy, and mechanical properties are frequently investigated in optimization studies [17,21-23]. Dikova et al. [24] compared the surface roughness and dimensional accuracy results using three different 3D printer technologies (SLA, DLP, FDM). They stated that all three methods did not provide the desired surface quality in the field of dentistry. They obtained bigger dimension values than the desired values in SLA printers and smaller dimension values in FDM printers. They stated that SLA printers give better surface quality results than FDM printers, but process improvements and optimization studies need to be carried out. Mou and Koc [25] examined the surface roughness and dimensional accuracy outputs of the parts that produced with FDM, SLA and material jetting methods. FDM printers produced parts with high roughness and poor edge sharpness. SLA printers produced the smoothest parts, but waviness was observed on thin parts. They stated that 3D technology is not yet ready to produce ready-to-use end products and that advanced post-processing is required to accomplish this task. Özdilli [26] investigated the surface quality of parts produced by plastic injection, FDM and SLA printers. It has been determined that the parts produced with SLA are smoother, easier to manufacture and have a better appearance. Ishida et al. [27] examined the dimensional accuracy and surface roughness outputs of printed parts using two consumer type 3D printer devices and two industrial dental 3D printers. While bigger surface roughness values were observed in the FDM printer, they found that the surface roughness was significantly better in the SLA printers. They stated that consumer SLA printers can provide surface roughness results as good as dental printers. As seen in the literature, dimensional accuracy and surface roughness are of great importance in SLA printers and have been investigated by many researchers. However, studies have generally investigated single-parameter optimization. In order to obtain better results in printing studies, instead of an optimization study based on surface quality or dimensional accuracy output alone, multi-response optimization of both surface roughness and dimensional accuracy outputs should be made at the same time. The multi-response optimization method is applied to investigate the effect of more than one output together. Multi-response optimization can be done with various experimental design and analysis methods [28-30]. Response Surface Method (RSM) method is one of the most used experimental design and analysis methods among these methods since the degree of importance of the outputs can be determined [31-34]. The response surface method is a mix of mathematical and statistical methods to optimize responses (output parameters) that are generally influenced by several independent variables (input parameters). An experimental design is made in the response surface method, and the response parameters corresponding to the selected input parameters are determined experimentally. Thus, more results can be obtained with less experimentation. The accuracy of the method and significant parameters are determined with the help of analysis of variance (ANOVA).

In this study, the dimensional quality of SLA printed parts was investigated according to surface roughness and dimensional accuracy outputs with RSM. The input parameters that contributed the most to the output parameters were found and the effective parameters were determined by ANOVA. Optimum printing parameters were found and compared with experimental results. The effect of printing parameters on surface quality in SLA printers has been proven by mathematical and experimental methods. Thus, it was determined which parameters are effective for printing 3D parts with improved surface quality and how they change the surface quality.

2. EXPERIMENTAL

2.1. Equipment

3D drawings of the parts were drawn in the Rhinoceros 6 program. In order to perform the surface roughness and dimensional accuracy measurements correctly, internal and external shapes with different geometries were created, as in Figure 1.

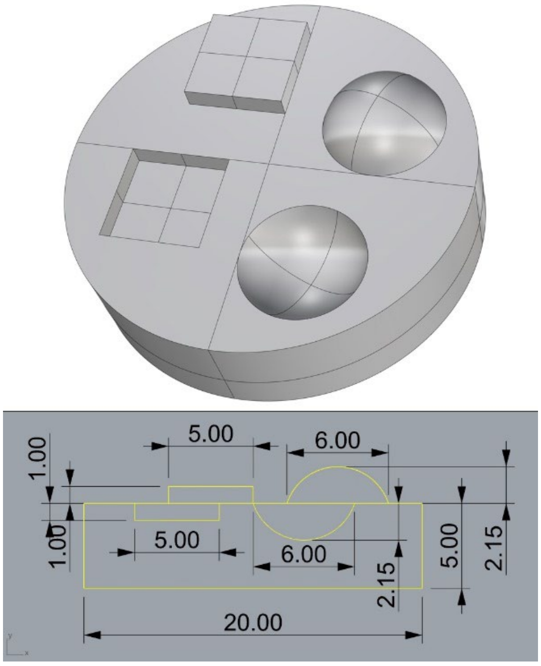

Figure 1. 3D view and technical drawing of the printed parts.

After the drawings were prepared, the slicing processes were done with the 3D printer program Chitubox V.1.9.5. Anycubic Photon Mono X 3D resin printer was used for printing (Figure 2). Fixed processing parameters of parts are given in Table 1. Translucent green (UV wavelength 405 nm) resin was used for printing studies.

Table 1. Fixed printing parameters.

Parameter	Hold Value
Bottom Layer Number	4
Transition Layer Number	10
Bottom Exposure Time	28 s
Lift Speed	60 mm/min
Retract Speed	90 mm/min
Orientation	30°
Bottom Lift Speed	60-120 mm/min

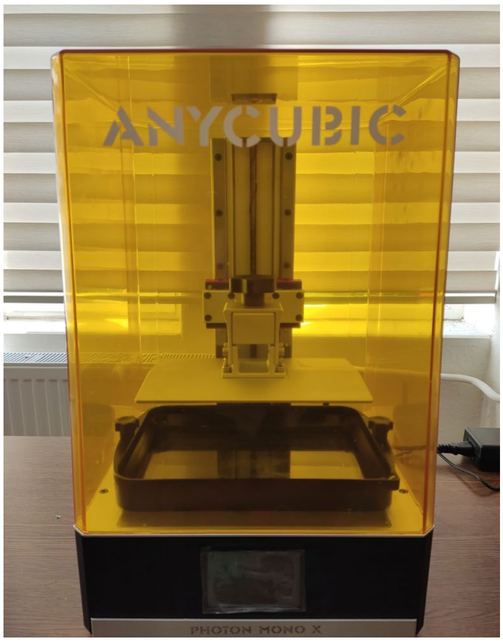

Figure 2. Anycubic Photon Mono X 3D printer.

2.2. Experiment Design and Printing Studies

The printing parameters created according to the RSM experimental design are given in Table 2. Three samples were printed for each experimental parameter by making a central composite design for three parameters and three levels. In the experimental design consisting of 8 cube points, six central points, and six-axis points, the value of α is taken as 1.

RSM was used for post-printing analysis by choosing the output parameters dimensional accuracy (DA) and surface roughness (SR). Variance analyses and optimization studies were carried out at a 95% confidence level. RSM allows to derive regression equations using a quadratic mathematical model given in Equation (1). Thus, it calculates the relationships between the input parameters and the predicted results.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} {X^2}_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} X_i X_j + \varepsilon \qquad (1)$$

Y is the dependent output parameter, Xi and Xj are independent input parameters that affect Y. β_o, β_i, β_{ii}, and β_{ij} are constant, first-order, second-order, and interaction input parameters, respectively. i is linear coefficient; ii, quadratic coefficient; ij is the interaction coefficient and ε is the error term. The excess resin remaining on the surface of the 3D parts after printing was cleaned with isopropyl alcohol. Afterward, the parts were cured in sunlight for 6 hours.

Table 2. RSM experimental design for 3D printing.

Std No	Run No	Layer Height (mm)	Exposure Time (s)	Lift (mm)
9	**1**	0,05	3	2,5
10	**2**	0,07	3	2,5
1	**3**	0,05	2	1,5
13	**4**	0,06	3	1,5
11	**5**	0,06	2	2,5
20	**6**	0,06	3	2,5
14	**7**	0,06	3	3,5
3	**8**	0,05	4	1,5
4	**9**	0,07	4	1,5
19	**10**	0,06	3	2,5
6	**11**	0,07	2	3,5
2	**12**	0,07	2	1,5
17	**13**	0,06	3	2,5
16	**14**	0,06	3	2,5
7	**15**	0,05	4	3,5
15	**16**	0,06	3	2,5
12	**17**	0,06	4	2,5
8	**18**	0,07	4	3,5
18	**19**	0,06	3	2,5
5	**20**	0,05	2	3,5

2.3. SR and DA Measurements

Surface roughness (Ra) of 3D printed parts was measured with the help of the Mitutoyo Surftest SJ-210 mechanical profilometer (Figure 3). The average surface roughness value of each sample was determined by making measurements from three different points for each sample. Then, the average surface roughness of three samples from each experiment was calculated.

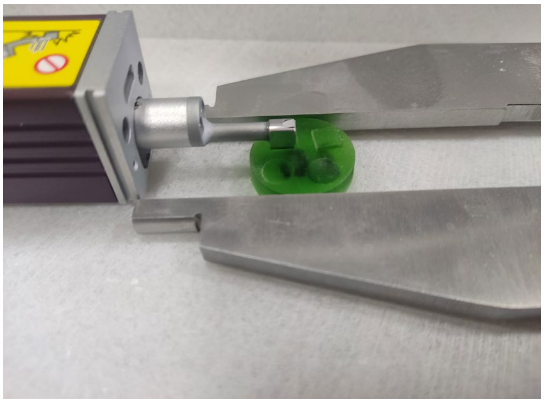

Figure 3. Surface roughness measurements.

Dimensional accuracies of printed parts were calculated as percentages. The dimensional deviation of the circle and square shapes on the samples was calculated as the absolute percentage difference with Equation (2). Dimensional accuracy measurements were performed with a Dino-Lite brand digital microscope at 30X magnification (Figure 4). The average dimensional accuracy of each sample was determined by measuring each shape on the samples. Then, the average dimensional accuracy of three different samples printed for each experiment was calculated. Thus, calculation errors from printing errors and shape differences are minimized.

$$DA\,(\%) = \left|\frac{Li - Lp}{Lp}\right| * 100 \qquad (2)$$

L_i is the measured length and L_p is the printed length value.

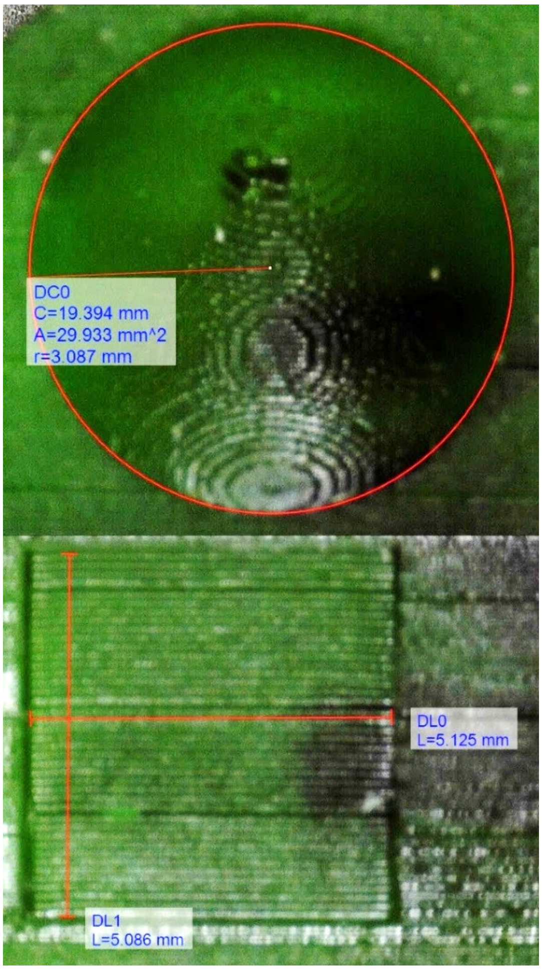

Figure 4. Dimensional accuracy measurement.

3. RESULTS AND DISCUSSION

The SR and DA results of the printed parts are given in Table 3. According to the results, the best SR and DA values were obtained in the 8th experiment (0.05mm-4s-1.5mm). After each solidification, the printer moves upwards. This movement greatly affects the surface properties of the part. As the lift decreases, the surfaces of the parts become smoother, and their accuracy increases. In addition, due to the decrease in layer thickness, the parts have better surface integrity. As the exposure time increases, UV rays applied to the resin provide a more uniform solidification in the material. Thus, reducing the gaps between the layers of the parts reduces the surface roughness. In the 12th experiment parameter, which gives the worst SR, the layer height is the highest, and the exposure time is the lowest. In the 18th test sample, which gives the worst DA, the layer height and lift are the highest. This shows that layer height and lift significantly affect the output.

Table 3. SR and DA results.

Run No	SR (µm)	DA (%)
1	10,06	2,14
2	15,78	2,69
3	9,56	2,04
4	11,95	1,99
5	12,31	2,15
6	11,97	2,14
7	12,95	2,49
8	7,55	1,69
9	13,51	2,10
10	11,95	2,12
11	15,21	2,87
12	15,45	2,25
13	11,98	2,09
14	12,18	2,07
15	9,05	2,15
16	11,80	2,01
17	9,31	2,05
18	13,47	3,21
19	11,61	2,09
20	12,09	2,23

3.1. Analysis of Variance (ANOVA)

3.1.1. ANOVA for SR

As a result of the analysis of variance for surface roughness, it was determined whether the parameters and parameter interactions were effective (Table 4). Parameters with a p-value < 0.05 are considered effective in printing. Layer height and lift were found to be effective parameters for SR. It has been understood that exposure time is not an effective parameter in printing. The parameter that affects the outputs the most is the parameter with the highest F-value [35]. Accordingly, the effective parameters for SR are lift and layer height. The effect of layer height and lift on surface roughness is almost the same. A lack of fit value greater than 0.05 indicates that the experimental design and analyses were done correctly and the experimental design was effective. Thus, it was determined that the parameters and outputs were directly related and were chosen perfectly. The R^2 value was calculated as 0.989 for SR. The relationship between effective parameters in printing and SR is given in Figure 5 with a surface plot. It is understood from the figure that as the lift and layer height increases, the surface roughness also increases. A rise in layer height triggers the stair-stepping effect, which raises surface roughness [36,37]. It is seen that the lowest surface roughness is at 0.05 mm layer height and 1.5 mm lift parameters. The highest surface roughness was seen at 3.5 mm lift and 0.07 mm layer height parameters. The effect of the lift on surface roughness was almost the same at each layer height value.

Table 4. Analysis of variance for SR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	86,6334	9,6259	95,87	p<0,0001*
Linear	3	4,6422	1,5474	15,41	0,0004
Layer Height	1	2,2131	2,2132	22,04	0,0009
Exposure Time	1	0,1769	0,1769	1,76	0,2139
Lift	1	2,2522	2,2522	22,43	0,0008
Square	3	4,9280	1,6427	16,36	0,0004
Layer Height*Layer Height	1	2,1000	2,0999	20,92	0,0010
Exposure Time*Exposure Time	1	4,2208	4,2208	42,04	p<0,0001*
Lift*Lift	1	0,4489	0,4489	4,47	0,0606
2-Way Interaction	3	2,6488	0,8829	8,79	0,0037
Layer Height*Exposure Time	1	0,2324	0,2324	2,31	0,1591
Layer Height*Lift	1	2,3281	2,3281	23,19	0,0007
Exposure Time*Lift	1	0,0883	0,0883	0,88	0,3704
Error	10	1,0040	0,1004		
Lack-of-Fit	5	0,8173	0,1635	4,38	0,0655
Pure Error	5	0,1868	0,0374		
Total	19	87,6375			

*: Very significant

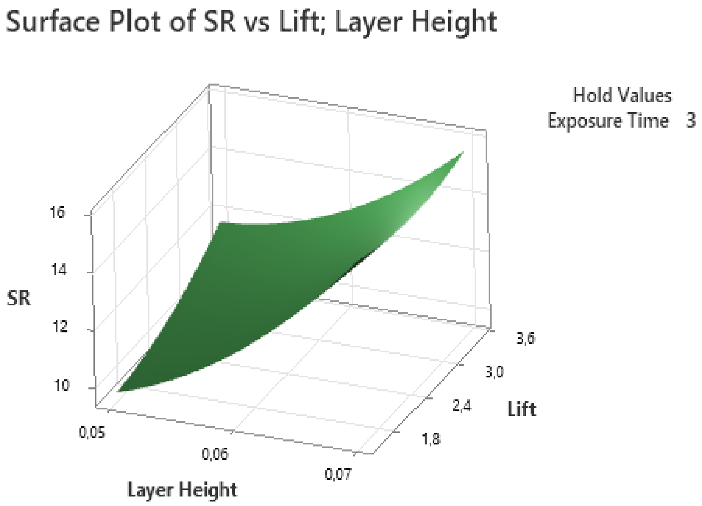

Figure 5. Surface plot for SR vs. layer height and lift.

3.1.2. ANOVA for DA

Effective parameters for dimensional accuracy are given in Table 5. It is seen that all parameters and the model are significant ($p < 0.05$), so the printing parameters are selected appropriately, and the experiments are carried out correctly. The effective parameters for DA are lift, layer height, and exposure time, respectively. Thus, the lift parameter was the most effective input parameter for both SR and DA. The fact that the lack of fit value is greater than 0.05 shows that the experimental design and analysis were done correctly. The R^2 value was calculated as 0.977 for DA. In Figure 6, the relationship between DA and input parameters is shown with the help of a surface plot. The best dimensional accuracy is seen at 0.06 mm layer height and 1.5 mm lift values. The worst accuracy is seen at 0.07 mm layer height and 3.5 mm lift parameters. While the effect of layer height on dimensional accuracy was low at lower lift values, the effect of layer height on accuracy was much greater at high lift values. Layer height and dimensional accuracy generally have an inverse relationship. As layer height increases, dimensional accuracy decreases [38].

Table 5. Analysis of variance for DA.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	2,1871	0,2430	46,87	p<0,0001*
Linear	3	0,3589	0,1196	23,08	p<0,0001*
Layer Height	1	0,1534	0,1534	29,58	0,0003
Exposure Time	1	0,0474	0,0474	9,14	0,0128
Lift	1	0,1582	0,1582	30,51	0,0003
Square	3	0,2584	0,0861	16,61	0,0003
Layer Height*Layer Height	1	0,1499	0,1499	28,92	0,0003
Exposure Time*Exposure Time	1	0,0187	0,0187	3,60	0,0871
Lift*Lift	1	0,0088	0,0088	1,70	0,2220
2-Way Interaction	3	0,2639	0,0880	16,97	0,0003
Layer Height*Exposure Time	1	0,0482	0,0482	9,29	0,0123
Layer Height*Lift	1	0,1465	0,1465	28,25	0,0003
Exposure Time*Lift	1	0,0692	0,0692	13,35	0,0044
Error	10	0,0519	0,0052		
Lack-of-Fit	5	0,0421	0,0084	4,30	0,0677
Pure Error	5	0,0098	0,0020		
Total	19	2,2390			

*: Very significant

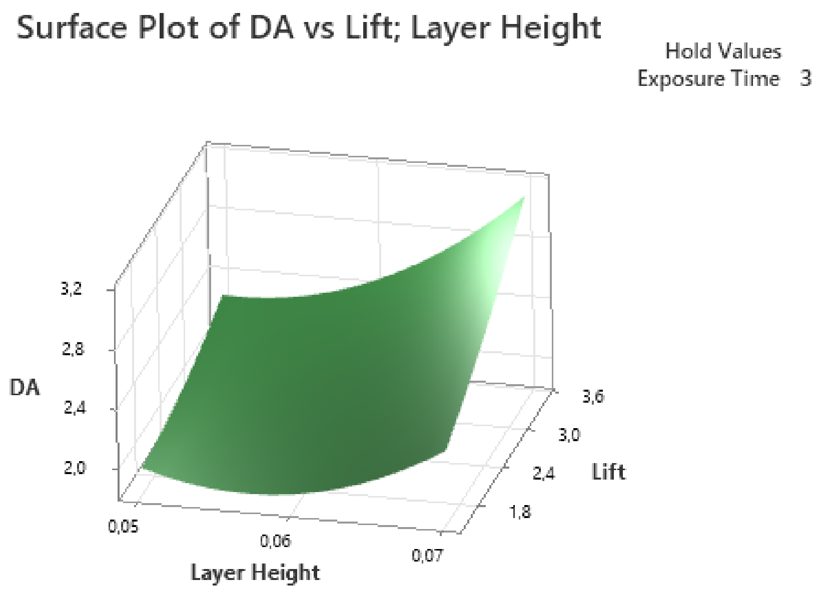

Figure 6. Surface plot for DA vs. layer height and lift.

3.2. Predict Results

The values of the output parameters can be predicted for any level of the parameters with the regression equations. The regression equations for SR and DA are given in Equation (3)-(4), respectively. Regression equations can be used to determine whether the experimental and expected findings match. The predicted and experimental results of SR and DA outputs are given in Figure 7-8. It is seen from the figures that there is a close relationship between the predicted results and the experimental results, and the results overlap. This proves that the selection of input parameters, experiments, and output analyzes are done correctly and reliably.

$$SR = 16,26 - 714\ \text{Layer Height} + 5,50\ \text{Exposure Time} + 2,01\ \text{Lift} + 8739\ \text{Layer Height} * \text{Layer Height} - 1,239\ \text{Exposure Time} * \text{Exposure Time} + 0,404\ \text{Lift} * \text{Lift} + 17,0\ \text{Layer Height} * \text{Exposure Time} - 53,9\ \text{Layer Height} * \text{Lift} - 0,105\ \text{Exposure Time} * \text{Lift} \quad (3)$$

$$DA = 11,93 - 308,6\ \text{Layer Height} - 0,239\ \text{Exposure Time} - 1,086\ \text{Lift} + 2335\ \text{Layer Height} * \text{Layer Height} - 0,0824\ \text{Exposure Time} * \text{Exposure Time} + 0,0566\ \text{Lift} * \text{Lift} + 7,76\ \text{Layer Height} * \text{Exposure Time} + 13,53\ \text{Layer Height} * \text{Lift} + 0,0930\ \text{Exposure Time} * \text{Lift} \quad (4)$$

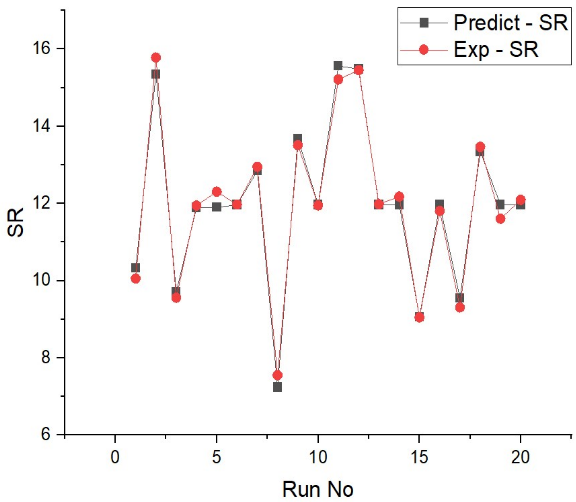

Figure 7. Predicted and experimental results for SR.

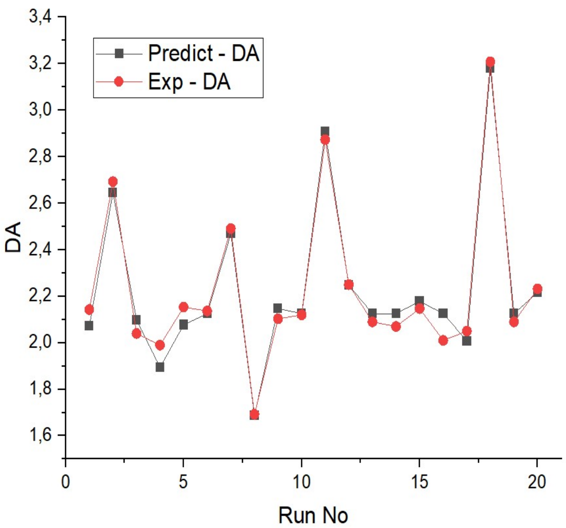

Figure 8. Predicted and experimental results for DA.

3.3. Multi-Response Optimization

Multiple output optimization is used to find the optimum input parameters and corresponding outputs in cases where more than one output is investigated. When two or more outputs are evaluated simultaneously, which is more important, it is essential for multi-response optimization. Optimum input parameters and predicted output results where SR and DA are of equal importance are given in Table 6. Because during manufacturing, both SR and DA must be at the desired values for precision production.

When the outputs are investigated with equal importance, the optimum parameter is seen in the 8th experiment, which is among the test parameters. The 8th experimental parameter, 0.05mm-4s-1.5mm, gave the best output values for both SR and DA, and it was also the best parameter for multiple output optimization. The surface roughness of the samples printed with the 8th test parameters was calculated as 7.55 µm, and the dimensional accuracy value was calculated as 1.69%. Figure 9 shows the values that make SR and DA minimum and desirability maximum while their importance levels are equal graphically. For multiple output optimization, the desirability level is calculated as 1.

Experimental and predicted results of multiple optimization parameters are compared in Table 7. Multiple optimization output results and experimental results were found to be very close to each other. The difference was 0.27% for DA and 4.28% for SR. These values prove that correct prediction and experimental studies are made as a result of an acceptable analysis.

Table 6. Optimum input parameters and predicted results.

Layer Height	Exposure Time	Lift	SR Fit	DA Fit	Composite Desirability
0,05	4	1,5	7,24334	1,68792	1

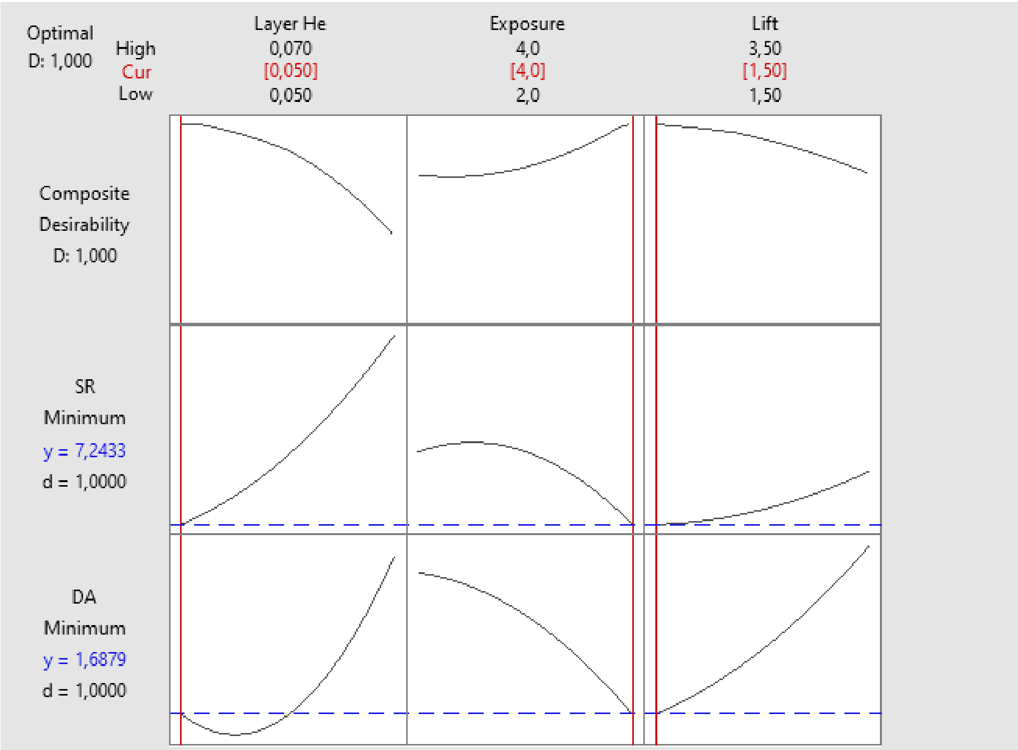

Figure 9. Multi-response optimization graph.

Table 7. Predicted and experimental results for optimum parameters.

Output	Layer Height	Exposure Time	Lift	Predicted	Experimental	% Error
SR	0,05	4	1,5	7,2433	7,5535	4,283
DA	0,05	4	1,5	1,6879	1,6925	0,273

4. CONCLUSIONS

The effect of parameters on SR and DA in the SLA 3D printing method, which is frequently used in precision manufacturing processes due to its usage areas, was investigated by multiple output optimization. Accordingly, the optimum machining parameter is 0.05mm-4s-1.5mm. The effective parameters for SR are lift and layer height. The effective parameters for DA are lift, layer height, and exposure time. The predicted output values obtained with the regression equations were found to be quite close to the experimental values. The optimum parameter was determined with equal importance for SR and DA. Experimental and predicted values of the optimum parameter were also found to be quite close. The results showed that the multiple output optimization with the RSM method in SLA printers effectively evaluated the results and helped to understand the effect of the parameters for precision production.

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