Improving the surface roughness in stereolithography by controlling surface angle, hatch spaces, and postcuring time

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Abstract
Stereolithography is considered as a well-known rapid prototyping technique that is widely used for injection molding and vacuum casting manufacturing regarding its higher dimensional accuracy and part strength. However, the extensive application of this process has been restricted due to the higher surface roughness and appearance of stair-step phenomenon. In this article, the influences of process parameters and part orientation on the surface finish are investigated. For this purpose, parts are fabricated with different surface angle, hatch space, and postcuring time. The surface roughness of the parts are measured by contact and noncontact methods. In noncontact method, a digital microscope is used for obtaining the surface profile, and then surface roughness is calculated using MATLAB software. The results showed that the surface roughness was affected by the hatch space, whereas postcuring time had insignificant and negligible effect on the surface roughness. By increasing the surface angle, a sharp increase of surface roughness in up-facing plane was observed, which was followed by a drop. Finally, with the help of analysis of variance, a mathematical model has been developed considering the process parameters and the responses. Moreover, maximum average estimation error of 14% was obtained between the experimental results of surface roughness values and the estimated ones.

KEYWORDS
ANOVA, hatch space, stereolithography, surface angle, surface roughness

1 | INTRODUCTION

Rapid prototyping (RP) technology is considered as dynamic and progressive manufacturing process, through which, the parts can be fabricated directly from three-dimensional (3D) computer-assisted design (CAD) models in a layer by layer manner.1-5 Decreasing the process stages, costs, and time of manufacturing are the superior features of RP technologies.6-10 Stereolithography (SLA) is a well-known branch of additive manufacturing processes,11-14 in which layer by layer fabrication of the part is conducted by curing photopolymer. For this purpose, the energy of the laser beam is used for connecting the large number of molecules to each other.15-18 However, regarding the insufficient energy of ultraviolet (UV) laser for
the complete curing of parts, a postcuring step is required for further curing. This can be accomplished by placing the parts in the postcure apparatus. 19

Achieving the desired dimensional accuracy besides attaining the favorable mechanical properties simultaneously are considered as the most important advantages of the parts fabricated by SLA. 20,21 However, poor surface quality of parts is the major drawback of this process. 20,22 Improved surface roughness is of great importance in the applications such as medical devices, lens, fluid flow, and assembling. 23,24 Hence, reducing the surface roughness is a mandatory prerequisite for the extensive application of this process in RP, rapid tooling, and direct mold manufacturing. 2,20 SLA has also found application in the manufacturing of injection molds and vacuum casting models; however, the excessive surface roughness is problematic. 25,26 Roughness measurement can be conducted through contact and noncontact methods with the respective advantages and disadvantages. High measurement accuracy is considered as the advantages of the prior methods; while applicability in measuring the sensitive surfaces is the beneficial feature of the latter group. 27 The previous investigations regarding the reduction of surface roughness in SLA can be categorized in three main groups, which are mentioned in the following.

• In some researches, the additive or abrasive processes have been used for improving the surface quality. The additive processes include coating or painting the surfaces; while machining or finishing the surfaces are classed as abrasive methods. Despite the significant improvement of surface roughness by these methods, higher required time because of the complicated workpiece geometries as well as manual application of this process, have limited the application of these processes in RP process. Furthermore, manual processes are characterized by lower dimensional and geometrical accuracies, less repeatability and higher processing times and cost. 25,28

• Recently, adaptive slicing method (ASM) has attracted several attentions to improve the surface quality. ASM involves the usage of additional layers with higher curvatures and angles for the surfaces. Through this process, an enhanced surface roughness in relatively same processing time can be achieved. However, this method is not applicable in all RP machines, and also for viscose photopolymers. 20,29

• The third category concerns with the study of influential process parameters on surface quality and obtaining the optimum conditions corresponding to the least roughness. This article can be classes in this category. Generally, the deteriorated surface roughness would be occurred as a result of stair-step effect and process of removing support materials. 30-33

Williams and Melton 28 investigated the effects of abrasive flow machining parameters (particle size and flow pressure) and SLA parameters (resin type and part orientation) on the surface roughness. Results showed the significant effect of flow pressure, grit size, and build orientation on the surface roughness, flatness, and material remove rate.

Kim and Lee 30 introduced stair-stepping effect and supports removing as the main sources of roughness in SLA. The optimization of part orientation was also performed to achieve the minimum processing time and costs as well as improved surface roughness. In addition, parts with various dimensions and geometric complexity were studied and the surface roughness and postprocessing times and costs were measured. The obtained results declared the different behavior of surface roughness for different orientations of the studied samples. Finally, using the obtained data, they established a relation for determining the optimized part orientation.

To evaluate the effect of surface angle on the roughness, Reeves and Cobb 20,25 studied the Truncheon part fabricated by SLA 250, SLA 350, and SLA 500 machines. The surface roughness was also measured by Taylor-Hobson surface measuring gage. Their results revealed a nonlinear relationship between the surface roughness and surface angle. Moreover, they declared that the print-through effect was resulted in a reduced surface roughness for the surface angles in the range of 90° to 150° as compared with 30° to 90°.

The effects of surface angle on the surface roughness of Truncheon part in various RP processes were explored by Campbell et al. 34 They studied different procedures such as fused deposition modeling, selective laser sintering, multijet modeling, laminated object manufacturing, and SLA. Their results represented the deteriorated surface roughness in SLA for the surface angle in the range of 90° to 150°.

Sager and Rosen 29,35 introduced stair-stepping effect as the most influential factor on surface roughness. They studied different specimens fabricated with various surface angle, postcuring time, and layer thickness. According to the obtained results, they presented a new method for obtaining print-through phenomenon by controlling scan speed so that minimum surface roughness was achieved in the down-facing planes.
A novel SLA (Solvent-based Slurry SLA) was presented by Ray et al with the capability of fabricating 3D ceramic membranes with the surface roughness in the range of 0.17 to 0.18 μm and thickness in the range of 200 to 250 μm. Wang et al investigated the fabrication of partially stabilized zirconia molds using SLA in metal casting. The results showed the ability of this process in the fabrication of molds with the flexural strength and young modulus of 803 MPa and 203 GPa, respectively. However, the higher surface roughness of molds was considered as a disadvantage.

By reviewing the published investigations in this field, it was found that in some studies, layer thickness and surface angle were considered as the most influential factors on surface roughness in SLA. While, in some others, hatch spacing and postcuring time in the ultrasonic chamber were introduced as the most important parameters on the surface quality. However, the simultaneous effects of these parameters to optimize the performance of SLA process has not investigated yet. Hence, in this study, it is aimed to study the simultaneous effects of the mentioned parameters for achieving the improved surface roughness of the parts fabricated by SLA. In addition, it is shown that all roughness parameters (Ra, Rq, and Rz) should be considered in the complete characterization of the surface quality.

In this study, the effect of different parameters, including surface angle, hatch space, and postcuring time on the surface quality of specimens produced through SLA process are investigated. The roughness parameters of Ra, Rq, Rz, and Sm are measured in each of the fabricated specimen. In addition, an improved noncontact method for measuring the surface roughness is proposed. The higher accuracies can be achieved by the use of the proposed method for measuring the surface roughness of soft materials. In addition, the surface roughness is also measured with the contact technique to provide a comparison. Finally, a mathematical equation is established for relating the process parameters and the responses using analysis of variance.

2 | EXPERIMENTAL DETAILS

To investigate the effect of SLA parameters on the surface quality, the specimens should be fabricated under various conditions and then, the output parameters should be measured. The effect of surface angle was studied on a specimen designed by Reeves and Cobb with the geometrical and dimensional properties as depicted in Figure 1A.

The designed specimen in this research had some differences with the truncheon part used in the previous research so that a space was considered between the samples for the easy separation after fabrication. This specimen was consisted of 23 rectangular cubes with the dimensions of 20 × 20 × 5 mm as depicted in Figure 2. As it is obvious from this figure, each sample was aligned with the angle of 2° with respect to the adjacent sample. By rotating the rectangular cube along

![Figure 1](image-url)

**Figure 1** Comparison of the specimens geometry: A, Reeves. B, Present research
its 5 mm edge up to 44° in 2° steps, the surface angles of surface A would vary between 0° and 44°; while the surface angles of surface B would be changed in the range of 90° to 46°. Moreover, the surface angles of surfaces C and D would be in the range of 90° to 134° and 180° to 134°, respectively.

The surface angle is defined as the angle between the normal vector of the surface and the built direction.28 The considered levels for the input parameter are provided in Table 1. As can be seen, the variation of surface angle ranging from 0° to 180° is corresponding to 90 levels. In addition, three and four levels were considered for the postcuring time and hatch spacing, respectively. Furthermore, the values of constants parameters are presented in Table 2.

2.1 | Preprocessing

In this research, a Viper Si2 SLA system was used to manufacture the specimens. This machine was of top exposing type with the maximum laser power of 100 mW, resolution of 7.6-μm in XY plane and resolution of 2.5-μm in Z direction. Continuous-wave Nd:YVO4 solid-state laser with the wavelength of 354.7 nm and diameter of 250 μm was utilized. After creation of 3D-CAD models in SolidWorks 2012 software, the model was imported as an STL file into the machine software. The Watershed 1120, DSM Somos photopolymer (build material) was used for fabricating the specimens. The minimum height of support was 10 mm, and the sweeper became active only after the supports were created. Then the CAD file was uploaded into the machine. The final arrangement of the parts in the setup is shown in Figure 3. In the next step, the build platform was cleaned using acetone (CH₃COCH₃) and then it was mounted on the machine.
2.2 | Processing

The specimens were produced in two setups. In the first setup, three groups of similar specimens were produced under the same conditions to evaluate the effect of postprocessing time. In the second setup, three groups of specimens were produced with different hatch spacing and then, they were postcured with the same postcuring time.

2.3 | Postprocessing

After that the specimens were produced, they were cleaned using acetone and separated from the build platform and supports as depicted in Figure 4A,B. Then, as shown in Figure 4C, the specimens were postcured in an UV bath to achieve complete curing. Finally, the specimens were separated from each other and their surface roughness were measured according to Figure 4D,E.

2.4 | Surface roughness measurement

In this work, the surface roughness of specimens were measured through contact and noncontact methods. Initially, the noncontact method was used to measure the surface roughness of the specimens considering the possible damages on the specimens surface by contact method, then the contact method was utilized for measuring and finally, the obtained results were compared.
2.4.1 Noncontact method

In this method, the surface of the specimen was photographed by Dino-lite Digital microscope AM413T as shown in Figure 5A. In order to achieve higher accuracy, three images were captured from each surface with the magnification of 200 and the mean value was reported as the surface roughness.

The microscope software was capable of measuring both length and angle. So, two perpendicular lines with the length of 1.5 mm were drawn along the surfaces of the workpiece. Then using “Get Date graph digitizer 2.24” software and considering the plotted lines as a coordinate axis, the coordinate of the surface points were recorded as (Xi, Yi) ordered pairs as shown in Figure 5B. Then, with the use of the gathered data and MATLAB software, the surface roughness parameters were calculated. As depicted in Figure 5C, a third-order curve was fitted to the gathered data.

The similar slope and concavity between adjacent curves were considered as the boundary conditions. So, for each successive three points, eight equations with eight unknown constants would be achieved as illustrated below:

\[(x_{i-1}, y_{i-1}), (x_i, y_i), (x_{i+1}, y_{i+1}),\]
\[f_{i-1,j} = a_1x^3 + b_1x^2 + c_1x + d_1,\]
\[f_{i,j+1} = a_2x^3 + b_2x^2 + c_2x + d_2,\]
\[f_{i-1,j}(x_i) = y_i,\]
\[f_{i,j+1}(x_i) = y_i,\]
\[f_{i-1,j}(x_{i-1}) = y_{i-1},\]
\[f_{i,j+1}(x_{i+1}) = y_{i+1}.\]
\[ f'_{i-1,j}(x_i) = f'_{i-1,j}(x_i), \]  
\[ f''_{i-1,j}(x_i) = f''_{i-1,j}(x_i). \]  

Finally, a third-order equation was obtained for each curvature as Equation (11). The coefficients matrix of this equation is provided in Equation (12). Moreover, the coefficients for each curvature could be obtained through Equation (13). By integrating the provided function in Equations (11), Equation (14) can be written. 

\[
 f_{i,i+1}(x) = \frac{K_i}{6} \left[ \frac{(x-x_{i+1})^3}{(x_i-x_{i+1})} - (x-x_i)(x_i-x_{i+1}) \right] + \frac{K_{i+1}}{6} \left[ \frac{(x-x_{i+1})^3}{(x_i-x_{i+1})} - (x-x_i)(x_i-x_{i+1}) \right] \\
+ \frac{y_i(x-x_{i+1}) - y_{i+1}(x-x_i)}{x_i-x_{i+1}}. 
\]  

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \\
0 & a_2 & 2b_2 & c_2 & 0 & \cdots & 0 \\
0 & 0 & a_3 & 2b_3 & c_3 & \cdots & 0 \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
K_1 \\
K_2 \\
K_3 \\
\vdots \\
K_n
\end{bmatrix}
\begin{bmatrix}
0 \\
f_2 \\
f_3 \\
\vdots \\
f_n
\end{bmatrix},
\]

\[
i_i = (x_{i-1} - x_i) \\
b_i = (x_{i-1} - x_{i+1}) \\
c_i = (x_i - x_{i+1}) \\
f_i = 6 \left( \frac{y_{i-1} - y_i}{x_{i-1} - x_i} - \frac{y_i - y_{i+1}}{x_i - x_{i+1}} \right),
\]

\[
\int_{x_i}^{x_{i+1}} f_{i,i+1}(x) = (x_i - x_{i+1})^3 \left[ \frac{K_i}{24} + \frac{K_{i+1}}{24} \right] + (x_{i+1} - x_i) \left[ \frac{y_i}{2} + \frac{y_{i+1}}{2} \right].
\]

To calculate the mean value, the height of the lowest point along X axis was assigned zero (ie, \( Y = 0 \)), in other words, all the points were transferred above the X axis as shown in Equation (15). In each iteration, the X axis was moved upward with a defined step of 0.0001 mm, and then the integrated value was calculated. The iteration was stopped when the integral value reached the values less than defined error as shown in Equations (16) and (17).

\[
y_i = y_{i-1} - (y_{i-1}^{\text{Min}}),
\]

\[
y_i = y_i + \text{(Step)},
\]

\[
\sum_{i=1}^{n-1} \int_{x_i}^{x_{i+1}} f_{i,i+1}(x).d x < \text{error}.
\]

Finally, the roughness parameters (Ra, Rq, and Rz) were calculated using Equations (17) to (19).

\[
Ra = \frac{\sum_{i=1}^{n} \int_{x_i}^{x_{i+1}} |f_{i,i+1}(x)|.dx}{(X_{\text{max}} - X_{\text{min}})}, \tag{17}
\]

\[
Rq = \sqrt{\frac{\sum_{i=1}^{n} \int_{x_i}^{x_{i+1}} (f_{i,i+1}(x))^2.dx}{(X_{\text{max}} - X_{\text{min}})}}, \tag{18}
\]

\[
Rz = Y_{\text{max}} + |Y_{\text{min}}|. \tag{19}
\]
| Row | Function | Range   | Ra estimated | Ra calculated |
|-----|----------|---------|--------------|---------------|
| 1   | $Y = 3X$ | $0 < X < 2$ | 1.5          | 1.5000        |
| 2   | $Y = \sin(X)$ | $0 < X < 2\pi$ | $\frac{1}{2\pi}$ | 0.6369        |

**TABLE 3** Evaluation of the proposed method accuracy

To validate and evaluate the performance of the proposed method, two functions with known roughness values were considered and the results are provided in Table 3 and Figure 6. A precise convergence between the calculated roughness values and real roughness values can be observed. In previous investigations concerning the cured surfaces, a curve was plotted through the evenly distributed points to calculate the surface roughness. However, in this research, the computation of surface roughness was performed using analytical approach with no limitation on the amount of used data; additionally, the points can be distributed unevenly.

### 2.4.2 Contact method

The second technique for measuring the surface roughness in this research was contact method. In this method, “Taylor Hobson Precision Surtronic 3P Machine,” which is depicted in Figure 7, was implemented for the roughness measurements. Since the surface roughness in SLA specimens was in the range of $2 < Ra < 10$, the specimens length ($L_r$) was selected to be 2.5 mm. For achieving an improved measurement with an adequate accuracy, the roughness measurements were repeated five times on each surface and then the average value was reported as the surface roughness of the desired specimen.

### 3 RESULTS AND DISCUSSION

As explained in the previous section, the surface roughness measurement was repeated five times for each specimen, and the average of the measured values was considered as the surfaces roughness.
3.1 | Surface angle

3.1.1 | Contact method

First, the effect of surface angle on the surface roughness was investigated. For this purpose, the graphical results of surface angle vs surface roughness parameters were evaluated at constant postcuring time and hatch spacing. The hatch spacing was considered to be 0.100 mm for each specimen. The considered roughness parameters of Ra, Rq, Rz, and Sm are represented in Figure 8.

According to this figure, an increasing trend of surface roughness value by increasing the surface angle from 0° to 22° can be deduced for all conditions. Further increase in the surface angle from 22° to 110° resulted in a deteriorated surface roughness. The stair-stepping phenomenon was found to be the main reason for this behavior as shown in Figure 9. The nature of SLA process involves the division of 3D specimen into the layers with equal (or unequal) thicknesses along Z axis. Hence, complete curing in areas whose surface normal vectors were not parallel or perpendicular to the Z axis would not be occurred, and consequently, stair-stepping effect would be observed in the surface.

This phenomenon was found to relate the surface roughness with the surface angle. A surface with an angle between 0° to 90° is referred to up-facing surface; while down-facing surface is defined as a surface with an angle in the range of 90° and 180°. It was expected that down-facing surfaces have higher roughness than the up-facing surfaces. This can be justified by the fact that the specimens were connected to the platform by needle tip supports from the down-facing side, and in the postprocessing step, during removal of these supports, a small part of the workpiece surface was also removed. Moreover, a small piece of the support material was also remained on the workpiece surfaces. This phenomenon was reported as the main source of roughness in this process by previous researchers.

However, this expectation (higher roughness of the down-facing surfaces) is not always correct. According to the obtained results, in some cases, lower roughness of the down-facing surfaces was observed. Reeves reported the decrease in the surface roughness of down-facing surfaces as a result of print-through phenomenon, in which, the applied energy for curing the next layers resulted in an unwanted curing of the resin among the stairs of former layers and hence,
the consequent reduction in roughness was occurred. Finally, it can be concluded that stair-stepping, support removing and print-through are the influential factors in the determination of roughness in down-facing surfaces. Moreover, approximately similar trends of all roughness parameters at various angles with reasonable accuracy were inferred.

3.1.2 Noncontact method

As explained in section 2-4-1, for the calculation of surface roughness through noncontact technique, the image of specimen's surface was captured using a digital microscope. Then, the coordinates of the surface were sent to MATLAB software for the calculation of $R_a$ value. The plotted diagram by MATLAB software after calculating the position of mean value line for C14 specimen with the surface angle of $18^\circ$ is depicted in Figure 10. In addition, the surface angle vs $R_a$ diagram is shown in Figure 11A for specimens manufactured using the hatch spacing of 100 μm and postcuring time of 80 minutes. By comparing the results of $R_a$ for contact and noncontact methods, approximately a similar variation trend of $R_a$ against the surface angle was concluded. The comparison showed an increasing trend of surface roughness by increasing the surface angle in the range of $0^\circ$ to $30^\circ$. This increasing trend was followed by a decreasing trend by further increase of the angle from $30^\circ$ to $90^\circ$.

In this method, the images were captured from the edges of the workpiece, so the calculated surface roughness would not be exactly the same as entire surface and hence, it cannot be considered for the entire surface. However, the same range can be considered for these values due to the nature of SLA process. The comparison results of calculated surface roughness from contact and noncontact methods is shown in Figure 11B for the surface angle in the range of $0^\circ$ to $90^\circ$ and postcuring time of 80 minutes. The results showed approximately the same roughness variation of the both methods; however, the values of $R_a$ obtained from the noncontact method were slightly higher.

This difference may be attributed to the inadequate magnification, limitation in data line length, and the difference in roughness value between the surface and edges. As a result of insufficient magnification, determination of the exact
position of peaks and valleys may be impossible. Moreover, the sampling length in contact method was 2.5 mm; while the maximum available length in the noncontact method was 1.5 mm. Hence, some discrepancies in the results may be originated from this difference in sampling length.

In order to improve the results of the proposed methodology, the specimen surface was manufactured with the surface angle of 76° and photographed using Leitz WETZLAR microscope with a magnification of 500× as shown in Figure 12. Then, the gathered data from the surface were sent to MATLAB software for the calculation of roughness parameters. The results of this measurement are listed in Table 4. According to the acceptable convergence of the results, the accuracy of the surface roughness measurement with noncontact method can be concluded. However, this method encounters some limitations, especially in measuring the surface roughness of the smooth surfaces (low surface roughness), which requires higher magnification and resolutions. Furthermore, the results of this method would be unreliable for the processes, in which, the quality of the surface and edge has a significant difference. This difference is considered as one of the error sources of noncontact method.

### 3.2 Postcuring time

According to Figure 8, no definite variation trend of surface roughness with postcuring time can be observed. Hence, the effect of postcuring time on surface roughness can be neglected. The insignificant differences between the obtained data
in various postcuring times may be attributed to the effect of manual cleaning and postprocessing. In addition, as will be presented in section 3-6, the coefficient of postcuring time in roughness equation is very small, which confirms the negligible effect of this parameter.

### 3.3 Hatch spacing

The effect of hatch spacing on surface roughness can be investigated by considering the specimens with the same surface angles and postcuring times. The graphs of hatch spacing vs Ra, Rq, Rz, and Sm are shown in Figure 13.

According to these diagrams, the increasing behavior of surface roughness with increasing the hatch spacing in all surfaces can be deduced. For different surface angles, diagrams with different slopes can be observed due to the simultaneous effect of surface angle and hatch spacing on surface roughness. Finally, it can be concluded that the hatch spacing and surface quality are inversely related to each other.

### 3.4 Mathematical simulation

As explained earlier, the measurements were repeated five times for each surface and then, the average of the measured values was taken as the surface roughness value. To prove the negligible difference of the gathered data, the graph of surface angle vs coefficient of variation (C.V) of Ra and Rq is shown in Figure 14. According to this diagram, it was found that more than 89% of Ra data have less than 30% C.V, and less than 12% of Rq data have C.V greater than 30%.

Next, the Design Expert software was used to model the surface roughness and to establish a mathematical relationship between the input and output parameters of this process. According to the diagrams of surface roughness vs surface angle, it can be inferred that with the use of fourth-order or higher order equations, better convergence to the data can be achieved. However, considering the limitation of this software in simulating the maximum third-order equations, the
simulation was done in two angle ranges separately (ie, one simulation for 0°-90° [Equation 18] and another simulation for 90°-180° [Equation 19]).

\[
Rq_{(0-90)} = 7.134717 - 6.94583 A - 0.14566 B - 0.06333 C + 0.33511 A C + 0.002221 B C + 0.001271 B^2 - 0.00031 C^2 - 0.38894 A^2 C - 0.00277 C^2 A - 1.9E-05 \times B^2 C - 1.7E-07 \times C^2 B
\]

(20)

\[
Rq_{(90-180)} = 0.689128 + 34.60113 A + 0.048246 B - 0.02311 C + 0.052146 A C - 0.0003 B C - 434.122 A^2 - 0.00056 B^2 + 0.00019 C^2 + 3.190653 A^2 C - 0.00242 C^2 A + 3.97E-06 \times B^2 C - 3.5E-07 \times C^2 B
\]

(21)

After that, according to the effect of each parameter on the responses, the maximum order of each parameter was determined. In addition, the interaction between the coefficients of each parameter was specified. The correlation coefficient of each parameter is presented in Table 5. From these results, it can be concluded that:

- For the correlation coefficient higher than 0.8, an adequate convergence between the theoretical model and experimental data can be inferred.
- The values higher than 4 represents the adequacy and efficiency of the model in predicting the response.

Due to the negligible effect of postcuring time on surface roughness, lower coefficient of this parameter compared with the other two parameters was observed. In addition, it's interaction with the surface angle and hatch space was considered to be zero due to its negligible value.

The obtained model was validated by the use of test data, which were not used for training. Accordingly, the test data were imported into the point prediction section, and then the error between the predicted and real value was calculated. The real value, predicted value, and the error for Ra, Rq, Rz, and Sm are presented and compared in Figure 15. It was found that the average value of the error is less than 14%.
CONCLUSION

In this article, the effects of surface angle, hatch space and postcuring time on surface roughness in SLA process were investigated using the manufactured specimens under various experimental conditions. The results showed the minimum value of surface roughness in the surface angles of 0°, 90°, and 180°. It was found that by increasing the surface angle from 0° to 90°, the surface roughness was increased sharply, which was followed by a slow drop. In the range of 90° to 180°, the surface roughness increment was occurred gradually, and then it was dropped rapidly. Moreover, the increasing trend of the surface roughness by increasing the hatch spacing was observed. However, this would be resulted in the increased manufacturing time. So according to desired surface quality and process cost, an appropriate hatch spacing value should be chosen. Regarding the obtained results, the effect of postcuring time on surface quality was negligible. So, this parameter value should be chosen according to other desired parameters such as stiffness, process time, and so on. The selection of surface angle or part orientation should be performed considering the desired application. If the surface quality of specified surface is important, like the core in an injection mold, the part orientation should be selected to achieve the minimized roughness on the surfaces. But, if the minimum roughness in the entire part is favorable, the part orientation should be selected so that the multiplication of total surface area and surface roughness becomes minimal for the entire workpiece.

ACKNOWLEDGMENTS

This research received no specific grant from any funding agency.

PEER REVIEW INFORMATION

Engineering Reports thanks the anonymous reviewers for their contribution to the peer review of this work.

AUTHOR CONTRIBUTIONS

Javad khodaii: Data curation; formal analysis; investigation; writing-original draft. Abdolreza Rahimi: Conceptualization; investigation; project administration; supervision; writing-review and editing.

CONFLICT OF INTEREST

The author declares no potential conflict of interest.

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**How to cite this article:** Khodaii J, Rahimi A. Improving the surface roughness in stereolithography by controlling surface angle, hatch spaces, and postcuring time. *Engineering Reports.* 2020;2:e12193.

https://doi.org/10.1002/eng.212193