

Surface Finish Improvement Using Retraction Method for Fused Deposition Modeling Printed Samples

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ABSTRACT

In additive manufacturing, retraction is a key technique for minimizing stringing, oozing, and blobs when the print head moves between model sections without extruding the filament. Proper retraction tuning is critical for improving print quality, as overly aggressive settings can cause under-extrusion, nozzle clogs, or extruder wear, while weak retraction may fail to eliminate artifacts. This study explores the effects of three retraction parameters such as z-lift, speed, and length on the surface roughness of 3D printed parts using an orthogonal array design. 27 samples were printed using Folgertech open-source FDM 3D printers with ABS-M30i material. Test samples were modeled using SolidWorks CAD software and printed using Repetier software to optimize quality. Surface roughness (Ra) was measured using the Mitutoyo Surftest SJ 301, and surface structures were analyzed with a Stereo Microscope. Results show that Sample 11, with a z-lift of 1 mm, speed of 20 mm/s, and retraction length of 1 mm, achieved the lowest Ra value (1.33 μm). In contrast, Sample 23, with a z-lift of 2 mm, speed of 40 mm/s, and length of 5 mm, produced the highest Ra value (5.93 μm). These findings demonstrate that surface finish quality is significantly influenced by retraction parameters. The experimental design approach effectively identifies optimal process parameter combinations with minimal trials, providing a strategy for optimizing surface finish in FDM 3D printing.

Keywords: Additive manufacturing; Fused Deposition Modeling; surface roughness; Retraction Method; ABS-M30i

INTRODUCTION

Additive manufacturing (AM) can be defined as the process of combining materials to create items from 3D model data, often layer by layer, as opposed to subtractive manufacturing approaches such as traditional machining (Rasiya et al. 2021). The subtractive manufacturing process removes material from stock using tools such as a drill, lathe, or mill (Davis et al. 2022).

AM process lets designers construct complex shapes that were previously impossible to imagine, allowing for the realization of intricacies never seen before (Liu et al. 2021; Maidin et al. 2024). AM process operates unmonitored, requiring a low level of operator knowledge and reducing the amount of human contact required to make an object (Li & Yeo 2021). It will minimize the time between design iterations, and parts will be made exactly reflecting the designer's intent and reducing inaccuracies (Rasiya et al. 2021; Shahrum et al. 2024). AM methods are

capable of producing complicated or basic parts at no added lead time (Blakey-Milner et al. 2021).

AM is capable of responding fast to markets (Kunovjanek & Wankmüller 2021). Furthermore, AM can enable new manufacturing alternatives outside of factories, such as mobile units that can be deployed near the source of local materials, and spare parts can be created on demand, decreasing or eliminating the need for inventories and complex supply chains (Hegab et al. 2023). In the AM process, the material is added layer by layer, and only the material required for the item is utilized in production, unlike traditional subtractive manufacturing processes, such as machining, where the desired part is cut out of stock, leaving behind wasted material chips. Thus, AM can reduce the amount of material needed (Ashima et al. 2021; Maidin et al. 2023). AM can also reduce production costs allowing products made through the AM method to be priced competitively (Goodacre & Goodacre, 2022). AM processes can eliminate production steps, utilize

significantly less material, allow for the reuse of by-products, and produce lighter products, reducing the amount of energy used (Majeed et al. 2021; Sun et al. 2021). Using the AM process, goods can be built as soon as the 3D digital description of the part is created. This removes the need for costly and time-consuming component tooling and prototype fabrication, allowing faster prototyping (Maidin et al. 2023; Tian et al. 2022).

The constraints of the AM prevent it from being a viable solution to all production problems. Problems include high lead time which takes approximately an hour to complete a 1.5-inch cube using AM. It differs from an injection molding machine, which takes only a few minutes to produce multiple comparable pieces. This constraint only applies to the production of a few thousand of a common part (B.A et al. 2022; DEMİRALP et al. 2021). AM techniques employ proprietary polymers that are not well characterized, are weaker than their traditionally made counterparts, and part strength is inconsistent. This is due to porosity and the lack of high pressure and consolidation during the layer-by-layer building (du Plessis et al. 2020; Shahrum et al. 2024).

There are many applications of AM in industries such as the medical industry. Building a jawbone implant using AM takes only a few hours. It is no longer necessary to make ten thousand parts to construct the prosthetic jaw thanks to AM (Al-Tamimi et al. 2020). The use of AM reduces the build time for making automotive parts. As a result, the time-to-market will be greatly reduced. Because the usage of AM can lower costs, car manufacturers, particularly high-end and low-volume automakers, will incorporate AM into their production processes (Basu et al. 2023). AM technology will be used in the aerospace industry to lower the cost of tools, materials, and labor. AM technology can eliminate the requirement for tooling and machining. Furthermore, design flexibility can be achieved because AM technology allows for easy design changes to achieve strong design levels (Rajendran et al. 2024).

The optimal surface finish of a model is built by altering build orientation and layer thickness while keeping other FDM process parameters constant using the experimental design technique. The experiments were carried out using a fractional factorial design with two levels for layer thickness and three levels for orientation component. The authors concluded that roughness values for 20 and 45 degrees-built orientations are linearly proportional to layer thickness, whereas roughness values for 70 degree created orientations decrease as layer thickness increases (Vijay et al. 2012).

The retraction method is primarily used to reduce stringing and oozing by pulling back the filament slightly during non-printing movements. This technique has been

explored in several studies to assess its impact on surface quality. The study in (Kelvin et al. 2024) that higher retraction speeds effectively reduce stringing by quickly halting filament flow, while lower speeds tend to result in more stringing. However, excessively high retraction speeds can lead to issues such as filament grinding, which negatively affects print quality. The research emphasizes the importance of optimizing retraction speed, temperature, and retraction distance to minimize stringing and improve overall print quality and surface finish. The interplay between retraction speed, deposition angle, and the number of walls significantly influences the visual quality and mechanical strength of 3D-printed parts, as explored in (Jackson et al. 2022). The study shows that while the number of walls minimally affects part strength, retraction speed significantly influences ultimate tensile strength, emphasizing its optimization for better mechanical and visual quality in 3D-printed components.

The study by (Radomir Mendricky, 2020) investigates the impact of retraction settings on the quality and accuracy of FDM/FFF 3D printing using PLA. It focuses on optimizing parameters like retraction rate, length, and crossing speed. The analysis, using the Taguchi method, examines factors affecting printing time, material consumption, surface quality, and dimensional accuracy. The study emphasizes the importance of retraction settings in minimizing stringing and improving surface finish, while also highlighting the influence of layer height and print speed on print time.

The study by (Shieh Em & Chee Kiong, 2023) examined the impact of retraction distance on dimensional accuracy in FDM 3D printing. Particle Swarm Optimization suggested a retraction distance, but validation ranked it 17th out of 25 models, indicating it was not optimal. Experimental trials identified the optimal retraction distance, while (Ekinici & Ehrmann, 2022) highlighted the importance of optimizing retraction settings for complex geometries, emphasizing reduced stringing and improved dimensional accuracy.

In conclusion, the retraction method plays a vital role in improving the surface finish of FDM-printed samples. By optimizing retraction parameters such as speed, distance, and filament retraction rate, it is possible to significantly reduce surface defects like stringing and oozing. However, achieving the best surface finish requires a careful balance of retraction settings with other printing parameters to ensure both surface quality and part accuracy. Future research may focus on developing more advanced retraction algorithms, possibly integrated with real-time monitoring systems, to further enhance the surface finish of FDM-printed parts.

In this research, an orthogonal array of 27 samples was printed for three parameters: z-lift, speed, and length,

each of which had three different values. SolidWorks CAD software was used to create the test sample, which was then 3D printed using Folgertech open-source FDM 3D printers printed with ABS-M30i material. The repetier software was linked to the 3D printer to improve the quality of a product or process. The surface roughness of the samples was determined using the Mitutoyo Surftest SJ 301. The experimental design was used to ensure that the samples generated produced the best surface finish. The samples printed have a unique outcome that varies with changes in the machine's process parameters such as z-lift value, speed, and length.

METHODOLOGY

CAD MODEL DESIGN

A simple cube sample (20mm x 20mm x 20mm) was modeled using Solidworks software. The SolidWorks drawing file must be converted to STL format. This is because the AM machine can only accept STL files and slice them into thin cross-sectional layers. Each machine has some configuration options. Figure 1 depicts a CAD model with dimensions.

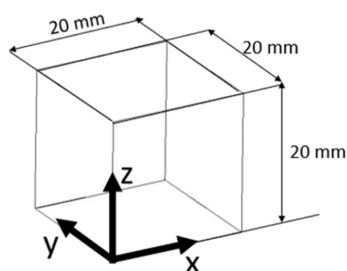


FIGURE 1. CAD model with dimensions

DESIGN OF EXPERIMENT (DOE)

Design of Experiment or DOE is a tool for determining all feasible experimental combinations and creating a design matrix table. The experimental preparation and process acted as a guide for creating consistent samples and conducting experimental tests. Retraction length, speed, and z-lift are the parameters to consider while using the retraction method.

EXPERIMENTAL PREPARATION AND PROCEDURE

First, a 20mm*20mm cube sample was modeled in SolidWorks. The 3D model file must be converted to STL

format. The STL file was transferred to the Repetier software. Inside the software, a few parameters must be adjusted for the retraction procedure to obtain the ideal parameter to increase the surface finish. The software has changed three parameters: retraction length, retraction speed, and retraction z-lift. These combinations were evaluated using DOE, which allows for the determination of every conceivable experiment combination using a design matrix table. From here, it will be possible to obtain up to 27 samples by employing matrix 3 x 3 combinations. All 27 test samples had their surface roughness measured using a surface roughness tester (Figure 2). From that test, it was determined which parameter in the retraction resulted in the best surface finish.



FIGURE 2. Portable Surface Roughness Tester

To complete the FDM printing process, the machine and its standard operating procedure must be identified and thoroughly understood. This is to avoid overuse of the machine, which would result in a breakdown. After the samples were printed utilizing a Folgertech FDM 3D printer, the surface roughness was determined with a Stereo Microscope to see the difference in structure as illustrated in Figure 3.



FIGURE 3. Meiji Stereo Microscope

METHOD OF DESIGN OF EXPERIMENT

DOE was used at this stage to assist in planning relevant experiments with the parameters selected. Orthogonal Arrays were used to create a combination of various parameters. The experiment was designed utilizing parameters in retraction approaches to calculate the combinations and number of runs. Using three parameters with three distinct values, the total number of runs will be 27. The 27 test samples were printed with ABS-M30i. The optimal combinations of parameter settings for surface roughness are then discovered. The parameter will be taken as the optimal value for each of them as shown in Table 1.

TABLE 1. Parameter using DOE

Parameter	z-lift a, b, c	Speed A, B, C	Length 1,2,3
Sample 1	a	A	1
Sample 2	a	B	1
Sample 3	a	C	1
Sample 4	a	A	2
Sample 5	a	A	3
Sample 6	a	B	2
Sample 7	a	B	3
Sample 8	a	C	2
Sample 9	a	C	3
Sample 10	b	A	1
Sample 11	b	B	1
Sample 12	b	C	1
Sample 13	b	A	2
Sample 14	b	A	3
Sample 15	b	B	2
Sample 16	b	B	3
Sample 17	b	C	2
Sample 18	b	C	3
Sample 19	c	A	1
Sample 20	c	B	1
Sample 21	c	C	1
Sample 22	c	A	2
Sample 23	c	A	3
Sample 24	c	B	2
Sample 25	c	B	3
Sample 26	c	C	2
Sample 27	c	C	3

RESULTS AND DISCUSSION

PARAMETER COMBINATION

Table 2 displays several parameter combinations achieved using Repetier software with three major retraction parameters. Table 2 shows the results of an experimental run utilizing various parameter combinations from the Repetier software. Three critical parameters, z-lift, speed, and length were utilized to study the effect of response characteristics on surface roughness.

TABLE 2. Different combinations of parameter settings for each experimental run

Parameter	z-lift 0,1,2	Speed 40,20,60	Length 1,3,5
Sample 1	0	40	1
Sample 2	0	20	1
Sample 3	0	60	1
Sample 4	0	40	3
Sample 5	0	40	5
Sample 6	0	20	3
Sample 7	0	20	5
Sample 8	0	60	3
Sample 9	0	60	5
Sample 10	1	40	1
Sample 11	1	20	1
Sample 12	1	60	1
Sample 13	1	40	3
Sample 14	1	40	5
Sample 15	1	20	3
Sample 16	1	20	5
Sample 17	1	60	3
Sample 18	1	60	5
Sample 19	2	40	1
Sample 20	2	20	1
Sample 21	2	60	1
Sample 22	2	40	3
Sample 23	2	40	5
Sample 24	2	20	3
Sample 25	2	20	5
Sample 26	2	60	3
Sample 27	2	60	5

SURFACE ROUGHNESS

The surface roughness parameter used in this investigation was the Roughness Average (Ra). Ra is defined as the

arithmetic mean of the absolute deviation of the surface profile from the mean line over the evaluation length. The surface roughness results for the 27 fabricated samples are presented in Table 3.

TABLE 3. Analysis of Data

Experimental Runs	Parameter Combination (z-lift, speed, length)	Surface Roughness, Ra (μm)			
		1	2	3	Average (μm)
Sample 1	(0,40,1)	3.34	3.26	3.28	3.29
Sample 2	(0,20,1)	3.61	3.61	3.71	3.64
Sample 3	(0,60,1)	3.28	3.17	3.16	3.20
Sample 4	(0,40,3)	2.91	3.12	3.42	3.15
Sample 5	(0,40,5)	5.71	5.88	5.66	5.75
Sample 6	(0,20,3)	2.78	2.73	2.79	2.76
Sample 7	(0,20,5)	4.92	5.17	5.25	5.11
Sample 8	(0,60,3)	4.53	4.71	4.88	4.70
Sample 9	(0,60,5)	3.18	3.34	3.29	3.27
Sample 10	(1,40,1)	1.71	1.89	1.29	1.63
Sample 11	(1,20,1)	1.73	1.12	1.15	1.33
Sample 12	(1,60,1)	3.12	3.29	3.41	3.27
Sample 13	(1,40,3)	3.41	3.43	3.44	3.43
Sample 14	(1,40,5)	3.43	3.45	3.16	3.35
Sample 15	(1,20,3)	5.01	4.79	4.88	4.89
Sample 16	(1,20,5)	3.31	3.41	3.42	3.38
Sample 17	(1,60,3)	4.17	4.26	4.34	4.26
Sample 18	(1,60,5)	1.97	1.83	1.79	1.86
Sample 19	(2,40,1)	2.12	2.24	2.30	2.22
Sample 20	(2,20,1)	2.14	2.73	2.62	2.49
Sample 21	(2,60,1)	1.98	2.02	2.10	2.03
Sample 22	(2,40,3)	1.88	2.01	1.99	1.96
Sample 23	(2,40,5)	5.88	5.92	6.01	5.93
Sample 24	(2,20,3)	4.77	4.28	4.61	4.55
Sample 25	(2,20,5)	4.18	4.29	4.41	4.29
Sample 26	(2,60,3)	4.24	4.25	4.25	4.25
Sample 27	(2,60,5)	4.09	3.98	3.97	4.01

The surface roughness of 27 Folgertech 3D printed samples was measured using a Mitutoyo Surftest SJ-301. Each area of the cubic sample was repeated three times to produce a significantly more accurate average surface roughness Ra value. The average Ra value (μm) was calculated by averaging the results of three sets of experiments. Table 3 shows that different combinations of parameter settings for retraction produce varied values for the surface finish. The combination of parameter values (1,20,1) in experimental run 11 resulted in the lowest average Ra value of 1.33 μm . Runs 10 and 18 had higher average Ra values of 1.63 μm and 1.86 μm , respectively. Experimental run 10 with the parameters (1,40,1) for z-lift,

speed, and length. While the experimental run 18 is a combination of parameters (1,60,5) that represent z-lift, speed, and length.

Surface roughness analysis reveals three experimental runs with a lower average Ra value than the other runs. They have a common z-lift value of 1mm. As a result, with a z-lift value of 1mm, it is possible to create an FDM product with lower surface roughness, indicating higher surface quality. Experimental run 23 with parameter (2,40,5) had the highest average Ra value of 5.93 μm , followed by experimental runs 5 and 7, with average Ra values of 5.75 μm and 5.11 μm , respectively. Experimental run 5 uses (0,40,5) as a combination parameter for z-lift,

speed, and length, whereas experimental run 7 uses (0,20,5) for z-lift, speed, and length. For surface roughness, these three experimental runs have a greater average Ra value than the other runs. They share the same z-lift value of 0mm or 2mm. As a result, a z-lift of 0mm or 2mm will produce a part with increased surface roughness, indicating poor surface quality. The average Ra value indicates that

the part's surface quality improves as the average Ra value decreases. The combination of parameter values (1,20,1) in experimental run 11 resulted in the lowest average Ra value of $1.33\text{ }\mu\text{m}$, making it possible to build an FDM part with high surface quality. For further analysis, the data in Table 4.2 is converted into the histogram as shown in Figure 4.

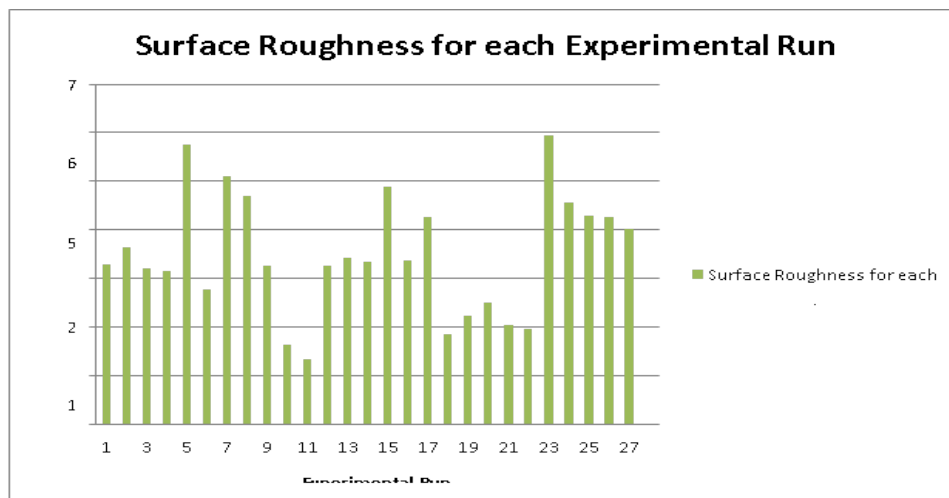


FIGURE 4. Average Surface Roughness, Ra value for each experimental run

Figure 4 shows that each experimental run produces unique surface roughness data based on the various parameter combinations generated using the Retraction Method. The Ra value is lower in some experimental runs and greater in others. This illustrates that the varied parameter combinations in retraction settings affect the surface roughness characteristics of the FDM parts generated. As a result, trial run 11 was chosen as the optimal combination for producing the finest surface quality in part printed using FDM.

ANOVA ANALYSIS

Analysis of variance (ANOVA) was performed to determine the significance of parameters and their percentage contribution to the surface roughness of the FDM process. The three parameters that were optimized in this research are z-lift, speed, and length. To determine the magnitude of the parameter's effect on surface roughness, the percentage of contribution is calculated using Minitab 17 software. Table 4 displays the proportion of contribution for each parameter, which is then summed in a pie chart as shown in Figure 5.

TABLE 4. Percentage contributions of parameters on surface roughness

Parameter	Sum of Square	Percent Contribution (%)
Z-Lift	0.854621	90.11
Speed	0.068885	7.34
Length	0.016121	1.76
Error	0.008261	0.79
Total	0.947979	100

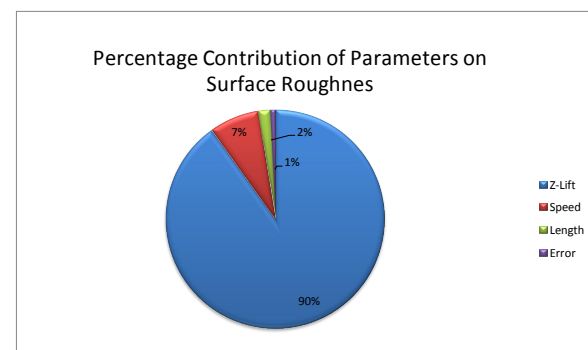


FIGURE 5. Percentage contribution of parameters

The pie chart in Figure 5 shows that z-lift is the dominant factor influencing surface roughness, contributing approximately 90% to the total variation, followed by speed at 7%. Length has a relatively minor effect, accounting for 2% of the variation. The remaining 1% is attributed to statistical error (residuals), which represents the unexplained variation in the experimental data. Analysis of Variance (ANOVA) was performed to determine the significance of the process parameters using the F-value and P-value. Figure 6 presents the Pareto chart generated from the F-values obtained through ANOVA using Minitab 17 software. In the ANOVA table, the F-value represents the test statistic of Fisher's test and is used to evaluate the significance of each factor on the response variable. A larger F-value indicates that the corresponding factor has a more significant effect on surface roughness. Therefore, factors with sufficiently high F-values are considered to have a statistically significant influence on the response.

Figure 6 depicts a Pareto chart for surface roughness, which reveals that z-lift is the most significant factor influencing surface roughness. The z-lift parameter is expected to have the greatest impact on the surface roughness of the FDM part produced. This finding is

consistent with the results reported by Nancharaiah et al. (2020), who identified z-lift as the most influential parameter affecting the surface roughness of FDM parts. As illustrated in Figure 6, the F-value for z-lift is considerably higher than that of the other factors, indicating its strong influence on the response. However, p-value analysis is required to statistically verify the significance suggested by the Pareto chart. Table 5 presents the results of the p-value analysis obtained using Minitab 17 software.

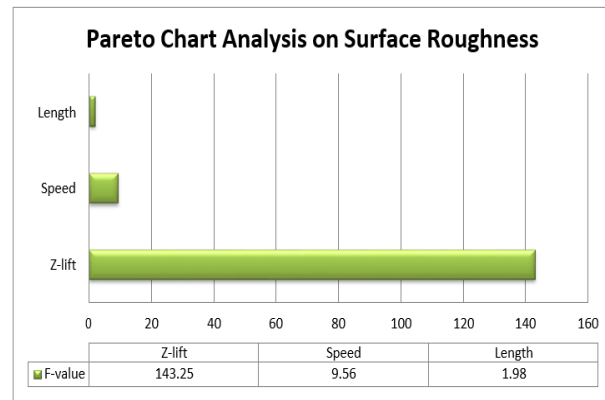


FIGURE 6. Pareto Chart on surface roughness

TABLE 5. P-value analysis

Parameters	F-value	P-value	α -value	Analysis	Significant
Z-lift	143.25	0.010	0.05	P value < α value	Yes
Speed	9.56	0.345	0.05	P value > α value	No
Length	1.98	0.108	0.05	P value > α value	No

The P-value is used to determine whether the parameter affects the response characteristic. If the P-value is less than the α value, it means that the source has a significant effect on the response. This experiment employed the hypothesis testing value of $\alpha=0.05$. $\alpha=0.05$ is commonly used for hypothesis testing. Table 5 reveals that only z-lift has a significant effect on surface roughness, with a P-value (0.01) less than the α value (0.05). Furthermore, the F-value for z-lift is adequately large when compared to speed and length. Usually, changing the process parameters affects the response characteristics. As a result, the only parameter that has any substantial effect on surface roughness is z-lift. It is validated using the P-value from Minitab 17.

MACROSCOPIC INSPECTION

A macroscopic inspection was performed to evaluate the surface finish of the printed samples. Two cubic samples with the best and worst surface roughness were investigated under a Meiji Stereo Microscope to see the difference in

structure. Figure 7 indicates that using the parameter (1,20,1) results in the lowest average Ra value of 1.33 μm and voids between deposition beads of 0.01 mm. As a result, surface roughness diminishes, indicating increased surface quality.

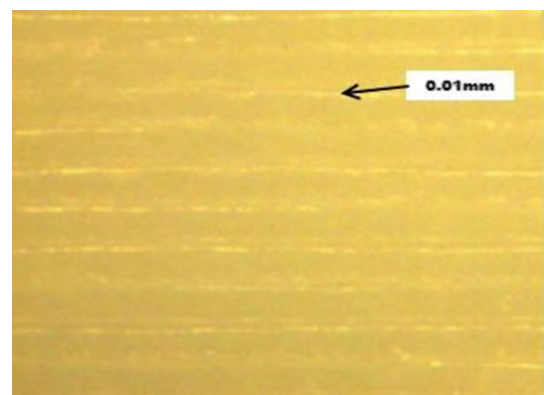


FIGURE 7. Experimental run 11 with the combination of parameter with value (1,20,1) gives the lowest average Ra-value which is 1.33 μm gives the lowest surface roughness, which indicates the best surface quality

Figure 8 shows that the parameter combination (2, 40, 5) produces the highest average Ra value of $5.93\text{ }\mu\text{m}$, with voids of 0.04 mm between ABS deposition beads. This leads to increased surface roughness, indicating poorer surface quality. In contrast, increasing the z-lift value from 0 mm (low level) to 1 mm (high level) reduces the voids between ABS deposition beads from 0.04 mm to 0.01 mm. These findings are consistent with those reported by Nancharaiah et al. (2010), who identified z-lift as a significant parameter influencing the surface roughness of FDM-fabricated parts. The reduction in void size due to higher z-lift values contributes to improved inter-layer bonding and reduced surface irregularities. Consequently, decreasing voids between layers reduces the step effect between deposited ABS beads, leading to improved surface finish.

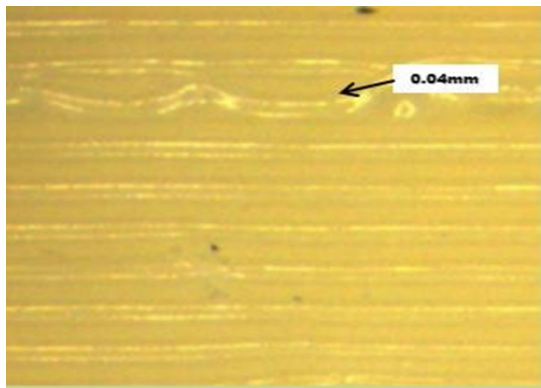


FIGURE 8. Experimental run 23 with a combination of parameters with value (2,40,5) has the highest average Ra value which is $5.93\text{ }\mu\text{m}$ gives the highest surface roughness which indicates bad surface quality

CONCLUSION

In today's fast-paced manufacturing environment, using rapid prototyping technology to produce functioning parts would be an excellent option. However, the product generated still exhibits significant variation in terms of performance. This research provides an overview of optimizing the parameters of an FDM machine to achieve the desired results for the created product.

The primary goal of this research is to develop and print test samples to examine the 3D-printed surface finish improvement technique. In design and print, the surface roughness of the part produced varies with different combinations of parameters; thus, a design of experiment approach is required to determine the optimum combination of parameters for the lowest surface roughness using the

part produced. The basic cubic sample produces excellent results in terms of lowering the number of pieces required for production and testing, resulting in substantial time and cost savings.

The second goal is to create a CAD model of the test samples and print it with an open-source FDM 3D printer with ABS-M30i material. A cubic (20mm*20mm) is chosen as the design sample because it displays the measurement layer thickness. Furthermore, the sample meets the surface roughness measurement standards, as the Mitutoyo Surftest SJ-301 can only measure to a minimum range of 4mm or above. After modeling the sample with SolidWorks, it was fabricated with Folger 3D Printer with ABS-M30i thermoplastics material. The third goal of this research is to investigate how to optimize retraction parameters for the best quality of 3D printed sample surface finish. The process parameters include retraction length, retraction z-lift, and retraction speed, all of which are available on the Repetier Software. With the execution of the DOE technique, 27 samples were produced with various combinations of factors. The 27 samples were then examined, and sample 11, with a retraction z-lift value of 1, a retraction speed of 20, and a retraction duration of 1, outperformed the other samples, resulting in the lowest average surface roughness and Ra value, indicating the greatest surface quality. Sample number 23 with the parameter's combination of z-lift of 2mm, speed of 40mm/s, and length of 5mm gives the highest average Ra value ($5.93\text{ }\mu\text{m}$).

As a recommendation, a different material should be explored as it might have different results of surface roughness than current materials. In addition, the full factorial analysis consists of conducting experiments that take all the possible combinations of the factors and their levels into consideration must be conducted to improve the analysis of the study.

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DECLARATION OF COMPETING INTEREST

None.

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