Optimization of the Parameters for Surface Quality of the Open-source 3D Printing

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ABSTRACT

Fused deposition modeling (FDM) or three-dimensional (3D) printing are becoming ubiquitous today because it allows the fabrication of 3D products directly from computer-aided design software. The quality of 3D parts is influenced by several parameters that need to be carefully tuned to obtain a high-quality final product. The surface finish of the finished parts is one of the major factors to consider because it affects both the dimensional accuracy and the functionality of the piece. Thus, the present study focuses on improving the surface finish of parts produced by FDM by manipulating different parameters such as layer height, raster angle, extruder temperature, printing speed, and percent infill. Polylactic acid was used for this study, which is a material present in filament form, and was extruded using a newly developed 3D printer; the Taguchi's 3^5 design-of-experiment method was used to design the experiment. The results indicate that raster angle, extruder temperature, and layer thickness are the most influential process parameters of the surface quality of the final product.

Introduction

Fused deposition modeling (FDM), also known as additive manufacturing (AM), has significantly improved since it was patented by Crump [1] in

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1992. The idea of FDM is quite simple: a three-dimensional (3D) object is constructed from a melted material that is deposited layer by layer and allowed to solidify [2]. Acrylonitrile butadiene styrene and polylactic acid (PLA) are the most common materials used in FDM. Since the original patent expired a few years ago, a variety of software and hardware designs for FDM have become available on the market. Because of its low cost, the demand for FDM technology is increasing. In 1996, Stratasys introduced the Genisys machine, which uses the inkjet printing mechanism. In the same year, Z Corp. also launched its Z402 3D printer. Other companies commercializing this technology include Beijing Yinhua Laser Rapid Prototypes Making & Mould Technology Co., Ltd. and BPM Technology [3]. However, Stratasys dominates the FDM market with a 41.5% share of all systems in 2010, making it the biggest manufacturer of AM technology [4].

The development of low-cost 3D printing began in 2004 with an open-source 3D printing project called RepRap (replicating rapid prototyping). Since then, several 3D printers have become available on the market for as little as $5000 [5]. However, the performance of such low-cost 3D printers remains questionable; many research and development have been done to improve this situation. For example, Melenka [6] evaluated the dimensional accuracy of parts made with the MakerbotBot Replicator 2 desktop 3D printer; the results demonstrated that settings need to be carefully monitored if a consistent geometry is required. In addition, research on how process parameters affect parts made from PLA materials shows that different process parameters (e.g., infill orientation or the number of shells) significantly impact the mechanical performance of the material [7].

Surface finish is a vital quality of the finished part because it directly affects the dimensional accuracy and, therefore, the functionality of finished parts. Previous research applied Taguchi method governing process parameters with three levels and orthogonal array of L9, which manipulating several process parameters, including print speed, layer height, and percentage infills to investigate which parameters that most affect the quality of surface finish [8]. The present research investigates the surface finish of parts made of PLA materials using Taguchi method by varying the process parameters of layer height, raster angle, extruder temperature, printing speed, and percentage infill. All process parameters are analyzed to find, which are the most influential for optimizing the printing process.

Experimental Setup

Sample Preparation

The experiment was conducted by using a newly developed three-axis 3D printer with a more accurate lead screw specifically designed for this research as shown in Figure 1. The open-source software Repetier-Host, which is freely available online, was used for this work.

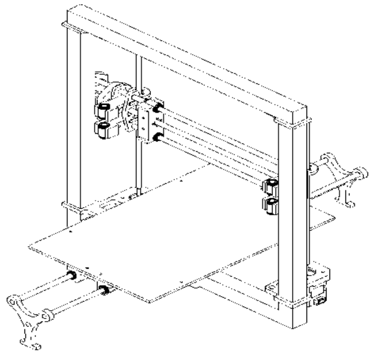


Figure 1: Three-axis 3D printer

A sample was designed by using Autodesk Inventor (Autodesk, USA) and comprised a 20 × 20 × 5 mm^3 rectangular cuboid (refer Figure 2) converted into standard triangular language (STL) format. Various process parameters were fixed throughout the experiment at the values given in Table 1.

Table 1: Parameters held constant throughout the experiment

Parameters	**Description**
Nozzle diameter	0.3 mm
Shell thickness	1.2 mm
Bead temperature	45°C

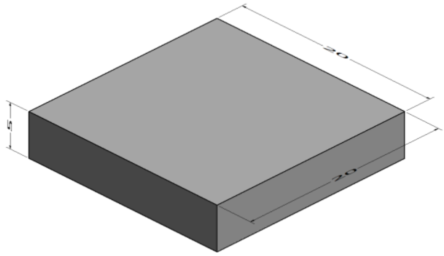


Figure 2: Specimen used for surface-roughness test

Materials and Method

White PLA with a diameter of 1.75 mm was used. The specimen was fabricated with all parameter combinations considered by using Taguchi's 3^5 design-of-experiment method with an orthogonal array of L27 was implemented in Minitab 16.0 software (Minitab, USA), which gave a total of 27 experiments. The parameters were varied as shown in Table 2.

Table 2: Five parameters varied for measuring surface roughness

Layer thickness (mm)	**Raster angle (degrees)**	**Percentage infill (%)**	**Liquefier temperatur e (°C)**	**Printing speed (mm/s)**
0.2	90	20	200	60
0.3	70	60	230	80
0.4	45	100	260	100

Surface-roughness Measurements

To measure the surface roughness, we used a Perthometer S2 PGK (Mahr, Germany) surface analyzer as shown in Figure 3. To ensure consistent data, three readings were taken, each at three different spots on the sample surface.

Figure 3: Surface analyzer for measuring surface roughness (Perthometer S2 PGK)

Results and Discussion

A total of 27 3D samples were printed with all five parameters varied as indicated in Table 2. The arithmetic average of the roughness profile (Ra) of all the samples was measured and recorded for later analysis. Figure 4 shows the raster variation of the printed parts.

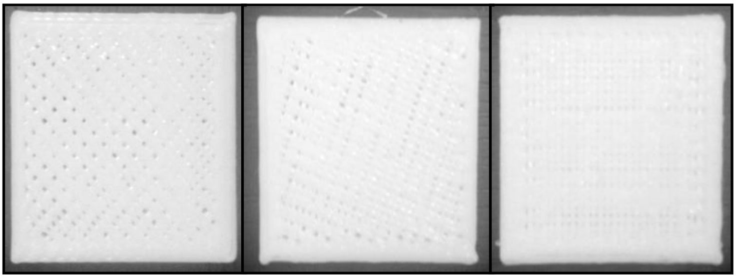
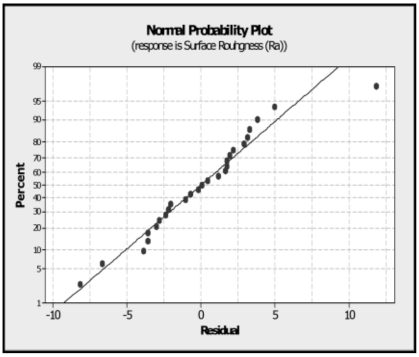


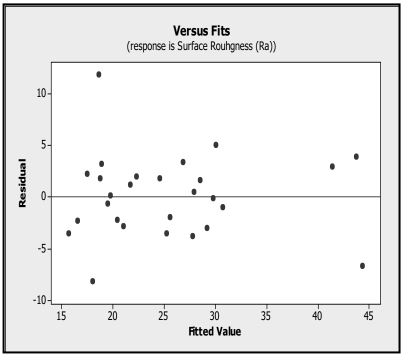
Figure 4: Samples made with raster angle (from left to right) 45°, 70°, and 90°

Analysis of variance

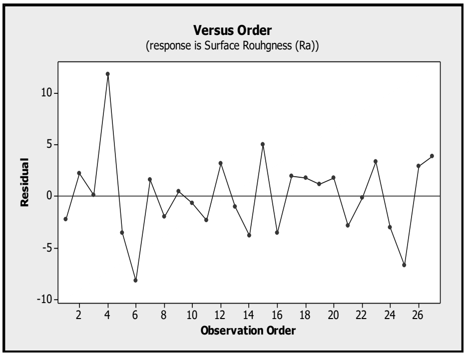
Figures 5(a) and 5(b) show a normal probability plot and residual versus fit, respectively. These show a normal distribution plot and random scatter of the residual, the latter of which shows a non pattern about the zero. Figure 5(c) shows residual versus order and shows that the assumption of randomly scattered data is satisfied.



(a)



(b)



(c)

Figure 5: (a) Normal probability plot; (b) Residual versus fits; (c) Residual versus order

Figure 6 shows the mean function of all the process parameters involved in this study. Meanwhile, Table 3 shows the result of analysis of variance and the result show that the raster angle is a dominant parameter (*p*-value = 0.000) for determining surface roughness, which is consistent with previous results [9, 10]. The parameter "liquefier temperature" is also significant for the surface roughness (*p*-value = 0.003), and the liquefier temperature of 200°C gives the highest Ra. The liquefier temperature must be carefully monitored to determine the optimum temperature for printing. The effect of printing temperature was observed by imaging with a scanning electron microscope (Hitachi SU1510, Japan). If the temperature is too low, the bonding between each layer is affected and the surface finish is rough [cf. Figures 7(a) and 7(b)]. In addition, the road width of each layer becomes inconsistent if the liquefier does not sufficiently heat the filament. However, if the temperature is much higher than it should be, the road width causes expansion, as shown in Figures 7(c) and7(d), and this phenomenon affects the accuracy of the final product. Based on this analysis, 230°C is the optimum temperature because it gives the lowest Ra as shown Figure 8(a). The layer thickness also shows a significant impact on surface roughness (*p*-value = 0.003) which also consistent with the previous result [11]. Table 4 shows the S/N ratio values for the experiment by factor level. The result found that the raster angle (B) is the main contribution affecting the surface roughness followed by liquefier temperature (D), layer thickness (A), printing speed (E), and percentage infill (C).

Table 3: Results of analysis of variance

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	***p*-value**
Layer Thickness (mm) (A)	2	426.58	426.58	213.29	8.26	0.003
Raster Angle (degree) (B)	2	668.33	668.33	334.17	12.95	0.000
Percentage Infill (C)	2	27.63	27.63	13.82	0.54	0.596
Liquefier Temperature (Celcius) (D)	2	453.93	453.93	226.96	8.79	0.003
Printing Speed (mm/s) (E)	2	43.37	43.37	21.69	0.84	0.450
Error	16	412.94	412.94	25.81		
Total	26	2032.78				

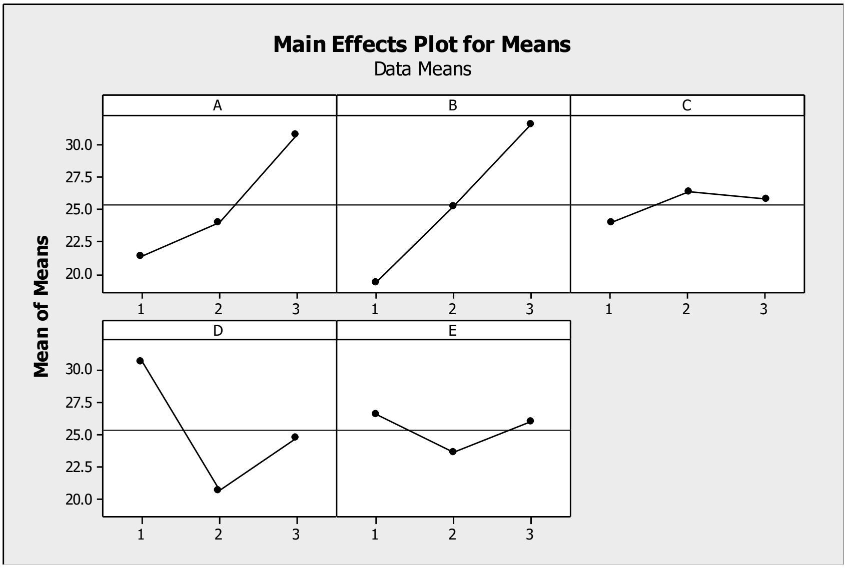


Figure 6: (A) Mean as a function of layer thickness; (B) Mean as a function of raster angle; (C) Mean as a function of percentage infill; (D) Mean as a function of extruder temperature; (E) mean as a function of printing speed

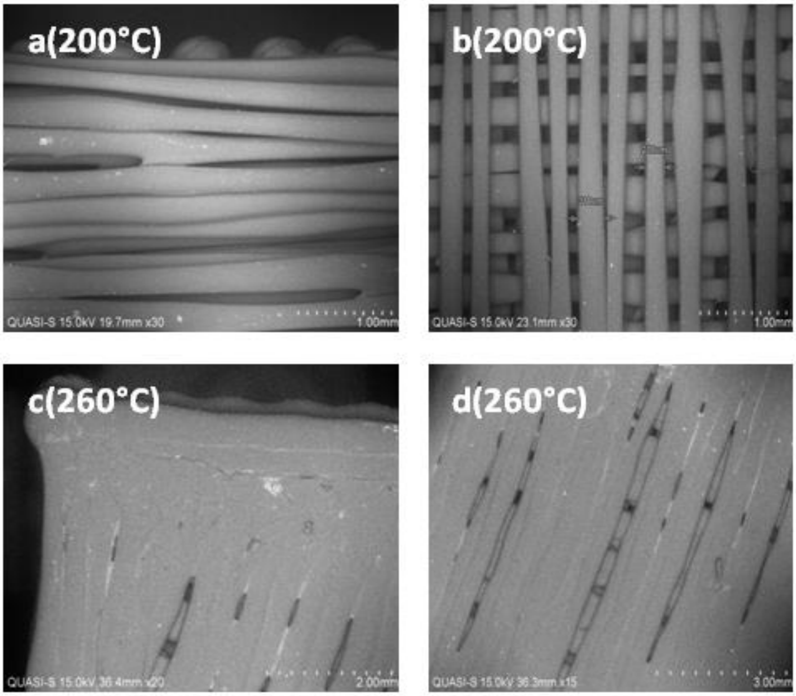


Figure 7: Finished parts made at different temperatures

Table 4: S/N ratio values for the experiment by factor level

Level	A	B	C	D	E
1	21.35	19.36	23.97	30.66	26.56
2	23.97	25.20	26.33	20.67	23.61
3	30.78	31.54	25.81	24.78	25.94
Delta	9.43	12.18	2.36	9.99	2.94
Rank	3	1	5	2	4

The other parameters, including printing speed and percentage infill, do not significantly affect the surface roughness, which is consistent with previous results [11]. The *p*-value for printing speed and percent infill is 0.450 and 0.596 respectively.

Optimum parameters

Based on our analysis, the optimum parameters include a raster angle of 90° to optimize the surface finish. This factor is statistically dominant, as seen from the results presented in Table 3. Figure 9 shows that the optimum extruder temperature is 230°C, but a more accurate evaluation may be obtained by varying the temperature from 210°C to 250°C. Layer thickness should be set to a low value to obtain a smoother surface finish; in this case, we used 0.2 mm. However, surface finish also depends upon the nozzle; different nozzles have different tip diameters and die angles, and these factors affect the stability and the accuracy of the extrusion process. Another research has addressed the stability of the extrusion process by analyzing the die angle of the material being extruded [12].

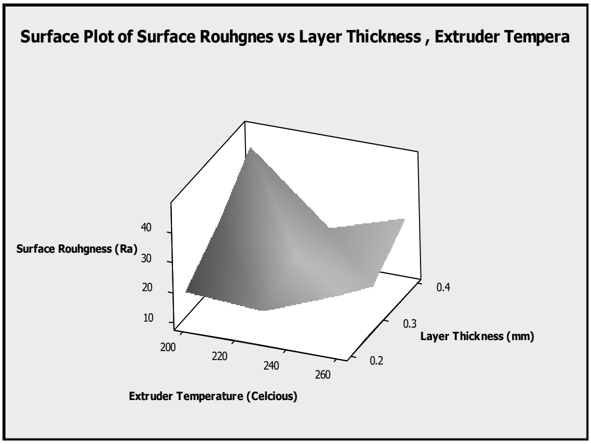


Figure 9: 3D surface plot of surface roughness as a function of layer thickness and extruder temperature

Parts with a fine finish are obtained by tuning the factors mentioned above, which leads to the finish shown by scanning electron microscopy in Figure 9.

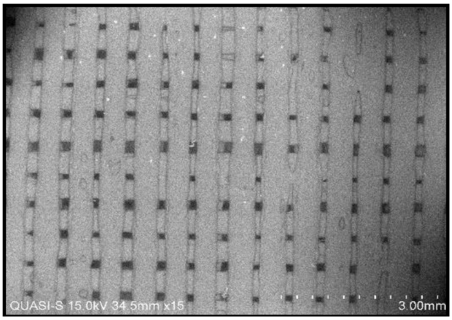


Figure 10: Scanning electron microscopy image of fine finish obtained with optimum parameters

Conclusion

All parameters of the 3D printing process were analyzed to obtain optimum results. Based on our analysis, the raster angle, extruder temperature and layer thickness exert the strongest influence on the surface roughness of the final pieces. The other two parameters which are printing speed, and percentage infill not significantly affect the surface roughness. Finally, tuning the right parameters will have fine and smooth surface finish.

Acknowledgements

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References

[1] Crump, S. S., "Apparatus and method for creating three-dimensional objects. " U.S. Patent 5,121,329, issued June 9, 1992.

[2] Gibson, I., Rosen, D. W., and Stucker, B., Additive Manufacturing Technologies. Springer New york Heidelberg Dordrecht London, 2010.

[3] Wohlers, T. and Gornet, T., "History of additive manufacturing Introduction of non-SL systems Introduction of low-cost 3D printers," Wohlers Rep. 2011, pp. 1–23, 2011.

[4] Turner, B. N., Strong, R., and Gold, S. A., "A review of melt extrusion additive manufacturing processes: I. Process design and modeling," Rapid Prototyp. J., vol. 20, no. 3, pp. 192–204, 2014.

[5] Roberson, D. A., Espalin, D., and Wicker, R. B., "3D printer selection: A decision-making evaluation and ranking model," Virtual Phys. Prototyp., vol. 8, no. 3, pp. 201–212, 2013.

[6] Melenka, G. W., Schofield, J. S., Dawson, M. R., and Carey, J. P., "Evaluation of dimensional accuracy and material properties of the MakerBot 3D desktop printer," Rapid Prototyp. J., vol. 21, no. 5, pp. 618–627, 2015.

[7] Lanzotti, A., Grasso, M., Staiano, G., and Martorelli, M., "The impact of process parameters on mechanical properties of parts fabricated in PLA with an open-source 3-D printer," Rapid Prototyp. J., vol. 21, no. 5, pp. 604–617, 2015.

[8] C. Mendonsa, K. V Naveen, P. Upadhyaya, and V. D. Shenoy, "Influence of FDM Process Parameters on Build Time Using Taguchi and ANOVA Approach," Inetrnational J. Sci. Res., vol. 4, no. 2, pp. 2013–2016, 2015.

[9] Vasudevarao, B., Natarajan, D. P., and Henderson, M., "Sensitivity of Rp Surface Finish To Process," Solid Free. Fabr. Proc., pp. 251–258, 2000.
[10] Kaji, F. and Barari, A., Evaluation of the Surface Roughness of Additive Manufacturing Parts Based on the Modelling of Cusp Geometry. IFAC-PapersOnLine, vol. 48, no. 3, pp.658–663, 2015.
[11] Akande, S. O., "Dimensional Accuracy and Surface Finish Optimization of Fused Deposition Modelling Parts using Desirability Function Analysis," vol. 4, no. 04, pp. 196–202, 2015.
[12] Sukindar, N. A., Ariffin, M., and Anuar, M. K., An Analysis on Finding the Optimum Die Angle of Polylactic Acid in Fused Deposition Modelling. Applied Mechanics & Materials, no. 835, 2016.