OPTIMIZING SURFACE QUALITY AND PROCESSING TIME OF 3D PRINTED POLYLACTIC ACID MATERIAL FOR RAPID TOOLING

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ABSTRACT*: The 3D printing process has been implemented in rapid tooling processes including manufacturing the casting pattern. The pattern must have a surface roughness value as small as possible to reduce the costs of the finishing process. In addition, the printing time must be as short as possible to reduce the production cost. Therefore, the parameters of 3D printing that influence surface roughness and printing time need to be investigated and optimized. The investigated parameters are layer thickness, printing speed, and extrusion temperature. The Taguchi-Gray Relational Analysis using an orthogonal array L9 is implemented as the optimization method in this research. The optimal parameter combination that results in the lowest surface roughness and printing time is obtained at an extruder temperature of 240°C, a printing speed of 20 mm/s, and a layer thickness of 0.06 mm. The printing speed contributes 73,3% of the total parameter contribution and the layer thickness contributed 18 %. Meanwhile, the extruder temperature contributed the least to both responses.*

KEYWORDS: *optimization, surface roughness, printing time, 3D printing, PLA*

1 INTRODUCTION

The 3D printing process has been implemented in various industries for rapid prototyping and rapid tooling. The process can be used in casting for rapid tooling processes, such as pattern making. It can be used as a substitute for subtractive manufacturing to build the patterns in the casting process. The pattern for the casting process must have a surface roughness value as small as possible to reduce the costs of the finishing process. In addition, the printing time must be as short as possible to reduce the production cost. Various parameters of subtractive manufacturing that affect the surface roughness and the required time have been investigated and optimized (Suteja, 2016, Suteja and Hadiyat, 2019). As 3D printing also brings many benefits in making casting patterns, the parameters of 3D printing that influence surface roughness and printing time need to be investigated.

The surface roughness of the pattern printed by using the 3D printing process is influenced by various process parameters. The parameters that influence the surface roughness are layer thickness (Alsoufi, El-Sayed and Elsayed, 2017, Pérez et al., 2018, Kovan V et al., 2018, Buj-Corral, Bagheri and Sivatte-Adroer, 2021, Buj-Corral, Sánchez-Casas and Luis-Pérez, 2021, Taşdemir, 2021, Kholil et al., 2022, Terephthalate et al., 2023), nozzle diameter (Alsoufi, El-Sayed and Elsayed, 2017, Buj-Corral, Sánchez-Casas and Luis-Pérez, 2021), wall thickness (Pérez et al., 2018, Taşdemir, 2021), infill angle (Buj-Corral, Domínguez-Fernández and Durán-Llucià, 2019, Christodoulou et al., 2022, Milde et al., 2021, Kholil et al., 2022, Terephthalate et al., 2023), ironing (Butt, Bhaskar and Mohaghegh, 2022), build orientation (Christodoulou et al., 2022, Milde et al., 2021), bed temperature (R, R and S, 2021), retraction speed (Jackson, Fouladi and Eslami, 2022), and material (Alsoufi and Elsayed, 2018). Based on the result of the previous research, the layer thickness and nozzle diameter have the most significant effect on the surface roughness. Thin layer thickness produces a smoother surface roughness than a thick one when measured diagonally across the building direction. Nozzle diameter affects the surface roughness similar to the layer thickness. Using a large nozzle diameter reduces the surface quality.

The 3D process parameter also affects the required printing time. The influenced parameters are layer thickness (Alsoufi, El-Sayed and Elsayed, 2017, Vyavahare, Kumar and Panghal, 2020, Nguyen et al., 2020, Jaisingh Sheoran and Kumar, 2020, Sai, Pathak and Srivastava, 2020, Moradi, Meiabadi and Kaplan, 2019, Dey, Hoffman and Yodo, 2020, Sumalatha, Malleswara Rao and Supraja Reddy, 2021), nozzle diameter (Alsoufi, El-Sayed and Elsayed, 2017), wall thickness(Vyavahare, Kumar and Panghal, 2020), infill pattern (Derise and Zulkharnain, 2020, Sai, Pathak and Srivastava, 2020), infill angle (Jaisingh Sheoran and Kumar, 2020, Sai, Pathak and Srivastava, 2020), infill density (Jaisingh Sheoran and Kumar, 2020, Sai, Pathak and Srivastava, 2020, Moradi, Meiabadi and Kaplan, 2019, Derise and Zulkharnain, 2020, Dey, Hoffman and Yodo, 2020, Sumalatha, Malleswara Rao and Supraja Reddy, 2021), ironing (Butt, Bhaskar and Mohaghegh, 2022), build orientation (Vyavahare, Kumar and Panghal, 2020, Dey, Hoffman and Yodo, 2020), and printing speed (Vyavahare, Kumar and Panghal, 2020, Nguyen et al., 2020, Sumalatha, Malleswara Rao and Supraja Reddy, 2021). Layer thickness and printing speed influence the printing time significantly. Thinner layer thickness requires a longer processing time. Meanwhile, the faster the printing process, the shorter the time required.

Surface roughness and printing time contradict to each other. Shorter printing time decreases the surface quality of the printed part as it increases the surface roughness (Pérez et al., 2018, Buj-Corral, Bagheri and Sivatte-Adroer, 2021, Buj-Corral, Sánchez-Casas and Luis-Pérez, 2021, Terephthalate et al., 2023). On the opposite, a lower surface roughness requires a longer printing time. Therefore, finding the optimum parameter to achieve the shortest printing time and the lower surface roughness is crucial. As layer thickness significantly affects both the printing time and surface roughness, this research investigates layer thickness as one of the controlled variables. The other controlled variable of this research is printing speed. The printing speed must be as high as possible to reduce the cost. However, faster printing speed increases the width of the profile formed between raster and increases the surface roughness (Jain et al., 2021).

Various research has investigated the influence of extrusion temperature on surface roughness (Pérez et al., 2018, Kovan V et al., 2018, Buj-Corral, Bagheri and Sivatte-Adroer, 2021, Buj-Corral, Sánchez-Casas and Luis-Pérez, 2021, Terephthalate et al., 2023, Jiang et al., 2022). Jiang et al. investigated the influence of layer thickness in the range of 0.1 to 0.2 mm and extrusion temperature between 190 °C to 210 °C (Jiang et al., 2022). When the extrusion temperature is increased, the surface roughness will be decreased. In contrast, a literature review by Sheoran et al. shows that low extrusion temperature increases surface roughness (Jaisingh Sheoran and Kumar, 2020). For that reason, this research investigates the influence of extruder temperature on surface roughness, especially for high extruder temperatures.

2 METHODOLOGY

ANET A8 3D Printer Prusa I3 as shown in Figure 1 is used to perform the printing process in this research. It is manufactured by Shenzhen Anet Technology Co., Ltd., with a print area of 220 mm x 220 mm x 240 mm. The printer has extruder equipment with a 0.4 mm nozzle diameter. It is used to print Polylactic Acid (PLA) material. The material is prefabricated into a filament shape with a diameter of 1.75 mm before it is extruded through the nozzle. Slic3r Prusa software, developed by Prusa Research, and Repetier-Host software, developed by Hot-World GmbH & Co. KG, are implemented to generate the printing path of the nozzle. Both are also used to set the 3D printing process parameters.

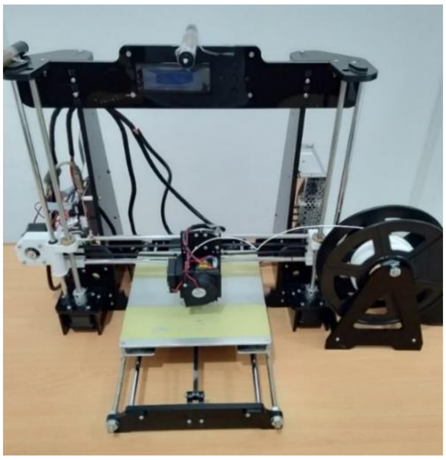

Fig. 1 ANET A8 3D Printer Prusa

This research aims to determine the values of layer thickness, printing parameter, and extruder temperature to achieve the optimum surface roughness and printing time. First, a preliminary experiment is conducted to determine the parameter levels of the main experiment. Then, the main experiment is performed to investigate three controlled 3D printing parameters with three different levels of each parameter, as shown in Table 1. Other process parameters are set as constant values, as shown in Table 2. The Taguchi-Gray Relational Analysis using an orthogonal array L9 is implemented as the optimization method in this research. This method was applied because it reduces the number of experiments and can achieve multi-objective optimization (Lin, Hung and Tan, 2021, Huang et al., 2022). The investigated dependent parameters in this experiment are surface roughness and printing time. The experiment is repeated twice to test its validity. In total, nine times two experimental runs have been conducted that combine three parameters with three levels. Finally, a confirmation experiment was carried out to validate the optimization results.

Based on the preliminary experiment, the extruder temperature levels for PLA used in this research are 200°C, 220°C, and 240°C. The minimum value is set based on the temperature used in the previous studies that can achieve low surface roughness. The maximum value is selected as higher temperature results in the irregular shape, concave or convex corners, and non-flat surfaces of the printed part. The printing speed levels used are 20 mm/s, 25 mm/s, and 30 mm/s; lower speed increases the required printing time. On the contrary, higher speed creates concave or convex corners and non-flat surfaces of the printed part. The layer thickness level used is 0.06 mm, 0.08 mm, and 0.1 mm. Using layer thickness higher than 0.1 mm cannot be used in combination with high extruder temperature. This combination builds the irregular shape, concave or convex corners, and non-flat surfaces of the printed part.

Table 1. Value of controlled parameter's level

Parameter	**Level**		
	Low	**Middle**	**High**
Temperature (°C)	200	220	240
Printing Speed (mm/s)	20	25	30
Layer Thickness (mm)	0.06	0.08	0.1

Table 2. Value of constant parameter

Parameter	**Value**
Number of outer shell layers	3
Layer width (mm)	0.4
External Infill pattern	Rectangular
Infill angle (°)	45
Infill density (%)	20
Bed temperature (° C)	55

Eighteen specimens according to the number of conducted experimental runs are printed using the 3D printer. The shape and dimensions of each specimen are shown in Figure 2. Each specimen's surface roughness value is measured using a Mitutoyo Surftest SJ-210 portable surface roughness tester. The surface roughness measurement is conducted according to ISO 4288 using a 2.5 mm maximum sample length. The measurement is performed only on the six vertical surfaces of each specimen. The direction of the measurement is perpendicular to the printing direction shown in Figure 3. Then, all vertical surface roughness values of each specimen are averaged. The printing time to build each specimen is measured using a stopwatch with 0.1 seconds of accuracy. The printing time is measured from when the nozzle reaches the bed until the full specimen is printed.

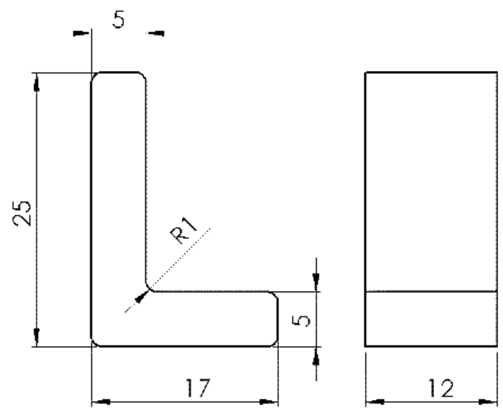

Fig. 2 Shape and dimensions of the specimen

3 RESULTS AND DISCUSSIONS

The surface roughness and printing time value of each specimen are shown in Table 3. Based on the results, the extruder temperature does not significantly affect the printing time. However, the extruder temperature influences the surface roughness. The higher the extruder temperature, the higher the surface roughness. Next, the printing speed significantly affects the surface roughness and printing time. The faster the printing speed, the required printing time decreases. Faster printing speed results in lower surface roughness. Last, the layer thickness also influences both responses. Higher layer thickness reduces the printing time. The layer thickness has a varied effect on surface roughness. The effect of the layer thickness is not linearly related to the average surface roughness. In addition, the combination of extruder temperature, printing speed, and layer thickness has various impacts on the printing time and surface roughness.

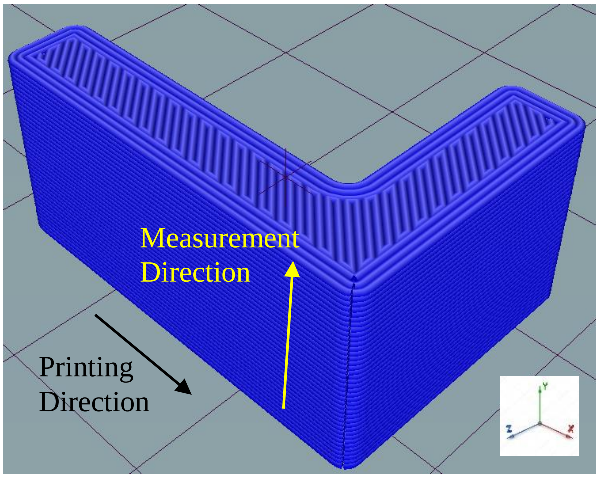

Fig. 3 The Direction of the Measurement

Table 3. Experiment Results

Extruder Temperature (°C)	**Printing Speed (mm/s)**	**Layer Thickness (mm)**	**Printing Time (s)**	**Surface Roughness (μm)**
200	20	0.06	4.522	13.527
200	25	0.08	2.795	9.849
200	30	0.10	1.945	12.139
220	20	0.08	3.421	16.383
220	25	0.10	2.252	13.937
220	30	0.06	3.136	12.595
240	20	0.10	2.758	18.472
240	25	0.06	3.688	15.424
240	30	0.08	2.397	12.730

Based on the results of the Taguchi-Grey Relational method, the optimum parameters to achieve the lowest surface roughness and printing time are shown in Table 4. The results indicate that the optimal process parameter combination is at TE Level 3, PS Level 1, and LT Level 1. TE Level 3 means the temperature extruder at the highest level, 240 °C. PS Level 1 refers to the lowest value of the optimum printing speed, which is 20 mm/s. And LT Level 1 is the lowest layer thickness level, 0.06 mm. The optimization result shows that a high extruder temperature that is combined with the thin layer thickness and slower printing speed generates the optimum surface roughness and printing time. Based on the literature, increasing the extrusion temperature will reduce the material's viscosity. For a thin layer thickness, the bonding between layers increases and the surface profile height decreases. Even though the thin layer thickness and slower printing speed increase the required time, the high extruder temperature decreases the surface roughness. As a result, the parameter combination achieves the optimum surface roughness and printing time.

Then, an analysis of variant (ANOVA) method is conducted to determine the degree of the influence of the 3D printing parameters on the combination of both responses. The result of the ANOVA is shown in Table 5 below. As shown in Table 5, the printing speed contributes the most to the combination of both responses. The printing speed contributes 73,3% of the total parameter contribution. The layer thickness contributed 18 %. And the extruder temperature contributed the least to both responses. As the extruder temperature does not have any influence on the response time, it does not significantly influence the combination of both responses. The optimization results have been validated by conducting the confirmation experiment.

Table 4. Grey Relational Grade Response

Parameters	**Level 1**	**Level 2**	**Level 3**	**Effect**	**Rank**	**Optimum Parameters**
Temperature Extruder (TE)	0.511	0.536	0.605	0.094	3	TE Level 3
Printing Speed (PS)	0.715	0.502	0.434	0.281	1	PS Level 1
Layer Thickness (LT)	0.633	0.497	0.521	0.112	2	LT Level 1

Table 5. Analysis of Variant

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**Contri-bution**
Extruder Temperature	2	0.014138	0.007069	12.62	8,067%
Printing Speed	2	0.128413	0.064206	114.67	73,279%
Layer Height	2	0.031566	0.015783	28.19	18,013%
Error	2	0.001120	0.000560		0,641%
Total	8	0.175237			100%

4 CONCLUSION

This study employed a hybrid Taguchi-Gray Relational Analysis method using an orthogonal array L9 to optimize the 3D printing process to improve the quality of the printed part and reduce the required time to manufacture the printed part. The results of the Taguchi-Gray Relational Analysis method indicate that the optimal parameter combination that results in the lowest surface roughness and printing time is obtained at an extruder temperature of 240°C, a printing speed of 20 mm/s, and a layer thickness of 0.06 mm. The printing speed has the most significant effect to surface roughness and printing time compared to other controlled 3D printing parameters. Meanwhile, the extruder temperature has the most minor contribution to both responses.

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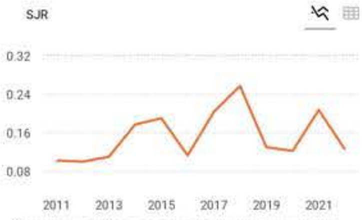

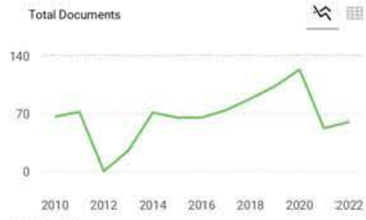

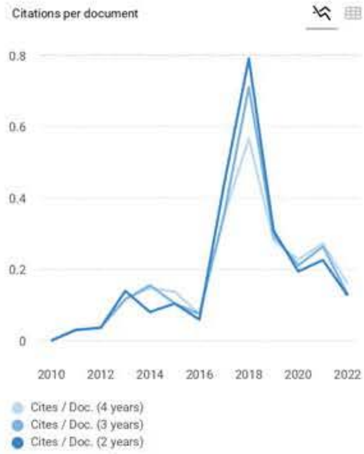

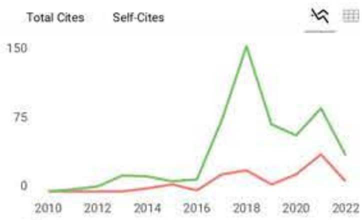

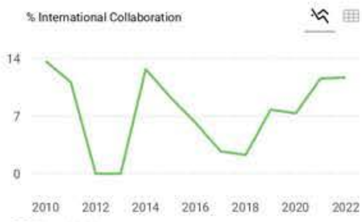

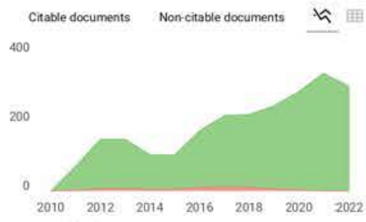

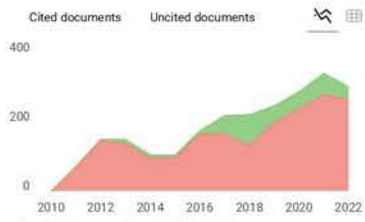

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Best Regards, SCImago Team

K **K Santarao** 4 years ago

Correct website of this journal please

reply

Melanie Ortiz 4 years ago SCImago Team

Dear K Santarao, thank you for contacting us. We will proceed to update the journal's website information as soon as possible. Greetings from Spain and thank you for using the SCImago products, SCImago Team

A **Agus Sudianto** 4 years ago

Dear AJME,

My name is agus sudianto, phd student at UTeM Malaysia. I am interested to submit my paper to your house. Kindly please give me an information regarding time duration from the due date submitted of paper till journal publishing, and cost of journal.
Thank you very much for your attention and cooperation.

Kind regards,
Agus Sudianto

reply

A **Arun** 4 years ago

Dear Sir,

I want to submit a manuscript. What is the procedure?

Regards.

reply

SCImago Team

Melanie Ortiz 4 years ago

Dear Arun, thank you very much for your comment, we suggest you look for author's instructions/submission guidelines in the journal's website. Best Regards, SCImago Team

A **Ayanesh Joshi** 5 years ago

Dear i have send a review article for publication on 2nd Feb. 2019. I have still not received any correspondence from you side regarding the same. Pl. update me for the same.

reply

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Academic Journal of Manufacturing Engineering

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Publisher: Editura Politehnica
ISSN: 1583-7904

Subject area: Engineering: Industrial and Manufacturing Engineering

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