

INVESTIGATION OF SURFACE ROUGHNESS OF PLA CARBON FIBRE PRINTED USING FUSED DEPOSITION MODELLING

Nor Aiman Sukindar^{1*}, Muhammad Asyraf Murad², Ahmad Shah Hizam Md Yasir³,
Sharifah Imihezri Syed Shaharuddin², Mohamad Nor Hafiz Jamil²,
Nor Farah Huda Abd Halim², Mohamad Talhah Al Hafiz Mohd Khata²,

¹School of Design, Universiti Teknologi Brunei, Tungku Highway, Gadong BE1410,
Brunei Darussalam.

²Manufacturing and Materials Department, International Islamic University Malaysia, 53100
Gombak, Selangor, Malaysia.

³Faculty of Resilience Rabdan Academy, 65, Al Inshirah, Al Sa'adah, Abu Dhabi, 22401, PO
Box: 114646, Abu Dhabi, UAE.

*noraimansukindar@gmail.com

Abstract. Polylactic Acid (PLA) infused with carbon fiber represents a significant advancement in 3D printing materials, combining PLA's biodegradability and ease of use with the enhanced strength and stiffness provided by carbon fiber. This composite material exhibits improved mechanical properties and thermal resistance, making it ideal for creating durable, high-performance parts with fused deposition modelling (FDM). FDM method is one of the popular 3D printing techniques currently being used. However, numerous factors such as printing parameters can affect the quality of the product fabricated using this method. There are a lot of printing parameters that need to be investigated to achieve the desired surface quality and accuracy. In this research, three parameters were selected; printing temperature, infill density, and printing speed with three different levels to analyse their effect on the surface roughness. By manipulating the three printing parameters, a total of 9 runs were executed. For each run, three samples were fabricated to get a consistent result. The Taguchi method was applied for the designing of the experiment and analysis was done based on analysis of variance (ANOVA). The best printing parameters were used to print the sample for the dimensional accuracy test. From the research, it was found that printing temperature significantly affects the surface roughness. Meanwhile for the dimensional accuracy, by using the best printing parameter found from surface roughness testing, most of the measured parameters have a percentage of deviation lower than 5%. By optimizing the printing parameters, parts with high-quality prints using PLA carbon fibre filament can be produced.

Keywords: Fused deposition modelling, PLA, carbon fiber, surface roughness, dimensional accuracy

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1. INTRODUCTION

3D printing is a common term used for a wide range of additive-based technologies. The principle of additive-based technologies is to create an object layer by layer from bottom to top. Currently, 3D printing is being widely utilized in almost all industries such as the food industry, medical industry, and even fashion industry. The development of additive manufacturing has led to the birth of many 3D printing techniques such as stereolithography (SLA), selective laser sintering (SLS), 3D plotting, fused deposition modelling (FDM) and PolyJet modelling. These 3D printing techniques can be methodically grouped according to the type of input materials used. For instance, SLS and FDM are respectively grouped under the powder-based method and solid-based method [1].

FDM, also called fused filament fabrication (FFF) has been one of the most widespread techniques used in additive manufacturing [2]. FDM can be used to create models, prototypes, and final products using polymeric-based material. The process in FDM can be influenced by several parameters such as printing orientation, infill density, layer thickness, raster orientation, temperature, printing speed, and the number of shells. Therefore, controlling the parameters is important to achieve accurately printed models with good mechanical properties [3]. The FDM method utilizes polymeric-based filaments that are melted and extruded through a moving nozzle to build up the object layer by layer. The nozzle is moved around by a computer-controlled system, following a path determined by the 3D model of the object being printed. As the nozzle moves, it deposits a thin layer of molten plastic on the build platform. Once this layer has been laid down, the build platform is lowered by a single layer height, and the process is repeated until the entire object is completely built [4]. According to Mwema et al. [5], the FDM process is relatively simple and inexpensive, making it a popular choice for home 3D printing enthusiasts. However, the finished objects tend to have lower resolution and poor surface finish compared to objects produced using other 3D printing technologies.

Polylactic acid (PLA) is a semi-crystalline thermoplastic that has been identified as having increasing potential in FDM. However, the application of pure thermoplastic materials is not recommended at the mature prototype development stage due to its insufficient mechanical strength. This has prevented FDM-built items from being used in industrial applications as fully functional, load-bearing parts. To overcome these drawbacks, it is imperative to increase the strength of pure thermoplastic parts produced using FDM by adding reinforcement materials such as fibre, ceramic, metal, and nanomaterial. Some examples of PLA composites that have been developed are continuous fibre-reinforced thermoplastic composites (CFRTPCs) and hydroxyapatite (HA) [6].

Continuous fibre-reinforced thermoplastic composites can be used as a replacement for traditional polymers and metals. Recently, carbon fibres (CF) have been a leading rival in the market [7] due to their high strength-to-weight ratio. CF also offers a more affordable alternative to more expensive materials like titanium. These materials can be used to make lightweight structures with outstanding mechanical performance. Li et al. [8] used the rapid prototyping method of 3D printing to create continuous carbon fibre-reinforced polylactic acid composite parts. Due to the weak bonding interface between carbon fibre and PLA, pre-processing of carbon fibres was done by adding methylene dichloride solution to partially dissolved PLA particles. The results showed an increase in the interfacial strength. In addition, the tensile and flexural strengths were, respectively, 13.8% and 164.4% higher than plain carbon fibre-reinforced samples [9].

FDM printed part's accuracy is affected by its poor surface characteristics. Radhwan et al. [10] study using analysis of variances (ANOVA) study showed that low layer thickness, slow printing, and low fill density are effective ways to lessen surface roughness. Researchers have investigated the dimensional accuracy of parts produced by various FDM machines. These findings are complemented by Syrlybayev et al. [11], who highlighted that part qualities are significantly influenced by process parameters such as infill density, layer thickness, and extrusion temperature, emphasizing the critical role of infill density in enhancing mechanical properties and surface quality of FDM printed parts.

Bakar et al. [12] investigated the machine's capacity to produce parts using various machine-available process settings, namely the FDM Prodigy Plus (Stratasys, USA). The analysis was centered on the FDM machines' capacity to manufacture the typical plastic part design elements. The study focus on investigation of surface quality and dimensional accuracy. This study concluded that when creating circular shapes, the FDM machine is less accurate since considerable deviations occurred that ranged from 0.1 mm to 0.2 mm radial distances. This is a result of the deposition head's movement being restricted by the gantry system. FDM printed features measured along the z-axis, are found to be within tolerance value with deviation of 0.3 mm.

According to Beniak et al. [13], there is a significant effect of printing temperature on the shape and dimensional tolerance of FDM-produced items. At high printing temperatures, the material becomes less viscous and flows easily sideways. Compared to specimens produced at lower printing temperatures, the dimensions and tolerances are less precise. The specimens with the highest printing temperatures have the worse surface quality, which also results in the lowest tolerances. Similarly, Anerao et al. [14] investigated the influence of FDM process parameters on the mechanical properties of 3D-printed bio composites, indicating that careful optimization of printing speed, infill density, and temperature can lead to improvements in surface finish and overall part quality

Layer height also affects the surface quality which shows that lower layer height contributes to a better surface finish. In addition to using thin layers, it is advised to use appropriate values of contour width and internal raster when creating small parts that need a decent surface finish. This investigation shows that both criteria can improve the surface quality and the bonding quality between layers [15]. A similar study has been done to investigate the effect of printing parameters on printing acrylonitrile butadiene styrene (ABS) and it was shown that the lesser printing speed enhances the surface finish of the printed parts [16].

The focus of this project is to analyses and determines the best value for different 3D printing parameters that produce low surface roughness. The material used for this study was PLA carbon fibre filament and the samples were printed using FDM (Artillery Sidewinder). The effect of printing parameters on surface roughness particularly layer thickness, printing temperature, and printing speed were analyzed using analysis of variance (ANOVA). Based on the ANOVA results, the best printing parameters were identified and were used for the dimensional accuracy test.

2. MATERIALS AND METHODS

The Taguchi method was employed for the design of the experiment (DOE) for the surface roughness test. Table 1 shows the experimental module while Figure 1 shows the design sample.

Table 1: Taguchi experimental module

Run	Control Factor and Levels		
	Layer thickness (mm)	Printing Temperature (°C)	Printing Speed (mm s ⁻¹)
1	0.1	180	30
2	0.1	210	60
3	0.1	240	90
4	0.2	180	60
5	0.2	210	90
6	0.2	240	30
7	0.3	180	90
8	0.3	210	30
9	0.3	240	60

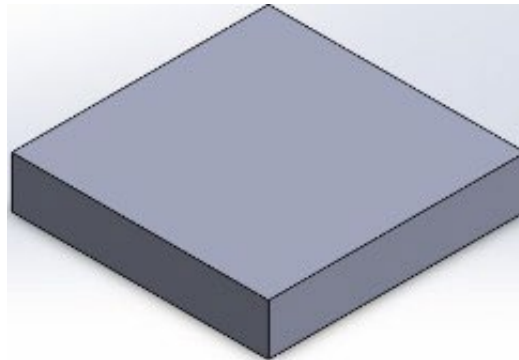


Figure 1: Surface roughness sample (30 x 30 x 3 mm)

For each run, three samples were printed which resulted in a total of 27 samples being printed. Three printing parameters have been manipulated during this run, that are layer thickness, printing temperature and printing speed. Others printing parameters have been kept constant as shown in Table 2. The printing orientation has been kept constant during the experiment run, with the largest surface area of the sample made facing the printing bed, as shown in Figure 1. The R_A value for each run was taken from the average of three readings of the sample. The R_a value measures surface roughness, calculating the average height deviations from the mean line over a specified area. Lower R_a values indicate smoother surfaces, while higher values denote rougher textures, crucial for assessing part quality and functionality. The optimal value for each parameter (layer thickness, printing temperature, printing speed) was determined using ANOVA and used to print samples for dimensional accuracy tests.

The geometrical product specification for the dimensional accuracy test samples were based on Mahesh et al. [17] which considered the following standards, ISO 12780 (measure straightness), ISO 12181 (measure roundness), ISO 12781 (measure flatness), and ISO 12180 (measure cylindricity). Figures 2 and 3 show the overall dimension of the specimen drawn using Solidwork 2020 (Dassault Systèmes, France).

Table 2: Printing parameters

Printing parameter	Value
Layer height (mm)	0.1, 0.2, 0.3
Printing temperature (C°)	180, 210, 240
Printing speed (m/s)	30, 60, 90
Infill Density (%)	100
Layer width (mm)	0.4
Wall count	2
Infill pattern	Rectilinear
Build plate temperature (C°)	50
Extrusion flow rate (%)	100

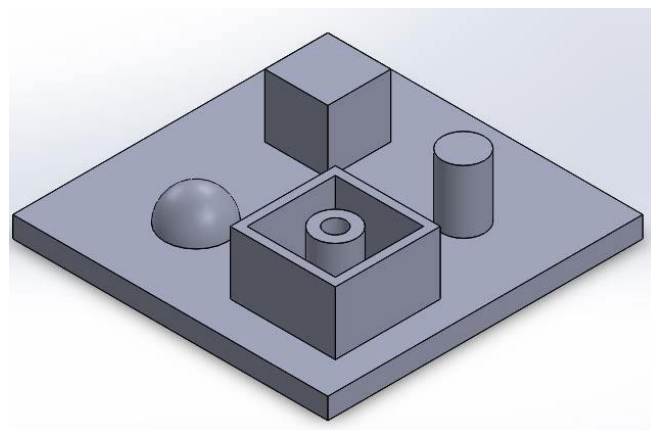


Figure 2: Dimensional accuracy sample design

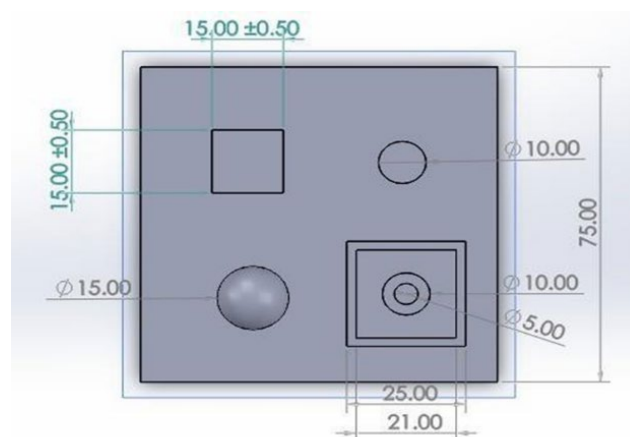


Figure 3: Dimension of dimensional accuracy sample design

2.1 Analysis of Surface Roughness

In this study, the test specimens were fabricated into nine specific shapes. Each specimen had the same dimensions but varied significantly based on the process parameters. The surface roughness was examined using the Alicona optical roughness measurement (IFS-118 Infinite Focus SL).

2.2 Analysis of Dimensional Accuracy

The test specimens were designed with six features which are square base, cube, solid cylinder semi-sphere, hollow cylinder, and hollow square. The dimensional accuracy of each geometric profile was measured using an electronic digital caliper. The readings were taken three times for consistent results and the percentage deviations were then calculated. Table 3 shows the features and the accuracy test that had been done on the features.

Table 3: Features and its accuracy test

Features	Accuracy test
Square base	Linear accuracy
Cube	Linear accuracy
Semi Spheres	Accuracy
Solid cylinder	Repeatability of radius and radial accuracy
Hollow cylinder	Repeatability of radius and radial accuracy
Hollow square	Linear accuracy and linear accuracy of the thin wall built

2.3 Analysis of Structure Observation

In this study, the surface structure of the sample design was analyzed using a scanning electron microscope (SEM) IT 100, to conduct an in-depth examination of the surface structure of the PLA carbon fibre samples produced via FDM (Artillery Sidewinder). This analytical technique was significant in visualizing the microscale surface features that directly influence the roughness and, consequently, the functional properties of the printed objects.

The SEM analysis facilitated a detailed observation of the filament's surface texture, including the distribution and orientation of carbon fibres within the PLA matrix. By magnifying the surface features up to several thousand times identification of specific patterns of deposition, material consistency, and anomalies such as gaps, voids, or agglomerations of carbon fibres have been successfully made. This in-depth microscopic examination assisted in identifying the surface irregularities seen with the printing parameters that were chosen. It was focused on looking at how layer thickness, printing temperature, and printing speed affected the surface structure. The SEM images served as a visual evidence base, supporting the ANOVA results by highlighting how variations in printing parameters manifest at the microstructural level.

3. RESULTS AND DISCUSSION

The samples for surface roughness can be seen in Figure 4 while Table 4 shows the average Ra value for each sample.

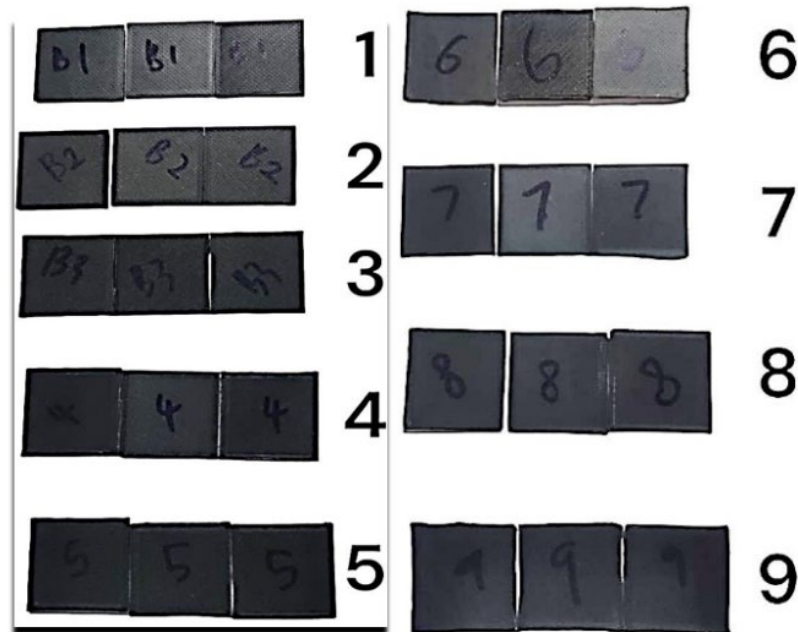


Figure 4: Surface roughness sample

Table 4: Data of average Ra value for each run

Run	Average RA
1	2.2169
2	3.0703
3	5.0611
4	2.8918
5	3.0641
6	5.3026
7	3.7792
8	4.0577
9	4.1771

3.1 Arithmetic Mean Roughness (Ra)

Arithmetic Mean Roughness (Ra) is quantified by averaging the absolute deviations of surface heights from a mean line over a designated length. The Ra values of the FDM-produced samples were precisely measured using an Alicona optical roughness measurement device (IFS-118 Infinite Focus SL). This non-contact optical 3D surface measurement system allowed for a detailed assessment of the topography, delivering high-resolution data of the surface variations which are essential for determining the Ra value.

Employing the Taguchi method, the effect of layer thickness, printing temperature, and printing speed were analysed on Ra values. Based on Table 5, the P value for printing temperature was notably significant at 0.024, suggesting a strong influence on surface roughness. The lowest Ra value which indicates the smoothest surface, was achieved at 180 °C (Run 1) with an Ra value of 2.2169. Although the roughest surface had the highest Ra value of 5.3026, which was seen when the printing temperature was 240 °C (Run 6). These observations from the Alicona optical roughness measurement confirm that a lower printing temperature is pivotal for attaining a smoother surface, with 180 °C emerging as the ideal temperature for optimizing surface finish in FDM processes.

Table 5: Analysis of variance of Ra

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	5.80596	1.93532	3.70	0.097
Layer Thickness	1	0.46247	0.46247	0.88	0.391
Printing Temperature	1	5.32565	5.32565	10.17	0.024
Printing Speed	1	0.01785	0.01785	0.03	0.861
Error	5	2.61881	0.52376		
Total	8	8.42477			

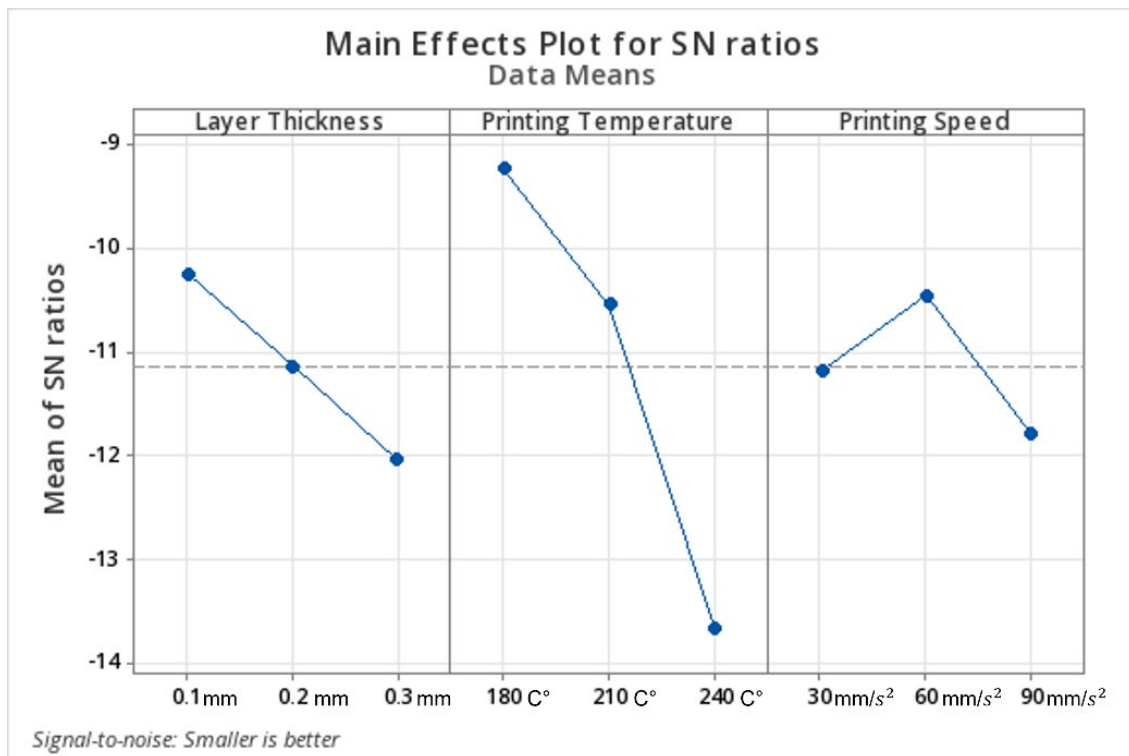
Table 6 show the response for signal-to-noise ratios corresponding to the surface roughness (Ra) value of the printed specimens, which are used to determine the impact of each printing parameter on the final surface quality. The 'Level' values for layer thickness, printing temperature, and printing speed represent the mean signal-to-noise ratios for each factor at different settings. A higher magnitude in these values indicates a more robust performance against noise factors affecting surface roughness.

The 'Delta' value signifies the range within each factor, reflecting the change in the signal-to-noise ratio from the lowest to the highest setting, thereby highlighting the sensitivity of Ra values to that specific parameter. In this context, a larger delta suggests a greater influence of the parameter on the surface roughness. From the delta values, rank was established to the parameters, establishing their relative importance; '1' being the most significant. The printing temperature, with the largest delta of 4.435, ranks as the most influential factor (Rank 1) and is correlated with a significant P value of 0.024 as per Table 5. Layer thickness follows with the second-largest delta of 1.796 and a P value of 0.391 (Rank 2). Printing speed, having the smallest delta of 1.325, is considered the least influential on Ra values, as reflected by its higher P value of 0.861 (Rank 3). This tabulated ranking provides a quantitative basis for determining the primary and secondary factors affecting the surface roughness in FDM processes.

Table 6: Response table for signal-to-noise ratios for Ra

Level	Layer Thickness	Printing Temperature	Printing Speed
1	-10.248	-9.229	-11.190
2	-11.146	-10.545	-10.462
3	-12.044	-13.664	-11.786
Delta	1.796	4.435	1.325
Rank	2	1	3

Figure 5 shows the main effect plot for means for Ra value. From Figure 5, the printing temperature of 180 °C is the best. For layer thickness, 0.1 mm is the best value and for printing speed, 60 mm s⁻¹ is the optimum value. Although layer thickness and printing speed do not have a significant impact on the Ra value according to the P value, a layer thickness of 0.1 mm and a printing speed of 60 mm s⁻¹ were found to help lower the Ra value. At high printing temperatures, the material becomes more fluid and causes a larger spread of the material than anticipated. This condition causes the printed samples to have larger and less defined lines, as different colors and types of PLA have demonstrated variations in surface finishes due to different printing temperatures [18]. The excessive spreading of the material at these elevated temperatures leads to surfaces that are rougher and have more imperfections. As the filament becomes overheated, its ability to retain intricate details diminishes, and fine features and sharp edges are lost. The blending of the melted filament can blur finer details, resulting in a less precise surface finish, a phenomenon also observed when printing speeds and associated temperatures are optimized for ABS polymers [16.] All these factors contribute towards the increase in Ra value.

**Figure 5:** Main effect plot for means for Ra value

Printing at low temperatures can also cause various problems. At low printing temperatures, the filaments do not melt completely, which makes it difficult for the material to flow and cover the entire designated printing area. This results in the surface of the printed object having gaps, curves, or complicated details that are not filled in. A surface with imperfections and discontinuities from the incomplete filling may have a coarser texture and possibly have higher Ra values. In addition, low printing temperature also leads to the layer lines being more pronounced and visible on the final printed surface. The increase in surface texture and roughness is caused by these layer lines. Pronounced layer lines also give the surface a step-like appearance, where each layer is visible. The distinct boundaries between layers create an uneven surface texture which contributes towards the increase in surface roughness or Ra value.

3.2 Microstructure Observation

Figure 6 illustrates the microstructure of the sample from Run 1, captured at 100 x magnification, which presents fewer and smaller imperfections when compared to the microstructure observed in Figure 7. This finding indicates that a printing temperature of 180 °C results in a lower Ra value, with diminished pore presence and reduced pore size. On the other hand, the sample printed at 240 °C (Figure 7) has a clearer printing line and more obvious flaws, which causes the Ra value to be greater. While temperature is a significant factor, it is essential to consider that printing speed could also play a contributory role in determining surface quality. Variations in printing speed may affect the cooling rate and solidification behavior of the PLA carbon fiber filament, thus altering the microstructure and the surface roughness of the final print. Future analyses should, therefore, include an examination of printing speed in conjunction with temperature to fully explain their combined effect on the microstructure and surface finish.

Although precise identification of carbon fibres and PLA in Figure 6 is not possible without employing compositional analysis techniques like EDX, their presence can be reasonably deduced. The carbon fibres are commonly distinguished by the presence of more rigid, rod-like formations within the PLA matrix, which is typically observed as the predominant material in the microstructure. Although this study lacks the precise compositional analysis to confirm the presence of each constituent, the distribution and orientation of the fibres can often be inferred from the consistency and directionality of the microstructural features, as well as the contrast in the SEM images, which is based on the difference in electron conductivity between carbon fibres and PLA. Further study, possibly incorporating EDX analysis or similar techniques, would be beneficial to confirm the distribution of carbon fibres and PLA material.

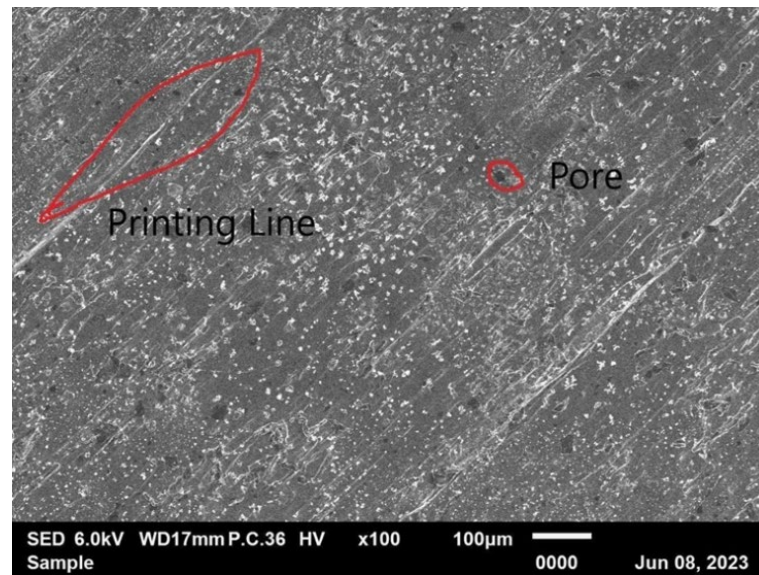


Figure 6: Microstructure of Run 1 at 100 x magnification (Parameter used in run 1: Layer thickness: 0.1 mm Printing temperature: 180 °C Printing Speed: 30 mm s⁻¹)

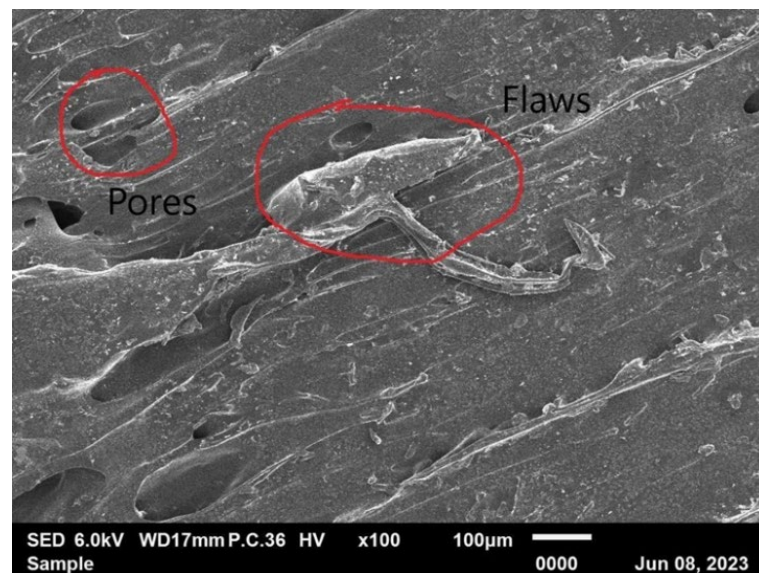


Figure 7: Microstructure of Run 9 at 100 x magnification (Parameter used in run 9: Layer thickness: 0.3 mm Printing temperature: 240 °C Printing Speed: 60 mm s⁻¹)

3.3 Analysis of Dimensional Accuracy

Figure 8 shows the printed sample based on the optimum printing parameters (printing temperature: 180 °C, layer thickness: 0.1 mm, and printing speed: 60 mm s⁻¹), through signal-to-noise analysis, as depicted in Figure 5. The 0.1 mm layer height strikes a balance between detailed resolution and practical print time, contributing to a high-quality surface finish. The chosen temperature, 180 °C, ensures the filament's proper flow and adhesion, optimizing viscosity for sharp details without compromising surface smoothness. The signal-to-noise ratio analysis, as shown in Figure 5, supports this conclusion, as the data indicates that this temperature yields the lowest Ra values, thus the smoothest surface and the most accurate dimensions. The 60 mm s⁻¹ speed aligns with these conditions, reducing

roughness while maintaining structural integrity, as supported by the data in Table 6 and the trends shown in Figure 5. The dimensional measurements of the samples are tabulated in Table 7.

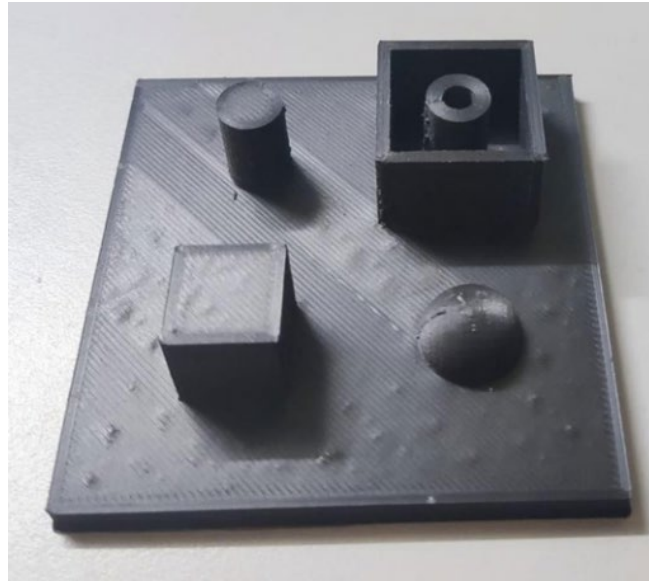


Figure 8: Dimensional accuracy sample

Table 7: Measurement of dimensional accuracy sample

Shape	Parameter	Average Reading (mm)	Nominal Dimension (mm)	Deviation (%)
Cube	Width	74.83	75.00	0.22
	Length	74.70	75.00	0.40
	Height	4.67	5.00	6.67
	Width	14.97	15.00	0.22
	Length	14.83	15.00	1.11
	Height	15.30	15.00	2.00
Semi sphere	Diameter	14.43	15.00	3.78
Solid cylinder	Diameter	9.83	10.00	1.67
	Height	15.37	15.00	2.44
Hollow cylinder	Outer Diameter	9.77	10.00	2.33
	Inner Diameter	5.10	5.00	2.00
	Height	15.53	15.00	3.56
Hollow square	Outer Length	25.03	25.00	0.13
	Outer Width	24.87	25.00	0.53
	Inner Length	21.23	21.00	1.11
	Inner Width	21.20	21.00	0.95
	Height	15.53	15.00	3.56

From Table 7, only one of the percentage deviations exceeds 5%. This proves that using optimal printing parameters obtained from the surface roughness test, parts with good accuracy can be printed using FDM. Notably, the height shows a more significant deviation, which might be influenced by several factors. The deviation in height could be attributed to the differential cooling rates experienced during printing, as documented by Lee et al. [19]. They explored the effect of chamber convection on the thermal history of PEEK components, revealing that fast melt cooling rates could result in a low degree of crystallinity, leading to

small spherulites that do not develop fully, contributing to variations in dimensional measurements. This phenomenon is particularly significant along the Z-axis, where gravitational effects on the cooling layers could further accentuate non-uniform shrinkage. Ensuring a level printing bed and cleaning it after each use is a standard procedure; however, the study by Lee et al. [20] implies that even with proper maintenance, the inherent cooling dynamics during the printing process can still induce significant dimensional variations, especially in height.

4. CONCLUSIONS

In conclusion, the study regarding the effect of different parameter values on the printed surface roughness and dimensional accuracy has been conducted successfully. Three parameters (printing temperature, layer thickness, and printing speed) with three different values were selected to analyse the effect on the printed surface roughness. The Taguchi analysis showed that the Ra value was significantly affected by printing temperature. Based on the study, the optimal value for the printing temperature for PLA carbon fibre filament is 180 °C. However, the other two parameters such as layer thickness and printing speed can be considered to have an effect in lowering the Ra value. The optimal printing parameters were used to print samples for the dimensional accuracy test. Based on the measurement of each shape, only one measurement for the cube sample exceeded a 5% deviation. This shows that the FDM can print parts with good accuracy. For future studies in FDM using PLA carbon fibre filament, the study of the effect of advanced FDM process parameters such as cooling rate and layer bonding techniques shall be conducted to help identify optimal parameter settings to achieve improved surface quality and high dimensional accuracy.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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