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THE EFFECT OF LAYER THICKNESS ON REPEATABILITY OF 3D PRINTED PLA PARTS PRODUCED USING OPENWARE 3D PRINTER

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ABSTRACT: Fused Filament Fabrication (FFF) is categorized as an additive manufacturing process, recognized as the simplest way to accomplish 3D printing. Previous studies have proven that FFF can be trusted to create custom parts with high complexity. However, some performance issues still exist with this method that must be resolved to improve conventional manufacturing techniques. One of them is its repeatability performance that is debatable when it comes to producing repetitive runs of similar parts. Printing parameter is one of the factors that play a significant role on the repeatability performance of parts produced. In this study, the effect of layer thickness on the repeatability of 3D printed PLA, produced using an Openware 3D printer (Espresso F220), was investigated. Two product geometries (Part A and Part B) were produced. Layer thickness was chosen as a variable parameter (0.1 mm, 0.2 mm, and 0.3 mm) for each geometry. Data to measure repeatability of the printed PLA parts were determined based on the measurements of length, width, thickness and surface roughness for each geometry. Then, repeatability performance was analyzed through One-way ANOVA analysis. From the results, the layer thickness parameter did influence dimensional quality and repeatability of samples produced. Part length and thickness offered better repeatability performance, to both product geometries being compared, in width and surface roughness. The study reveals that variations in sample properties depends on not only one, but also every printing parameter involved. Repeatability performance can be improved by identifying the ideal combination of printing parameters to produce good part quality.

ABSTRAK: : Fabrikasi Filamen Fius (FFF) yang dikategori sebagai proses pembuatan tambahan, diakui sebagai kaedah termudah bagi menghasilkan pencetakan 3D. Kajian terdahulu telah membuktikan bahawa FFF dapat menghasilkan komponen khas yang kompleks. Walau bagaimanapun, beberapa isu peningkatan mutu masih berlaku, iaitu kaedah ini masih perlu diperbetulkan bagi membaiki teknik pembuatan konvensional. Salah satu adalah peningkatan keterulangan bagi menghasilkan komponen yang serupa secara berulang. Parameter pencetakan adalah salah satu faktor yang berperanan penting bagi peningkatan keterulangan komponen yang dihasilkan. Kajian ini mengkaji tentang kesan ketebalan lapisan terhadap kebolehulangan PLA bercetak 3D yang dihasilkan melalui pencetak Openware 3D (Espresso F220). Dua geometri produk (bahagian A dan B) dihasilkan. Ketebalan lapisan dipilih sebagai parameter pemboleh ubah (0.1mm, 0.2mm dan 0.3mm) bagi setiap geometri. Data bagi mengukur keterulangan bahagian PLA yang bercetak ditentukan berdasarkan pengukuran panjang, lebar, ketebalan dan kekasaran permukaan bagi setiap

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geometri. Kemudian, peningkatan keterulangan dianalisa melalui analisis ANOVA Sehala. Dapatan hasil menunjukkan, parameter ketebalan lapisan mempengaruhi kualiti dimensi dan kebolehulangan sampel yang dihasilkan. Panjang dan ketebalan bahagian mempunyai peningkatan keterulangan yang lebih baik bagi kedua-dua geometri produk berbanding lebar dan kekasaran permukaan. Dapatan menunjukkan bahawa variasi sifat sampel tidak hanya bergantung pada satu, malah pada setiap parameter pencetakan yang terlibat. Peningkatan keterulangan dapat diperbaiki dengan mengenal pasti kombinasi parameter pencetakan yang ideal bagi menghasilkan kualiti bahagian terbaik.

KEYWORDS: *3D printing; FFF; PLA; repeatability; layer thickness*

1. INTRODUCTION

Fused Filament Fabrication (FFF) process comes under additive processes, which proves that this process is a filament extrusion-based process integrated with a CAD system, materials science, computer numeric control, and extrusion process to create 3D parts directly from a CAD model [1]. FFF is also known as Fused Deposition Modelling (FDM) which has been invented by Stratasys. Inc in the USA in 1990 and has become one of the world's best-known 3D printing techniques [1,2]. FFF shapes the 3D structure of individual layers of thermoplastic extruded filaments such as polylactic acid (PLA), which have sufficiently low melting temperatures for use in existing non-dedicated facilities in melting extrusion [2,3]. To date, FFF technology is widely present in different sectors, including engineering, biomedical, food and so forth [4,5].

With multiple printing parameters associated with the process, the substantial and ideal parameters for better structural and physical properties, such as accuracy and repeatability, of parts produced need to be identified, due to the applications of 3D printing in the market [6]. Researchers have taken various means to improve both structural and physical properties since FFF/FDM were introduced. Yet, for a long time, FFF work remained restricted to process parameters, such as layer thickness, and to individual materials [7]. Mohan N et al. [8] reviewed the optimization of the FFF process materials and process variables. FFF printers commonly embrace thermoplastic materials such as PLA, ABS, metal matrix composites, ceramic composites and natural fiber composites.

The simple and portable extrusion process is applicable in many different materials making FFF an affordable technology for research institutes, industries and domestic consumers with the capability of revolutionizing many different fields by providing the means to implementing innovative concepts [9,10].

Despite many applications and services offered by 3DP, this particular technology is still not completely utilized by manufacturers in terms of end-use goods due to numerous obstacles, one of them is the restricted variation in repeatability [11]. As the technology world grows, several series of 3D printing machines have been produced with different machines offering different repeatability performance. Other than that, process parameters also play a major role in determining the repeatability of parts produced by FFF. Since dimensional properties for functional components are crucial, the impacts of system parameters on repeatability are essential to examine as stated by Rebecca Kurfess [12]. The researcher stated that in order to characterize the relationships among the various parameters and the repeatability of the parts, further tests should be carried out before these 3D printed parts are used in positions where precision is important. Additional research is therefore needed to determine parameters of the printer such as the build orientation, layer thickness and feed rate, especially since the literature on the physical characteristics of parts being produced by FFF is rather scarce. FFF has proven to be able to produce good quality products. However, there are numerous procedural issues, with respect to product repeatability in particular. The machine's capability and whether it will be affected by type of FFF machine used or not, is essential in ensuring that the product's performance is highly predictable. Previous studies revealed that research on 3D printing has focused on aspects of accuracy rather than machine repeatability performance. Past studies have proven that some printing parameters influenced the finished product quality. Eventually, one of the printing parameters, layer thickness, should also affect this matter. Therefore, there is a possibility to determine the repeatability performance of FFF machine in producing PLA parts with different layer thickness.

Thus, in this work, repeatability performance of the 3D Espresso F220 is investigated. Two product geometries are proposed in this work to further investigate the repeatability of this machine. The two product geometries (part A and part B) of PLA samples were material printed with variation in layer thickness (0.1 mm, 0.2 mm, and 0.3 mm). Surface roughness, width, height, and depth of 30 fabricated parts were measured. The repeatability performance of the machine in producing PLA material has been concluded from this study through One-way ANOVA analysis.

2. METHODOLOGY

Four steps are conducted in this study to identify the effect of layer thickness on repeatability of 3D printed PLA parts. Details for each step are explained in the subsections below.

2.1 Product Geometry

In this study, to measure the reliability performance, two product geometries were used (Part A and Part B). Part A refers to ASTM D638 Type I standard dimension. The design and dimension of the products is shown in Fig. 1.

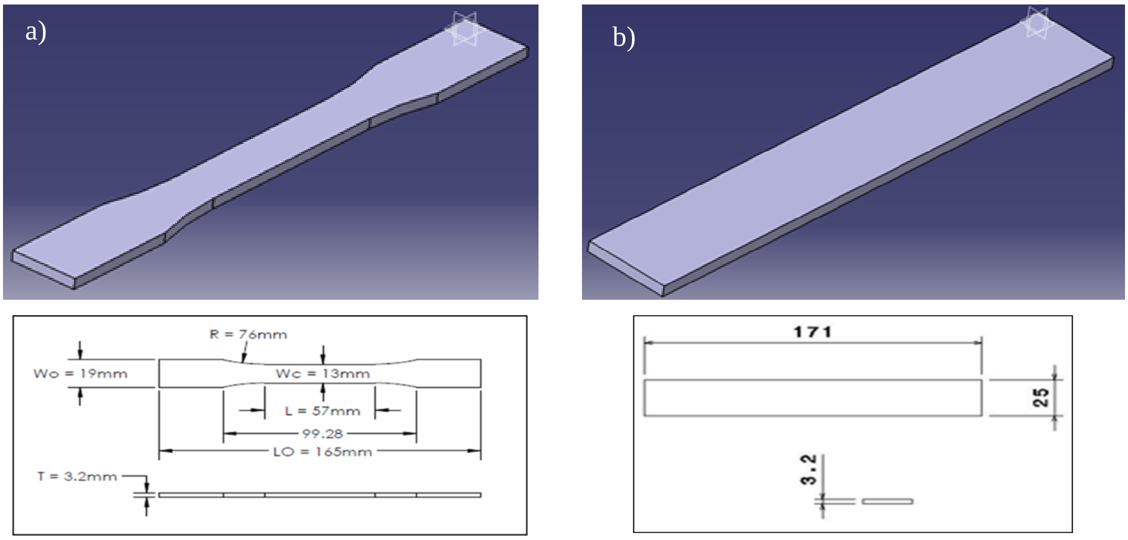

Fig. 1: (a) Part A (above: geometry, below: dimension) and
(b) Part B (above: geometry, below: dimension).

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2.2 Sample Fabrication

Part A and Part B were printed using an Openware 3D printer (3D Expresso F220). Printing parameters for 3D printing of product geometries is shown in Table 1. PLA feedstock filament was used for all samples. All printing parameters in Table 1 were fixed except layer thickness. In this study, layer thickness varies in three levels which were 0.1, 0.2, and 0.3 mm. Five replications were produced for each layer for both Part A and Part B product geometries. Therefore, the sampling size was 30. Figure 2 shows a 3D Expresso F220 machine that was used in this study.

Table 1: 3D printing parameter

Printing Parameter	Value
Feedstock filament	Polylactic acid (PLA)
Feedstock filament (diameter)	1.75 mm
Liquefier / Extruder temperature	210 °C
Bed temperature	50 °C
Infill percentage	90%
Infill pattern	Line
Printing direction	30°/60°
Layer thickness	0.1 mm, 0.2 mm, 0.3 mm
Printing orientation	X, Y, Z
Printing speed	60 mm/s

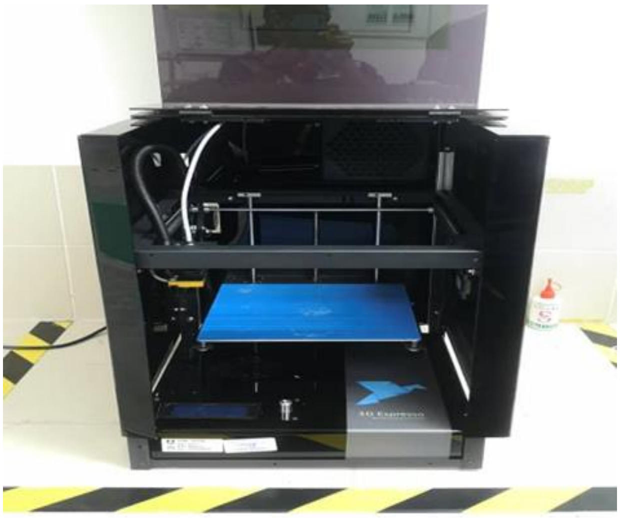

Fig. 2: 3D Espresso F220 machine.

2.3 Sample Measurement and Data Collection

The data to measure repeatability of the printed PLA parts are determined based on the measurement of length, width, thickness, and surface roughness for each product geometry (Part A and Part B). A digital vernier caliper was used to measure length, width, and thickness while a Mitutoyo surface roughness tester (SURFTEST SJ-210) was used to measure surface roughness. Table 2 shows the measurement location for each product geometry. For surface roughness, the dial indicator was placed at the midline of the top surface for both geometries.

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2.4 Repeatability Performance

In this study, one-way ANOVA is used to get repeatability performance. The null hypothesis, H_o and alternate hypothesis H_1 used described in Table 3.

Table 2: Location of measurement for length, width, and thickness

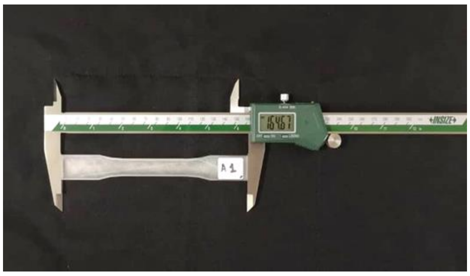
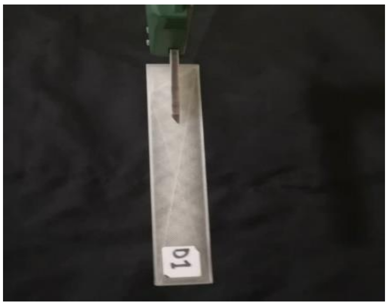
Measurement	Location of measurement (Part A)	Location of measurement (Part B)
Length		
Width		
Thickness		

Table 3: Repeatability Hypothesis

Hypothesis	Description
Null Hypothesis	H_o = Different layer thickness does not affect the repeatability of 3D printed PLA produced using 3D Espresso F220.
Alternate Hypothesis	H_1 = Different layer thickness does affect the repeatability of 3D printed PLA produced using 3D Espresso F220.

Data recorded was analyzed using one-way ANOVA where the single factor would be layer thickness. By using this method, data was analyzed and variance was evaluated between and within groups, which were then identified by F-value, critical F-value, and P-value. Calculations involved in identifying these three significant values were presented in equations (1) through (12).

$$\text{Mean value, } \bar{x} = \frac{\sum x}{n} \tag{1}$$

Where $\sum x$ is the total of samples value of each group, while n is the number of samples. Then, all mean values were added up together. Next, the sum of squares, $\sum(x^2)$ for each group was calculated before being added up. Later, the calculation continued with standard deviation, σ, of each layer thickness group before being summed together as eqn. (2). Then, from the data measurement table, degree of freedom was calculated through eqns. (3), (4), and (5).

$$\text{Standard deviation, } \sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{(n-1)}} \tag{2}$$

$$\text{Between groups (BG)} = k - 1 \tag{3}$$

$$Within\ groups\ (WG) = N - k \tag{4}$$

$$Totals\ degree\ of\ freedom = N - 1 \tag{5}$$

Where k acts as the number of groups, which are group of layer thickness, while N is the total sample size. From that, calculation moved onto Sum Square (SS) that involve correction factor (CF) (eqn. (6)) and sum of squares for totals (SST) (eqn. (7)), between (SSB) (eqn. (8)) and within groups (SSW) (eqn. (9)).

$$CF = \frac{(\sum \sum x)^2}{N} \tag{6}$$

$$SST = \sum \sum (x^2) - CF \tag{7}$$

$$SSB = \left\{ \sum \left[\frac{(\sum x)^2}{n} \right] \right\} - CF \tag{8}$$

$$SSW = SST - SSB \tag{9}$$

This has led to the calculation of Mean Square (MS) that involves the mean square between (MSB) (eqn. (10)) and within groups (MSW) (eqn. (11)). Subsequently, F-value, F_o calculated using the result of MSB and MSW (eqn. (12)).

$$MSB = \frac{SSB}{BG} \tag{10}$$

$$MSW = \frac{SSW}{WG} \tag{11}$$

$$F_o = \frac{MSB}{MSW} \tag{12}$$

Then, P-value was determined using F_o through F distribution table. Lastly, alpha level, α (controlled by researcher and related to confidence levels), was determined before being used to find critical F-value, F_c through the same F distribution table. After all values were verified, all the data was then tabulated. Next, comparison was made between F-value and critical F-value, as well as between P-value and alpha level, α that will bring to conclusion in two conditions, as stated below.

$$(F_o > F_c), (P - value < \alpha) : Statistically\ significant$$

$$H_o \text{ is false and can be rejected.}$$

Whereas,

$$(F_o < F_c), (P - value > \alpha) : Statistically\ insignificant$$
$$H_o \text{ is true and accepted.}$$

From the comparison, the result obtained proved whether H_o was a false statement for both product geometry samples. Thus, this result reflected the repeatability efficiency of 3D printed PLA produced whether it was being influenced by layer thickness differences or not.

3. RESULTS

Table 4 shows a summary of result from one-way ANOVA that was conducted for data collection for both product geometries. In this study, 0.05 of confidence level was used. Thus, F_c= 3.89 is same for all measurements. Based on hypothesis stated in the previous section, an influence of layer thickness to the repeatability performance can be made. Based on Table 5, hypothesis conclusion on each measurement was made. In the process of producing parts for both product geometries, layer thickness did influence the repeatability performance of the printed part. This result showed that, during formation of length dimension and thickness dimension of the parts, the machine was able to produce repetitive length and thickness, regardless of the different product geometry, with a total of 30 samples produced at three different layer settings. The sampling size used was able to give a significant result for this study.

Table 4: One-way ANOVA results for all measurements for both product geometries

Measurement	Part A			Part B		
	F_o	F_c	P	F_o	F_c	P
Length	9.4957	3.89	0.0034	5.2588	3.89	0.0229
Width	2.4852	3.89	0.1250	12.6481	3.89	0.0011
Thickness	10.8723	3.89	0.0020	4.7981	3.89	0.0294
Surface roughness	52.4052	3.89	0.0000012	0.3243	3.89	0.7291

Table 5: Hypothesis conclusion

Measurement	Part A	Part B
Length	Layer thickness does effect	Layer thickness does effect
Width	Layer thickness does not effect	Layer thickness does effect
Thickness	Layer thickness does effect	Layer thickness does effect
Surface roughness	Layer thickness does effect	Layer thickness does not effect

On the other hand, for formation of width dimension, layer thickness did not affect the production of part A, but did affect the production of part B. Fig. 3 shows a trend of width measurement for part A. The trend showed a decrease in width over the number of samples due to repeatability performance of the machine during producing the samples and of the shrinkage factor of the material after the process. The width value seems to be repeatable for 0.1 mm layer thickness and 0.2 mm layer thickness. However, the variation of the samples dropped at 0.3 mm layer thickness as the width measurements showed obvious differences between each other. It showed that the longer the time taken to complete the process, the width became less varied (0.1 mm layer thickness took longer time compared to 0.3 mm). This can be proven by the standard deviation calculation, which has indicated that the standard deviation of the 0.3 mm layer thickness spread over a wide range of values is higher than the other two-layer thicknesses. For this study, the constant printing parameter fit with 0.1 mm layer thickness leads to an optimal shrinkage percentage of PLA (0.3%-0.5%) and moderate Coefficient Linear of Thermal Expansion (CLTE: 8.5 x $10^{-5}/^{o}C$), thus giving a low variation in the sample's width. Therefore, when the layer thickness increased, the shrinkage percentage also increased if the same value for other parameters was used throughout the study. The distance between the sample locations and the nozzle can also be taken into consideration. As the nozzle moved further from its natural position, the solidified rate for each layer in one sample became higher. Thus, this will affect the final dimension of the sample.

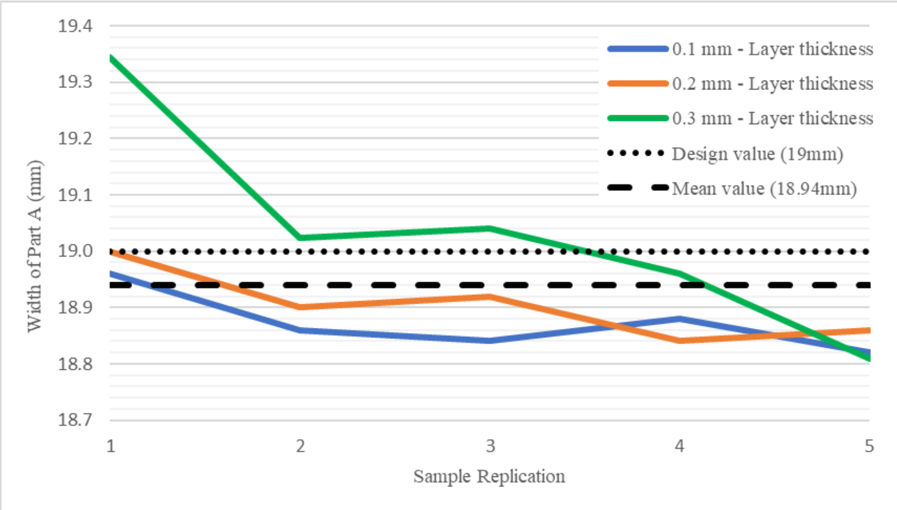


Fig. 3: Trend of width measurement for part A.

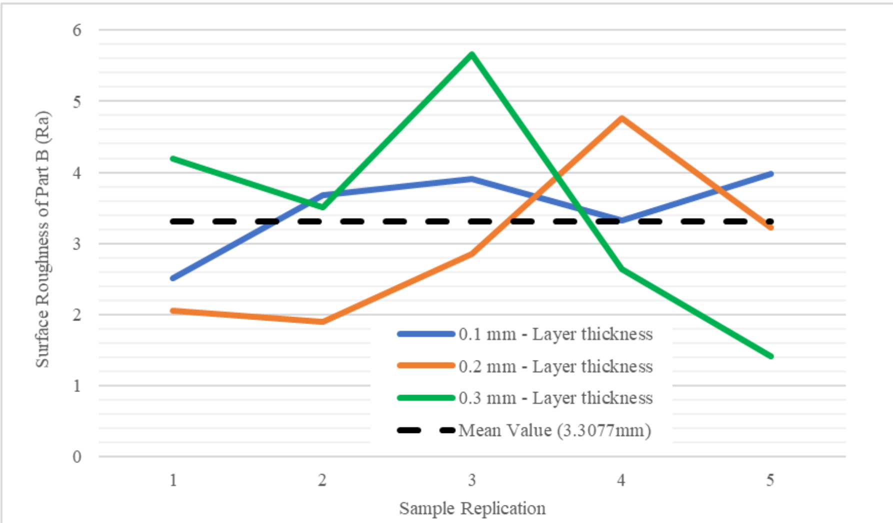


Fig. 4: Trend of surface roughness measurement for Part B.

Based on the results of surface roughness, layer thickness did not influence in the formation of part B, however it did affect in producing part A. For the surface roughness of 3D printed part B, based on Fig. 4, roughness value seems to be repeatable for 0.1 mm layer thickness. However, the variation of the samples dropped as the layer thickness increased, as the roughness readings had spread out over a large range of values. By standard deviation calculation, the statement can be proven, which showed that the standard deviation of the 0.3 mm layer thickness was higher (1.5979) than the other two-layer thicknesses (0.2 mm =

1.1482, 0.3 mm =1 .5979). Thus, it revealed that the constant printing parameter that was suitable for use with 0.1mm layer thickness that produced a low variation of roughness reading of straight cut samples. However, by changing the constant parameter value, the variation can still be improved.

The temperature of the bed was one variable that can be used to improve repeatability and surface roughness. According to previous studies, among printing temperatures, the lower printing bed temperature offers an increase in quality of surface between printing temperatures. If the temperature decreased for all the samples in the set of data, the surface roughness of all the samples decreased. Therefore, the results became better and had an increase in repeatability performance of the data. However, this will affect the final dimension of the sample, as a drop-in bed temperature will lead to an increase in thermal stress of PLA. This will then cause faster solidification process and in this case, warping deformation tended to occur. Regardless of the case, the optimal printing parameter combination should be defined to produce the highest possible repeatability of a set of samples.

4. CONCLUSION

In this study, two product geometries were proposed and fabricated to study the effect of layer thickness on repeatability of 3D printed PLA parts using an Openware 3D printer (3D Espresso F220). In total, 30 samples were produced that involved repetition of 5 samples for three variations of layer thickness (0.1 mm, 0.2 mm, 0.3 mm). The sampling size was significant to quantitatively measure the repeatability performance of the product geometry produced. Part length, width, thickness, and surface roughness for both product geometries was measured to analyze using the one-way ANOVA method. From the analysis, repeatability performance was achievable when length and thickness dimension were produced for both product geometries. For width dimension, layer thickness did not affect the fabrication of part A. For surface roughness, fabrication of Part B was not affected by layer thickness. However, the best layer thickness in ensuring repeatability of 3D printed parts in this study is 0.3 mm for part A that ensured repeatable performance in length and surface roughness. While layer thickness recorded at 0.1 mm for part B geometry ensured repeatable performance in thickness and surface roughness. Some improvements can be made to enhance the repeatability for measurements that were not achieved such as by using optimal printing parameter combinations, shrinkage factors, and temperature settings.

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