

Chapter 3

Investigation of the Effect of Surface Roughness and Dimensional Accuracy on the Layer Thickness of PLA Parts Produced by the FDM Process



Maria F. Jasim, Abdullah F. Huayier, and Tahseen F. Abbas

Abstract Fused deposition modeling (FDM) machines are becoming increasingly popular for producing functioning components. One of the drawbacks of used filament fabrication 3D printers is that the printed part's surface roughness is excessively rough due to the layer-by-layer deposition of the material. Therefore, it is necessary to verify that the components have a high-quality surface finish and precise dimensions. The purpose of this study is to identify the optimal layer thickness that may be used to manufacture components with both high surface quality and accuracy of dimension. Six different layer thicknesses of FDM were used to manufacture the test parts (0.1, 0.15, 0.2, 0.25, 0.3, and 0.35 mm). The optimum layer thickness levels for dimensional accuracy were discovered to be the same as that of surface roughness. The results of the experiment were confirmed by fabricating parts with the optimal layer thickness that had been determined. Reduced printing layers increased the specimens' surface smoothness. The smaller layer thickness was shown to be required for greater overall dimensional accuracy, according to the findings.

Keywords Fused deposition modeling (FDM) · Polylactide (PLA) · Layer thickness · Surface roughness · Dimensional accuracy

3.1 Introduction

In a manufacturing process known as additive manufacturing (AM), successive layers are bonded together to form the desired structure. Because of recent developments in process control, additive manufacturing is now a matching technology for the rapid,

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Fig. 3.1 Process flow of FDM

efficient, and cost-effective production of custom and complex parts, particularly in small quantities (Bakır et al. 2021). FDM is one of the most common AM methods for the manufacturing of plastic components because of the low equipment cost and easy operation (Boparai et al. 2016; Mohamed et al. 2015). Many factors influence the product quality and material quality, and it can be difficult to understand how these aspects interact (Casavola et al. 2016). A wide range of printing variables, including the building orientation and thickness of the layer, raster angle, width of the raster, air gap, as well as the density of infill and infill shape, and feed rate, has a significant impact on the quality and performance of FDM-produced components (Kristiawan et al. 2021). FDM's primary goal is to build three-dimensional objects using extruded thermoplastic filament, such as ABS or PLA, with temperatures of melting low enough to be used in non-specialist conditions (Chacón et al. 2017).

As shown in Fig. 3.1, a CAD 3D model of the finished product is exported in STL format before being sent to a 3D printer for fabrication using the FDM technology. An Ultimaker "Cura" slicer software, for example, prepares CAD 3D models into STL format for 3D printing and generates G-code with all the printing settings (Pandžić et al. 2021).

Layers of materials are fused in a pattern to form objects in the FDM. The filament is heated in the printer's nozzle until it melts, then extruded in a pattern over or adjacent to previous extrusions to build objects layer-by-layer (Milde et al. 2021). The nozzle should be heated to the proper temperature before use. The extrusion head feeds the filament into the nozzle where it is melted (Doshi et al. 2022). It is possible to move the extrusion head in direction of the X, Y, and Z-axes. The melted material is extruded from the extrusion head in very fine strands. The material is placed layer-by-layer on the platform, which cools and solidifies as it proceeds (Dave and Patel 2021). In certain machines, the build platform (or extrusion head) moves down, and a new layer is deposited when one layer is completed. This procedure is repeated until the component is complete (Dev and Srivastava 2021) as shown in Fig. 3.2.

The current study focuses on layer thickness on the physical properties (surface roughness and dimensional accuracy) of samples made from PLA with different layer thicknesses, which are (0.1, 0.15, 0.2, 0.25, 0.3, and 0.35 mm).

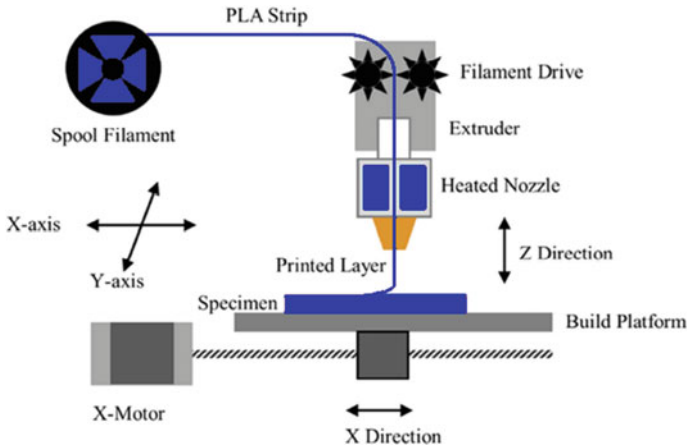


Fig. 3.2 Schematic diagram of FDM printing machine

3.2 Related Research

Many researchers have sought to enhance product quality by optimizing process parameters to achieve the best results for the physical external surface roughness and dimensional accuracy (Vaes and Van Puyvelde 2021).

For this purpose, many advanced statistical methods are used by DOE to improve the parameters of the process to achieve the best possible output by designing variable values and testing their impact on the process outputs to maximize or minimize the values of the process outputs according to the nature of the outputs (Hikmat et al. 2021).

3.2.1 Surface Roughness

Hafsa et al. (2013) used 3D printers with various layer thicknesses to test the dimensional accuracy and surface roughness of ABS and PLA precision casting models. The ABS model developed by lowering the layer thickness has a superior surface roughness than other models, according to the results. It has also been shown that PLA models produce a larger cast model, and the surface roughness improves as the layer thickness increases, making them ideal for casting.

Akande (2015) 3D Touch FDM machine with polylactide (PLA) material was used to create cuboid-shaped specimens and analyzed the impact of the thickness of the layer, fill density, and printing speed on the roughness of the surface. It was found that reducing each parameter to the lowest possible value resulted in the best surface finishing.

Kovan et al. (2017) noted that surface roughness affects the strength of adhesive bond connections between printed objects. It has been shown that the layers' thickness and the printing direction in printed parts have a substantial impact on the adhesion strength. In the case of low layer thicknesses, the layer created on the side edge has the biggest strength of adhesive, whereas in the case of the high layer thickness, the horizontal layer has the biggest strength of adhesive.

Pérez et al. (2018) utilized a cylindrical-shaped PLA specimen instead of a cuboid-shaped PLA part for this experiment. The layer thickness, printing speed, the extrusion temperature, and the shell thickness were some of the variables studied in this study. In this experiment, the low layer thickness was chosen because it would give the best surface finish. Extrusion temperature and print speed had little effect.

Ramli et al. (2018) investigated the surface roughness and dimensional accuracy of open-source 3D printers, Mendel Max and Kossel Mini, were studied. PLA and ABS materials were used to create spherical, cubical, and cylindrical objects on both machines, with varying layer thicknesses and filling ratios. Because of this, it has been discovered that PLA has a greater surface quality than ABS when comparing the models produced by the two machines. When the infill ratio was 20% and the layer thickness was 0.178 mm, surface qualities were found to be better.

Altan et al. (2018) researched the impact of printing parameters on the surface roughness and tensile strength. PLA samples are produced at various layer thicknesses, printing temperatures, and printing speeds. Layer thickness and print speed have been determined to be the most important parameters in determining the surface roughness of a product. The smaller the layer thickness, the lower the surface roughness.

3.2.2 Dimensional Accuracy

Nancharaiah et al. (2010) investigated the impact of the layer thickness, the raster width, the raster orientation, and the air gap on the dimensional accuracy. ANOVA was used to find important factors and their connections to assure dimensional accuracy. The Prodigy plus FDM machine was used to make ABS components for a variety of parameter combinations. In their experiment, ANOVA found that the raster width and the relationship between the raster width and the raster orientation were important determinants for the dimensional accuracy. Except for that, they found a link between layer thickness and dimensional accuracy. Based on the S/N ratio, they recommend that the layer thickness should be reduced to improve the dimensional accuracy.

Nidagundi et al. (2015) used a Julia 3D printing machine to study how the layer thickness, the raster orientation, and building orientation affect the precision of the ABS pieces. It was determined that an orthogonal array (L9) and a high S/N ratio provided the optimum parameter values. Low layer thickness, 0° orientation, and building orientation were shown to be the optimum characteristics for reducing dimensional deviations, with the most critical variable being the layer thickness.

Wu (2018) recommended that adopting a layer thickness of a minimum would result in high dimensional accuracy.

Alafaghani and Qattawi (2018) analyzed the dimensional correctness and tensile strength of PLA components. Minimum slice height and extrusion temperature values, as well as a hexagonal infill pattern with a minimum infill density, are all necessary for good dimensional accuracy, according to this research.

Mohamed et al. (2018) determined that FDM is capable of producing precise components after measuring the consistency of dimensions of parts produced by FDM using gauge repeatability and reproducibility.

Beniak et al. (2019) conducted investigations on the relevant layer thickness and extrusion temperature for dimensional accuracy. The layer thickness and extrusion temperature were compared and found to have a significant impact on the dimensional accuracy, and a low extrusion temperature was once again recommended.

3.3 Experimental Details

This section explains in detail the many factors, such as the material, selected process parameters, specimen manufacturing, and testing conditions used for printed parts testing.

3.3.1 Specimen Design and Material

The same 3D printer produced all specimens using the same PLA filament. The diameter of the used filament is 1.75 mm. Due to the potential for jamming a printer nozzle, PLA was chosen as a filament material since there is no need for the hotbed to print. Because of this, high-quality prototypes and functional components take less energy and temperature to process. The SolidWorks software is used to generate a 3D design model. After finishing the design with all dimensions (50 mm × 30 mm × 20 mm) in a standard form, the file was converted into STL format, which was then exported to the Cura software for establishing the required printing parameters. Cura's slicer provides 13 different infill patterns for the user to choose from. For this test, on all specimens, the "grid" pattern was used with six different thicknesses: 0.1, 0.15, 0.2, 0.25, 0.3, and 0.35 mm. Figure 3.3 illustrates the specimen design and infill pattern of the printed parts.

Samples created in SolidWorks and Cura need to be printed on a (FDM) 3D printer (Ender 5). The methodology for preparing the 3D printing specimens is illustrated in Fig. 3.4.

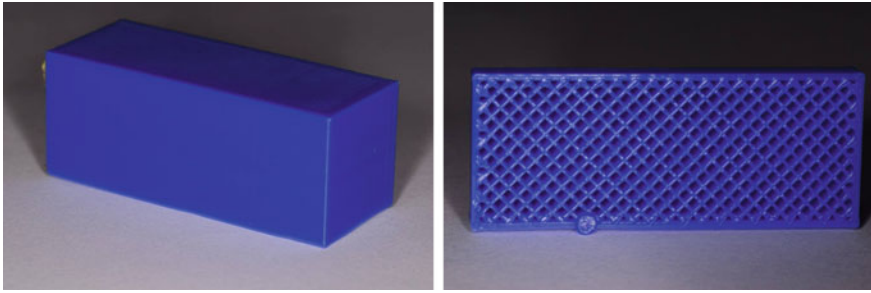


Fig. 3.3 Specimen design and grid pattern of the printed part

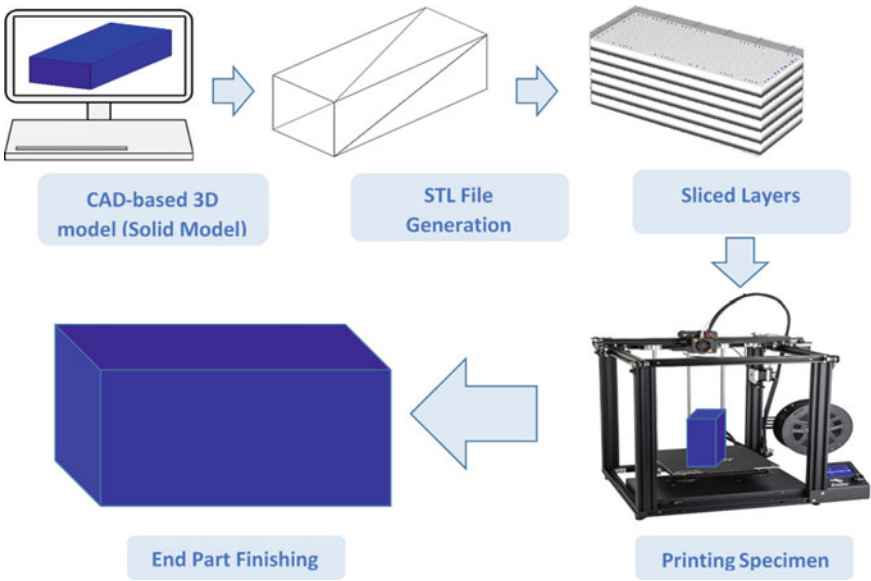


Fig. 3.4 Preparing 3D printing specimen

3.3.2 Process Parameter

Research shows that the thickness of the layers affects both surface polish and dimensional accuracy; they are thus considered in these experiments at six levels.

The layer thickness, or layer height, the height of the deposited layers is measured along the Z-axis, which is often the vertical axis of a FDM machine. In the majority of situations, it is smaller than the extruder nozzle’s diameter, and it changes based on the nozzle’s diameter. Figure 3.5 illustrates the layer thickness.

It is necessary to meet the parameters listed below. Table 3.1 shows the parameters used in the Cura 3D printing software to generate the G-code for 3D printing.

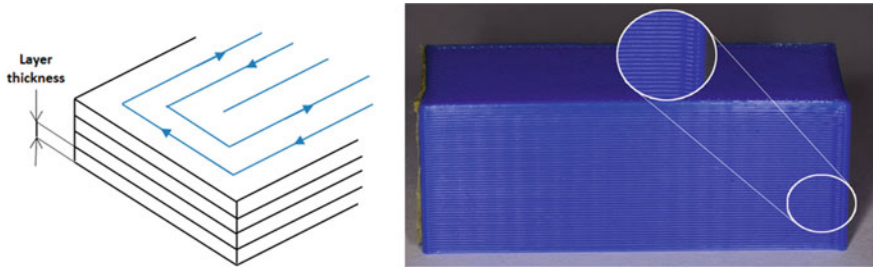


Fig. 3.5 Layer thickness

Table 3.1 Fixing parameters

Parameter	Value	Unit
Printing speed	60	mm/sec
Filling density	50	%
Bed temperature	60	°C
Printing temperature	200	°C
Shell wall thickness	0.8	mm
Orientation angle	0	°

3.4 Testing

3.4.1 Surface Roughness Test

The surface roughness test was carried out with the profilometer device (surface quality), and a surface analyzer (a sharp diamond stylus) is included, with a maximum distance that may be moved being 11 mm. The surface roughness (R_a) of printed block samples was measured at the side of the 3D printed block to investigate the effect of the thickness of the layer.

The surface is characterized by the profile of the surface imperfections and recesses, which are created on a scale. At the same time, each specimen was tested four times in different places on the same specimen, with the average value obtained from the four tests. Figure 3.6 shows the machine used in this test.

3.4.2 Dimensional Accuracy Test

The dimensions were measured with a digital Vernier caliper with the smallest count of 0.01 mm, which measured the length, width, and thickness of the part. Equation (3.1) is used to determine the accuracy of the length (L). In the same way, the width (W) and thickness (T) of the object are also determined.

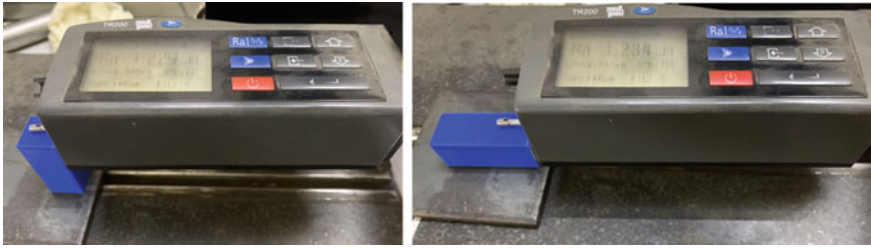


Fig. 3.6 Roughness test device

$$L = \frac{\text{length of CAD model} - \text{length of fabricated specimen}}{\text{length of CAD model}} \tag{3.1}$$

The deviation is defined as the difference between the nominal measurements and the dimensions that were measured. All of the molded specimens were measured and compared to the CAD model to see how the layer thickness affected the dimensional accuracy.

3.5 Results and Discussion

Table 3.2 shows that the thickness of the layer is the most important factor in determining the surface roughness and dimensional accuracy. Surface roughness ranges from 1.779 to 3.979 μm for specimens. The dimensional accuracy of manufactured specimens is determined to be in the range of 50.01–50.08 mm in the length direction, 30.02–30.08 mm in the width direction, and 20.01–20.26 mm in the thickness direction.

Our method of calculating each sample’s single-width value included averaging three measurements of width (W_1 , W_2 , and W_3), as shown in Table 3.2. The overall thickness measures of OT_1 , OT_2 , and OT_3 were all measured in the same way. The results of these measures are presented in Table 3.2. These measurements were

Table 3.2 Result of surface roughness for different levels of layer thickness

Levels	Layer thickness (mm)	Surface roughness (μm)	Overall length	Overall width	Thickness
1	0.1	1.779	50.01	30.02	20.01
2	0.15	2.798	50.02	30.03	20.02
3	0.2	3.308	50.04	30.02	20.07
4	0.25	3.574	50.08	30.04	20.10
5	0.3	3.944	50.96	30.05	20.14
6	0.35	3.979	50.98	30.06	20.26

compared to the design parameters, i.e., $OL = 50$ mm for overall length, $OW = 30$ mm for overall width, and $T = 20$ mm for thickness.

The CAD model was used to compare the dimensions of the produced specimens. It is important to note right away that the majority of the errors have positive values, which suggests that the printer prefers to produce larger parts than intended. The results indicated that to achieve higher dimensional accuracy, the thickness of the layers was reduced. Furthermore, as compared to the CAD model, the present FDM manufacturing technique often produces parts with bigger dimensions.

It has been shown that the accuracy of the dimension of FDM components is dependent on the dimensions (i.e., length, width, and thickness). In FDM components, layer thicknesses have been discovered to be important influencers of the accuracy of dimension in the length direction. Accuracy increases first with increasing layer thickness and then decreases with decreasing layer thickness. This is the same in width and thickness as shown in Fig. 3.7.

Figure 3.8 depicts the surface effect plots for the surface roughness. It is observed that the layer thickness influences the surface roughness of the parts. The surface roughness is essentially unaffected by a layer thickness of 0.1 mm. In addition, the lowest surface roughness value is at a layer thickness of 0.1 mm. The highest surface roughness values are at both 0.35 mm and 0.3 mm layer thicknesses. The higher the value of layer thickness, the higher the value of surface roughness. This is due to the smaller layer thickness; a smooth surface of the block was developed.

Because of the stair-stepping effect caused by stacking layers, the produced FDM part differs geometrically from the original CAD model. While using a FDM nozzle to deposit layers of material, the layer thickness is the measure of the thickness of each layer of material that is deposited. The forming accuracy of the printed specimen reduces as the layer thickness increases, the surface roughness increases, and the outer profile becomes more susceptible to the step effect. However, a reduction in the layer thickness improves the printed sample's accuracy, smoothness, printing time, and efficiency in a reverse way. For FDM parts made of PLA, the layer thickness levels

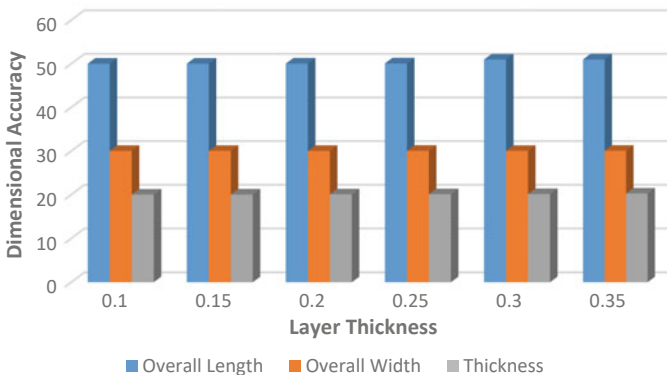


Fig. 3.7 Dimensional accuracy versus layer thickness

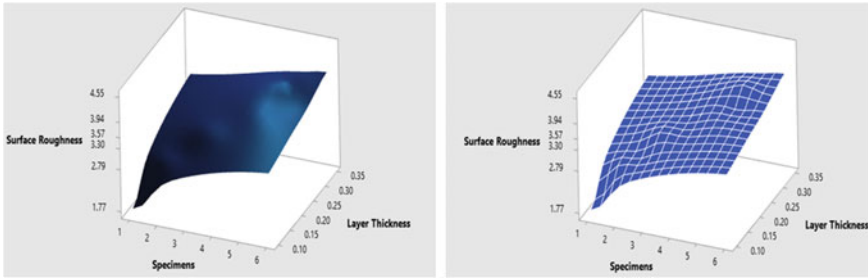


Fig. 3.8 Surface roughness vs. layer thickness

in the range of 0.1–0.2 mm are more likely to be optimum for surface roughness and accuracy of dimensions than other levels.

3.6 Conclusion

The effect of the layer thickness of the 3D printed block was studied, and it showed that variations of layer thickness affected the surface roughness and dimensional accuracy. It was also found that the range of roughness for all 3D printed materials in the study is between 1.779 and 3.979 μm . The desired function was then utilized to establish the optimal layer thickness for the reduction of both inaccuracy dimension and roughness of the surface in the final product. The findings of the experiments tend to indicate that it is feasible to make components with the best possible surface roughness and dimensional accuracy at the same time. A CAD model was used to make sure that the specimens had the same dimensions as the CAD model. To achieve improved dimensional accuracy in FDM products, we discovered that a smaller layer thickness is important. Reduced layer thickness means longer production times and a higher total cost because of the longer time it takes to print each layer. Based on test results and printing time, we have concluded that it was determined that layer thicknesses of 0.1 and 0.2 mm were the most optimal for the roughness of the surface and accuracy of the dimension of 3D printed PLA specimens.

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