Analysis and Investigation the Effect of the Printing Parameters on the Mechanical and Physical Properties of PLA Parts Fabricated via FDM Printing

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ABSTRACT

Fused deposition modeling (FDM) is a commonly used additive manufacturing (AM) technique that creates prototypes and parts with intricate geometrical designs. It is gaining popularity since it enhances products by removing the need for expensive equipment. The printed item’s mechanical properties are affected by the type of materials used, the printing process, and the printing parameters. The 3-D model of the polylactic acid (PLA) filament generated specimens was created using the Fused Deposition Modeling procedure and developed using Solid Works. This study investigates the effect of printing parameters on the mechanical and physical properties of samples printed using a Fused Deposition Modeling machine (Creality Ender-5 Pro). Six parameters are used: infill pattern, density, overlap percentage, layer thickness, shell thickness, and top/bottom layer number. Five levels were chosen for each FDM parameter. The results illustrated how printing parameters affected the mechanical and physical properties of samples, which were proven by ultimate tensile stress, surface roughness, and percentage of tensile average deviation. A comparison between the predicted results and the measured results was presented, and the maximum percentage error of the model, which fit the data well, was 0.54%, 0.3%, and 1.36% for ultimate tensile strength (UTS), surface roughness (Ra), and Tensile average deviation percentage respectively.

Keywords: fused deposition modeling, PLA, process parameters, tensile strength.

INTRODUCTION

Metals and polymers have been processed using a novel manufacturing technique known as additive manufacturing (AM), also referred to as 3D printing. AM is the technique of combining materials (usually layer by layer) with the assistance of 3D data. The advantages of the AM method include lower prototyping costs, quicker, less expensive production runs, and fewer inventories on hand, while the drawbacks include high production expenses, a slow build rate, and a limited range of component sizes. The use of additive manufacturing in current industries such as automotive sector development, arts and design development, aerospace and biomedical applications, and architecture has expanded because of its versatility and low cost in creating complicated designs. Currently, the electronics, aerospace, and biomedical industries all heavily rely on AM techniques. Plastic sheet lamination (PSL), selective laser sintering (SLS), fused deposition modeling (FDM), selective laser melting (SLM), and laminated object manufacturing (LOM) are the different AM techniques [1]. Due to their simplicity of production, low cost, and great performance, polymers are the most widely used materials in many applications [1–3]. The two alternative classifications for fused filament fabrication (FFF) that are most frequently used are fused deposition modeling (FDM) and three-dimensional printing (3DP). Due to the ease of the deposition process, the variety of materials on the market, the low cost of printer equipment, and the wide selection of inexpensive filaments, this approach is the most widely utilized of all.
AM methods. In environmentally friendly applications, a variety of cutting-edge materials and colors are regularly used, including wood for clothes, design, and furniture [4].

Numerous studies that were published made an effort to raise the production parameters for fused deposition modeling in order to produce parts of high quality. For instance, Mohd et al. (2022) [5] examined the optimum FDM printing parameters (printing speed, orientation, infill density, and layer thickness) utilizing thermoplastic composites supplemented with oil palm fiber that affect flexural strength, Young’s modulus, and tensile strength. The findings demonstrate that the optimum printing conditions were flat orientation, 0.4 mm layer thickness, 10 mm/s printing speed, and 50% density. Menderes et al. (2022) [6] determined the impacts of FDM process parameters (filling structures, occupancy rates, and table orientation) on the PLA mechanical characteristics. According to the findings, tensile strength and izod impact values have a direct relationship with occupancy rate. The estimating model’s discrepancy with the experimental findings did not exceed the maximum value of 1.8%. Maria et al. (2022) [7] investigated the impact of different infill patterns (Lines, Grid, Tri-Hexagon, Triangles, Zigzag, Gyroid, Cubic, Octet, and Concentric) on the PLA parts tensile strength. According to the findings, the triangle infill pattern has a lower tensile strength of 21 MPa than the concentric infill pattern, which has a greater tensile strength of 32.174 MPa. Tahseen et al. (2022) [8] investigated the impacts of FDM parameters (outer shell width, layer thickness, infill density, and pattern) on the PLA compressive property. The results confirmed that infill density has a higher impact on compressive resistance, while layer thickness has no impact on compressive resistance. R.A. et al. (2021) [9] analyzed the tensile strength of PLA-printed items made from red, blue, and yellow primer filaments to determine the most significant parameters (layer thickness, printing temperature, and printing speed) and their interactions with the tensile strength. From these findings, it has been illustrated that process parameters have a greater impact than filament colors do, with layer thickness having the greatest impact on tensile strength. In 2021, Selim et al. [10] examined how process parameters affected the PLA specimen’s tensile strength when fabricated using FDM. In the investigation, a 100% density rate produced a larger tensile stress than a density rate of 20%. By comparing the specimens with a 20% density rate to one another, the Grid-patterned specimen had the highest recorded tensile stress value. The cross-3D-patterned sample was found to have the closest specific strength to the full-filled sample. Mohd et al. (2021) [11] studied the impact of three pressing mechanisms (roller, ball, and press) on 3D printing components. They found that roller pressing has a better effect on FDM components and can improve tensile strength and surface roughness when integrated with a 3D printer. This suggests that roller mechanisms could be used as integrated pressing tools to enhance 3D printer properties. The combined infill patterns (honeycomb, solid, grid, wiggle, and rectilinear) that affect tensile characteristics in 3D printed objects were examined by Mohammadreza et al. (2020) [12]. The results showed that grid and honeycomb have greater strength while having lighter weights than solids. In this investigation, strength declines as build orientation increases. Digital image correlation (DIC) was used by Can et al. (2020) [13] to investigate the impact of process parameters on the yield strength, elastic modulus, densification strain, plastic platform stress, and tensile strength of printed PLA lattice structures. According to the experimental findings, the elastic modulus and tensile strength increase as the temperature of printing increases, while plastic platform stress, yield strength, and densification strain decrease as the speed of printing increases. The impact of the initial FDM parameters, such as layer height, infill percentage, and raster orientation, on the mechanical properties of thermoplastic polyurethane at a high strain rate (2500 s1) was described by Muhammad et al. (2020) [14]. Layer height was discovered to be the most important component at a quasi-static rate of loading (improvement in tensile strength). The resulting tensile strength of the sample decreased when the layer height of the sample increased. According to Teng et al. (2020) [15], a filament made of a wood fiber-polylactide acid composite (WPC) feedstock was utilized to print the specimen using FDM. The findings demonstrate that the printed WPC part’s density grew as printing speed decreased, but its surface color darkened in comparison to parts fabricated at a high speed. These findings demonstrate that the surface roughness, density, surface color, and compressive characteristics of
the fabricated part are significantly affected by
the printing speed. In 2020, Cristina et al. [16]
examined the impacts of size effect (various
thicknesses) and spatial printing direction on the
tensile characteristics of FDM parts. Spatial ori-
entation was found to have a higher impact on
tensile strength and a smaller impact on young
modulus. Additionally, the tensile strength and
Young modulus both decrease as the number of
layers increases.

The physical and mechanical properties of
the parts produced with the FDM system vary
depending on the specified parameters of the
printing process. Due to the values of the select-
ed printing parameters, which have significant
effects on the mechanical and physical prop-
erties of the produced samples, some printed
samples have poor mechanical and physical
properties. Therefore, the aim of the work is to
determine how the infill density, pattern, over-
lap percentage, layer thickness, shell thickness,
and top/bottom layer number affect the physical
and mechanical properties of printed samples
fabricated using the FDM method. Based on test
results, the ultimate tensile strength (UTS), sur-
face roughness (Ra), and average tensile de-
velopment percentage of the specimens are evalu-
ated and analyzed in order to recognize the variable
values that influence the properties of printed
specimens.

EXPERIMENTATION

Material and method

The effect of the FDM process parameters on
mechanical and physical properties has been in-
vestigated in previous works [17–19]. The major
objectives of this work were to demonstrate how
infill pattern, density, overlap, layer thickness,
shell thickness, and top/bottom layer number af-
fect tensile strength, surface roughness, and di-
mensioinal accuracy. In order to examine the im-
pact of these parameters on dog-bone specimens,
physical and mechanical properties analysis were
done in this work. This sample was created using
FDM printers and constructed in accordance with
ASTM D638 Type 4 standards.

The 3D model’s geometry was created us-
ing a set of linked triangles in a standard triangle
language (STL) file. This 3D design was trans-
formed into the language of machines (G-Code)
through the slicing process, making it ready for
printing. The STL file was prepared using Ul-
timaker Cura 4.13.1 software to generate ap-
propriate G-codes. Figure 1 (a, b) illustrates
the part’s solid work model (ASTM D638 Type 4)
and its STL file, respectively. Table 1 lists the
six input parameters and the various levels that
were used to produce the PLA type TORWELL
filaments.

![Fig. 1. (a) Part SolidWorks Model (all dimensions in mm), (b) SolidWorks Model STL File](image)

| Table 1. FDM process parameters and their levels |
|----------------|----------------|----------------|----------------|----------------|
| FDM parameters | Levels          | 1   | 2   | 3   | 4   | 5   |
| Infill density %| 20  | 40  | 60  | 80  | 100 |
| Infill pattern  | Grid | Triangles | Cubic | Lines | Tri-Hexagon |
| Layer thickness | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 |
| Shell thickness | 0.4  | 0.8  | 1.2  | 1.6  | 2.0  |
| Top/bottom layer no. | 2  | 3   | 4   | 5   | 6   |
| Infill overlap % | 0   | 5   | 10  | 15  | 20  |
A Creality Ender-5 Pro 3D printer, as shown in Figure 2, was used to print all specimens. Table 2 contains a list of the FDM setup’s specifications. A red polylactic acid (TORWELL PLA) filament with a 1.75 mm diameter was used as the work material due to its reliable properties. Table 3, contain the PLA material’s specification and properties.

An influential, straightforward, and systematic technique is produced through the design of experiments utilizing the Taguchi method for identifying the ideal machining conditions in the production process. The Taguchi approach was utilized to construct the experiment. Six process parameters were used to examine how FDM parameters affected tensile strength: the percentage of density, infill pattern, layer thickness, shell thickness, number of top/bottom layers, and percentage of infill overlap. There are five levels of variation for each of these parameters. The Taguchi method was used to measure the performance characteristic that deviates from the required values by using the signal-to-noise S/N ratio.

In order to maximize (tensile strength) and minimize (Surface Roughness, tensile average deviation%), the higher-the-better tensile strength and the lower-the-better Surface roughness and dimensional accuracy should be selected. Equations 1 and 2 can be used to represent the S/N ratio for the higher-the-better, smaller-the-better performance characteristic:

- Larger is better:
  \[ \frac{S}{N} = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i \right) \]  
  (1)

- Smaller is better:
  \[ \frac{S}{N} = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \]  
  (2)

where: \( n \) – measurements total number;
\( y_i \) – the value of the characteristics that were measured.

The specimens were tested in accordance with ASTM D638 Type 4 standards on a WDW-200E computer-controlled electronic universal testing machine, as shown in Figure 3, to evaluate the mechanical properties of the fabricated specimens.

At room temperature, the testing was conducted at a controlled speed of 1.5 mm/min [16, 20]. Load, deformation, stroke, and time data were
recorded during the experiments. The ultimate tensile strength was determined using the data that has been recorded. Based on the actual, not the CAD model, dimensions of each specimen, the stresses, and the mechanical properties can be determined. The tensile strength of each PLA test sample was estimated using equation 3. The various PLA filament test specimens are shown in Figure 4.

\[
\sigma = \frac{F}{A}
\]  

(3)

where: \( \sigma \) – Tensile stress (N/mm\(^2\)); 
\( F \) – Applied force (N); 
\( A \) – cross-section area of fabricated part (mm\(^2\)).

Using a profile measurement device (Pocket Surf), the surface roughness of each tensile test sample was determined with 0.25 mm measurement distance as indicated in Figure 5. The surface roughness of the printed parts is represented by the average value that was calculated by performing the Ra calculation three times perpendicular to layers direction in different places on the same specimen.

All of the molded specimens were measured and compared to the CAD model in order to evaluate the impact of the processing parameters on the tensile average deviation percentage (dimensional accuracy). Each specimen’s measurements were taken using a digital vernier caliper. Every
Table 4. Ultimate tensile strength, surface roughness, and tensile average deviation % of printed parts

<table>
<thead>
<tr>
<th>NO.</th>
<th>Infill density %</th>
<th>Infill pattern</th>
<th>Layer thickness (mm)</th>
<th>Shell thickness (mm)</th>
<th>Top/bottom layer no.</th>
<th>Infill overlap %</th>
<th>Ultimate tensile stress UTS (MPa)</th>
<th>Surface roughness Ra (μm)</th>
<th>Tensile average deviation %</th>
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thickness, 0.8 mm shell thickness, 6 top/bottom layer numbers, and 10% infill overlap produced by the printer was the strongest specimen with 55 MPa. In contrast, the 20% infill density, grid infill pattern, 0.1 mm layer thickness, 0.4 mm shell thickness, 2 top/bottom layers, and 0% infill overlap generated by FDM printer was the weakest specimen with 11 MPa, among other samples.

**Results for tensile test**

The ultimate tensile strengths of the specimens are displayed in Table 4. According to Figure 7, the study examined how the FDM processing parameters affected the ultimate tensile strengths of the specimens. The tensile strength is largely influenced by infill density. The experimental results presented for this study demonstrate that
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raising the infill density will increase tensile strength. As is clear, the specimen with an 80% infill density has a tensile strength of (55 MPa), which is approximately five times more than the specimen with a 20% infill density (11 MPa). The increase in infill density has been associated with an increase in the amount of material used. The maximum strength can be achieved with an infill density of 80%; however, this can have a negative impact on cost because it increases printing time and material consumption. Consequently, it would be crucial to determine the necessary infill density based on the type and application of the product.

Figure 8 displays the average tensile strength values (mean = 34.75) along with their corresponding standard deviations (StDev = 9.225). These values are presented to illustrate the variation in tensile strength among different samples under varying printing parameters. The grid pattern yielded the maximum tensile strength of 55 MPa among the five selected patterns. This can be explained by the fact that the grid pattern should have the optimal layer arrangement (in terms of layer bonding). Additionally, a layer thickness of 0.25 mm resulted in the highest tensile strength. This may be due to the fact that less material is extruded when using 0.25 mm layer thickness as opposed to 0.4 mm layer thickness, giving the filament more time to melt. On the other hand, as opposed to 0.1 mm layer thickness, 0.25 mm layer thickness has fewer layers, which lowers the risk of failure at the layers and improves the mechanical properties.

From Figure 7, between shell thickness and tensile strength, it is observed that the sample with a 2 mm shell thickness has the highest UTS value. Similarly, the specimen with 6 top/bottom layer number and 10% infill overlap has the highest UTS value. However, the specimens with 0.4 shell thickness have approximately the lowest UTS value. The UTS increases linearly with increasing top/bottom layer number. Between 5-6 changes of top/bottom layer number show the most significant effect in the UTS.

Results for surface roughness

The surface roughness criterion aids in the evaluation of fabricated parts functionality, which is as significant as the FDM parts strength and is influenced by the quality of the surface. The average surface roughness values, Ra, were determined by taking measurements perpendicular to the pull-out direction during a tensile test. The surface response of 25 FDM pieces was measured after they had been manufactured, as shown in Table 4. A line design with 60% infill density, 0.1 mm layer thickness, 1.2 mm shell thickness, 6 top/bottom layer numbers, and 5% infill overlap was found to produce the best results with a reduction in surface roughness from 10.2703 to 6.442 μm. The main effect plot for the effects of various machine parameters on Ra values is shown in Figure 9. The graphs show that layer thickness significantly influenced the surface roughness of the FDM pieces. This indicates that because the accuracy of the printed samples is decreasing and the layer is impacted by the step effect, the surface roughness increases proportionally with layer thickness. Figure 10 displays the average surface roughness values (mean
= 9.062) along with their corresponding standard deviations (StDev = 1.184). These values are presented to illustrate the variation in surface roughness among different samples under varying printing parameters. A 60% infill density, a triangle infill pattern, 0.25 mm layer thickness, 0.4 mm shell thickness, 4 top/bottom layers, and 20% infill overlap were found to result in the worst surface quality for PLA parts, reaching 10.2703 μm, as shown in Figure 10. The poor quality of the triangle pattern was due to the design and classified layer.

**Dimensional Accuracy results**

Out of all the parameters that were examined, as shown in Table 4, shell thickness had the greatest effect on the specimen’s tensile average deviation percentage. It was found that the smallest average percentage deviation was achieved with the machine parameters set as a grid pattern with 20% infill density, 0.1 mm layer thickness, 0.4 mm shell thickness, 2 top/bottom layer numbers, and 0% infill overlap. The percentage deviation decreased

![Fig. 9. Main effect plot for surface roughness](image)

![Fig. 10. Surface roughness variation with FDM parameters for printed parts](image)
from 3.5% to 0.556%. The main effect plot in Figure 11 shows how various machine parameters affect tensile average deviation percentage values. The graphs show that the tensile average deviation percentage (dimensional accuracy) of the FDM parts was significantly influenced by shell thickness. This indicates that there is a minimum deviation for FDM parts. The deviation increases proportionally with shell thickness. Figure 12 displays the average tensile percentage deviation values (mean = 2.132) along with their corresponding standard deviations (StDev = 0.8064). These values are presented to illustrate the variation in tensile percentage deviation among different samples under varying printing parameters. A 20% infill density, a Tri-hexagon infill pattern, 0.3 mm layer thickness, 0.2 mm shell thickness, six top/bottom layers, and a 20% infill overlap had the highest average percentage variation for PLA parts, reaching 3.5%, as shown in Figure 12.

Fig. 11. Main effect plot for tensile average deviation %

Fig. 12. Tensile average deviation % variation with FDM parameters for printed parts
Mechanical and physical properties changes of test specimens fabricated using different process parameters are given as interaction graphs in Figures 13, 14, and 15. Use the interaction plot to demonstrate how the value of the second categorical parameter affects the relationship between one categorical parameter and a continuous response. On the x-axis of this plot are the means for the levels of one parameter, and lines are shown separately for each level of another parameter. The lines in this interaction plot are not parallel. This interaction effect shows that the value of FDM parameters...
Table 5. Percentage error for ultimate tensile strength, Ra, and tensile average deviation % of PLA parts

<table>
<thead>
<tr>
<th>No.</th>
<th>Measured UTS (MPa)</th>
<th>Cubic predicted UTS (MPa)</th>
<th>Error %</th>
<th>Measured Ra (μm)</th>
<th>Cubic predicted Ra (μm)</th>
<th>Error %</th>
<th>Measured tensile average deviation %</th>
<th>Cubic predicted tensile average deviation %</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
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Affects tensile strength, Ra, and dimensional accuracy. Figure 13 demonstrates that for 80% infill density, layer thickness is 0.25 mm, shell thickness is 0.8 mm, there are 6 top and bottom layers, and with 10% infill overlap, strength levels are higher.

Smooth surface texture can be obtained, as illustrated in Figure 14, when infill density is equal to 60%, lines pattern, layer thickness is 0.1 mm, shell thickness is 1.2 mm, there are 6 top and bottom layers, and there is 5% infill overlap.

It can be observed from Figure 15 that the minimum average tensile deviation results at 20% infill density, grid pattern, layer thickness of 0.1 mm, shell thickness of 0.4 mm, 2 top and bottom layers, and 0% infill overlap.

The value of the percentage error between measured and predicted responses of PLA parts was calculated according to equation 7. It has been shown from Table 5 that the maximum values of percentage error between measured and predicted UTS, Ra, and tensile average deviation % of PLA parts were 0.54%, 0.3%, and 1.36%, respectively, while the minimum values of percentage error between measured and predicted ultimate tensile strength (UTS), Ra, and tensile average deviation % of PLA parts were 0.03%, 0.03%, and 0.27%, respectively.

\[
\text{Error} \% = \left( \frac{\text{measured UTS} - \text{Predicted UTS}}{\text{measured UTS}} \right) \times 100 \quad (7)
\]

CONCLUSIONS

The impact of FDM processing parameters on the tensile test mechanical characteristics, surface roughness, and dimensional accuracy of FDM specimens was examined using Taguchi’s L25 DOE. Prior to performing tensile testing, linear dimension measurements for the specimens’ dimensional accuracy as well as surface profile measurements were carried out in accordance with the ASTM D683-type 4 standard for inspecting the specimens.

According to the work results on the mechanical properties of fabricated specimens, a higher infill density of 80%, a grid infill pattern, 0.25 mm layer thicknesses, 0.8 mm shell thicknesses, six top and bottom layers, and 10% infill overlap optimize the tensile strength of parts with a value of 55 MPa.

For the physical properties of the FDM specimens, the lines pattern with 60% infill density, 0.1 mm layer thickness, 1.2 mm shell thickness, 6 top/bottom layer numbers, and 5% infill overlap had the best surface profile result obtained in this work according to the selected parameters, with a value of (6.442 μm), however the expected Ra is based on reference [22] ranges from 1.779 μm to 3.979 μm for specimens. The triangles pattern, on the other hand, was the worst because of its design and inadequate adhesion.

It was found that the smallest average percentage deviation of 0.556% was achieved with the machine parameters set as a grid pattern with 20% infill density, 0.1 mm layer thickness, 0.4 mm shell thickness, 2 top/bottom layer numbers, and 0% infill overlap.

It has been shown from Table 4 that the maximum value of percentage error between measured and predicted ultimate tensile strength of PLA parts was 0.54%, while the minimum percentage error between measured and predicted ultimate tensile strength of PLA parts was 0.03%.

The maximum value of percentage error between measured and predicted surface roughness of PLA parts was 0.3%, while the minimum percentage error between measured and predicted surface roughness of PLA parts was 0.03%.

The maximum value of percentage error between measured and predicted tensile average deviation % of PLA parts was 0.136%, while the minimum value of percentage error between measured and predicted tensile average deviation % of PLA parts was 0.27%.

Finally, it is obvious that it is impossible to maximize mechanical characteristics while minimizing physical properties when setting the values of FDM parameters. In order to enhance the strength of printed parts, a grid infill pattern, 80% infill density, layer thicknesses of 0.25 mm, a shell thickness of 0.8 mm, six top and bottom layers, and 10% infill overlap are recommended as FDM parameters. On the other hand, the line pattern with 60% infill density, 0.1 mm layer thickness, 1.2 mm shell thickness, 6 top/bottom layer numbers, and 5% infill overlap must be specified to reduce the surface roughness. Whereas 20% infill density, 0.1 mm layer thickness, 0.4 mm shell thickness, 2 top/bottom layer numbers, and 0% infill overlap must be selected as FDM parameters to minimize tensile average deviation%. As a result, it is required to sacrifice mechanical or physical characteristics in order to optimize another property or to carry out a multi-objective optimization.
REFERENCES


