The Effect of 3D Printing Process Parameters on the Mechanical Properties of PLA Parts

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Abstract. Taking the PLA molded by FDM as the research object, the influence of various process parameters on mechanical properties is investigated through comparative experiments, which provides reference and help for the promotion and application of FDM molding technology. During the molding process, the PLA material undergoes the process of melting to solidification, thus the performance of the molded part is worse than the original due to thermal shrinkage and other reasons. To improve the quality and mechanical properties of the molded parts, the experiment is designed using an orthogonal test method in parallel with nine different sets of process parameters (layer thickness, build direction, filling speed, and infill density, etc.). Ultimately, the mechanical properties of PLA are tested and the results are analyzed respectively to determine the main factors affecting the mechanical properties and their optimal level combination. Among them, fill rate is the crucial factor in compressive property, while build direction has a significant effect on surface roughness, tensile property and bending property.

1. Introduction

3D printing technology is widely used in various fields because of its ability to produce small and complex geometrical parts quickly and at low cost. Common 3D printing technologies are: Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Molding (FDM), Digital Light Processing (DLP), and Ultraviolet Sheet Printer (UV)[1][2]. The FDM printer system has the advantages of simplicity of construction, safety of operation, suitability for office environments, better structure and performance through topology optimization and computer-aided design, which has attracted much attention. The principle is that hot melt materials (PLA, ABS, etc.) are heated and melted, and extruded through the nozzle. After the deposition of the previous layer, the worktable is lowered by one layer thickness in predetermined increments, and the melt-jet deposition is repeated until the completion of the entire solid model[3][4]. The current researches mainly focus on surface roughness, dimensional accuracy, etc., while the build direction, layer thickness, air gap, infill density, filling type, filling speed, Raster angle and other parameters can also have a significant impact on the quality and mechanical properties of molded parts[5][6].
PLA is one of the main materials for FDM printing, which has advantages of being renewable and degradable, good Biocompatibility, good machinability, and no irritating odor when molting. At the same time, the FDM-molded parts have lower shrinkage, higher dimensional accuracy, and better mechanical properties than the original. Therefore, it is widely used in medical and industrial fields such as sutures, stents, artificial ears, and articular cartilage, etc.

The influence of FDM process parameters on the molding quality and mechanical properties is widely studied. Chen and his co-workers used the orthogonal test method to study the effect of layer thickness and forming temperature on surface roughness. They found that layer thickness has the greatest impact on surface roughness. Anitha and Nancharaiah investigated the effects of layer thickness, road width, air gap, and deposition rate on the molded parts by Taguchi and variance methods. The results showed that the layer thickness and air gap have significantly effects on the surface roughness and mechanical properties. When the layer thickness and air gap are low, the interlayer voids can be effectively reduced, improving the surface roughness and mechanical properties. Wang combined Taguchi's method with grey relational analysis, and used statistical optimization to investigate effects of parameters such as layer thickness, deposition method, support method, and deposition direction on surface roughness. The results showed that the surface roughness is improved by 62.27% through the setting of optimization factors, and the best combination of parameters for surface roughness is obtained. Sood studied the tensile, flexural, and impact strength at different layer thicknesses. For thicknesses of 0.127, 0.178, and 0.254 mm, respectively, the tensile strength first decreased and then increased with the increase in layer thickness. While Tymrak et al. studied the thickness of 0.2 and 0.4mm, finding the lowest thickness has the highest tensile strength.

In terms of build direction, Ang found that the mechanical properties and porosity of formed parts are mainly influenced by, for example, air gap, build direction, and filling type. Among them, air gap and build direction have a more significant influence on porosity and mechanical properties. Ahn also showed that build direction and air gap have the greatest effect on the mechanical properties of the molded part, followed by print temperature and platform temperature, which also has a significant impact on structural inhomogeneity. Gajdos reduced structural inhomogeneity by changing the printing and platform temperatures, so as to improve the mechanical properties of the molded parts. Yang and Han studied the effects of printing temperature, layer thickness, and build direction of PLA material on the quality and printing efficiency of molded parts, and analyzed the main parameters affecting the accuracy of the manufactured parts to obtain the optimal combination of parameters. Kumar and Regalla investigated the effect of process parameters such as layer thickness, raster angle, build direction, contour width, and raster width on build time. The results showed that the important factors for the minimization of build time are layer thickness and build direction.

Regarding filling speed and raster angle, Ning and Christiyana showed that tensile and flexural strengths decrease with increasing filling speed. Meantime, filling speed is positively correlated with build time and cost. Durgun investigated the effect of parameters such as raster angle on the mechanical properties of ABS material and found that the tensile strength of specimens printed perpendicular to the tensile direction is lower.

In other aspects, Han’s study used an interface instead of STL format, which could reduce errors in the process of file conversion. They also selected the appropriate molding direction and printer structure to improve accuracy. Giordano’s research found that low molecular weight polymers have the highest tensile strength. The use of the hot pressing process can effectively improve the tensile strength of the material.

2. Experiment

2.1 Experiment material
The material used in this test was Epson PLA plastic filament with a density of 1.26g/cm3, whose diameter was 1.75±0.04mm. The printing temperature was from 195°C to 210°C, and the hotbed temperature was from 50°C to 60°C.
2.2 Test equipment
The 3D printer was a high-precision FUNMAT HT with a single printhead. The test machine was the universal material testing equipment. See Figure 1 and Figure 2.

![FUNMAT HT](image1)

![Universal Testing Machine](image2)

Figure 1. FUNMAT HT  
Figure 2. Universal Testing Machine

| Parameters               | Values         |
|--------------------------|----------------|
| Maximum speed (mm/s)     | 300            |
| Printing accuracy (mm)   | 100±0.1        |
| Layer thickness (mm)     | 0.05~0.4       |
| Nozzle temperature (°C)  | 450            |
| Platform temperature (°C)| 160            |
| Chamber temperature (°C) | 90             |
| Forming dimensions (mm)  | 258*258*258    |
| Silk diameter (mm)       | 1.75±0.05      |

Table 1: Main parameters of 3D printer

| Parameters               | Values         |
|--------------------------|----------------|
| Maximum range (kN)       | 50             |
| Force resolution         | 1/250000       |
| Effective stretching stroke (mm) | 900         |
| Force accuracy           | ±0.5%          |
| Speed (mm/min)           | 0.01~500       |

Table 2: Main parameters of universal material testing equipment

2.3 Process parameters
STM D638, D790, and D695 standards were commonly used for the tensile, bending, and compressive properties of FDM specimens. There were many process parameters affecting the mechanical properties of FDM parts, and this paper focused on the analysis and study of layer thickness, build direction, filling speed, and infill density. Others process parameters remained unchanged during the experiment such as air gap with 0 mm, printing angle with 45°, nozzle temperature with 210°C, nozzle diameter with 0.4 mm, and grid filling algorithm.

| Parameters               | Values         |
|--------------------------|----------------|
| Layer thickness (mm)     | 0.05, 0.1, 0.2 |
| Build direction          | Flat, On-edge, Upright |
| Filling speed (mm/s)     | 20, 40, 80     |
| Infill density (%)       | 20, 40, 80     |

Table 3: Test process parameters
2.4 Tensile test
The thickness of the specimen and its specific shape and dimensions were determined according to the ASTM D638 standard for the tensile properties of plastics\(^{[24]}\).

| Parameters                        | 7 or under | Over 7 to 14 | 4 or under | tolerances |
|-----------------------------------|------------|--------------|------------|------------|
| Type I                            | 13         | 6            | 6          | 3.18       |
| Type II                           | 57         | 57           | 33         | 9.53       |
| Type III                          | 19         | 19           | 29         | 9.53       |
| Type IV                           | 19         | 29           | 19         | 9.53       |
| Type V                            | 165        | 183          | 246        | 63.5       |
| Type VI                           | 50         | 50           | 50         | 7.62       |
| Type VC                            | 115        | 135          | 115        | 25.4       |
| Type VD                           | 76         | 76           | 76         | 12.7       |
| Type VC,D                         | 115        | 135          | 115        | 25.4       |

Select the thickness of the specimen to be 3.2mm, the tensile test speed to be 5mm/min, and the type I specimen, as shown in Figure 4.

2.5 Three-point bending test
According to ASTM D790 plastic bending performance test standard, the parameters of bending specimen in this test were as follows: \( L = 52\text{mm} \), the length of both ends was 6.5mm. The radius of the support was 5mm, the radius of the indenter was 12.5mm\(^{[25]}\), as shown in Figure 5 for details.

2.6 Compressive test
According to ASTM D695 for compression of plastics, for the case of thicknesses with 3.2mm and above, a cross-section of 12.7mm was preferred, and the specimen should be a straight cylinder or prism with a length twice the width or diameter\(^{[26]}\), as shown in Figure 6 for details.
3. Experimental results and discussion

To ensure the accuracy of the test data, each group of specimens consisted of five samples, the average value of which was selected to analyze the results. The aim of the analysis and optimization of the test data was to analyze the importance and optimum level of each factor and thus to select the optimal combination of process parameters. To reduce the number of tests and improve efficiency, it was decided to use the orthogonal test method and the extreme difference method of analysis[27].

| Sample | Layer thickness Lt (mm) | Build direction | Filling speed Fr (mm/s) | Infill density (%) |
|--------|-------------------------|-----------------|-------------------------|-------------------|
| 1      | 0.05                    | Flat            | 20                      | 20                |
| 2      | 0.1                     | On-edge         | 40                      | 40                |
| 3      | 0.2                     | Upright         | 80                      | 80                |
Table 6  Table of mechanical test results

| Sample | A:Layer thickness Lt(mm) | B:Build direction | C:Filling speed Fr(mm/s) | D:Infill density (%) | Tensile strength $\sigma_t$(MPa) | Bending strength $\sigma_b$(MPa) | Tensile strength $\sigma_{ac}$(MPa) | Tensile strength $\sigma_{bc}$(MPa) |
|--------|-------------------------|-------------------|--------------------------|---------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 1      | 0.05                    | Flat              | 20                       | 20                  | 27.25                         | 96.73                         | 8.24                          | 24.24                         |
| 2      | 0.05                    | On-edge           | 40                       | 40                  | 18.04                         | 40.27                         | 9.26                          | 28.21                         |
| 3      | 0.05                    | Upright           | 80                       | 80                  | 5.20                          | 12.42                         | 58.64                         | 60.42                         |
| 4      | 0.1                     | Flat              | 40                       | 80                  | 28.00                         | 94.44                         | 17.14                         | 40.68                         |
| 5      | 0.1                     | On-edge           | 80                       | 20                  | 19.03                         | 27.16                         | 7.70                          | 22.90                         |
| 6      | 0.1                     | Upright           | 20                       | 40                  | 3.25                          | 85.88                         | 37.94                         | 33.31                         |
| 7      | 0.2                     | Flat              | 80                       | 40                  | 22.40                         | 87.74                         | 17.98                         | 27.78                         |
| 8      | 0.2                     | On-edge           | 20                       | 80                  | 24.78                         | 66.26                         | 12.52                         | 41.38                         |
| 9      | 0.2                     | Upright           | 40                       | 20                  | 2.80                          | 76.14                         | 25.75                         | 25.40                         |

3.1 Analysis of tensile test results

Table 7  Tensile test results

| K1  | 16.830 | 25.883 | 18.427 | 16.360 |
|-----|--------|--------|--------|--------|
| K2  | 16.760 | 20.617 | 16.280 | 14.563 |
| K3  | 16.660 | 3.750  | 15.543 | 19.327 |
| R   | 0.170  | 22.133 | 2.884  | 4.764  |

According to the extreme difference R, it was found that the primary relationship of the influencing factors was build direction > fill rate > fill rate > layer thickness. The test objective was to improve the tensile strength, the larger k, the better. The optimal level combination was A1B1C1D3 (0.05mm, Flat, 20mm/s, 80%). Layer thickness, infill density, and infill density had a negligible effect on the tensile strength. The tensile strength was the smallest in the vertical direction, however in this case the compressive mechanical property was much higher than the tensile mechanical property. Therefore it was suggested to avoid tension in this direction as much as possible. For the sake of intuition, a graph of the relationship between the factor indicators was shown in Figure 10.

3.2 Analysis of bending test results

Table 8  Bending test results

| K1  | 49.807 | 92.970 | 82.957 | 66.677 |
|-----|--------|--------|--------|--------|
| K2  | 69.160 | 44.563 | 70.283 | 71.297 |
| K3  | 76.713 | 58.147 | 42.440 | 57.707 |
| R   | 26.906 | 48.407 | 40.517 | 13.590 |

According to extreme difference R, it was found that the primary relationship of the influencing factors was build direction > fill rate > fill rate > layer thickness. The test objective is to improve the bending strength, and the larger k, the better. The better level combination was A3B1C1D2 (0.2mm, Flat, 20mm/s, 40%). The layer thickness with 0.2mm/s, build direction with Flat, infill density with 20mm/s, and infill density with 40% obtained the best-bending strength of the molded part, and its economy was relatively good. A graph of the relationship between the factor indicators was shown in Figure 11.

3.3 Analysis of compression test parameters

Table 9  Compression test results (a)

| K1  | 25.380 | 14.453 | 19.567 | 13.897 |
|-----|--------|--------|--------|--------|
| K2  | 20.927 | 9.827  | 17.383 | 21.727 |
| K3  | 18.750 | 40.777 | 28.107 | 29.433 |
| R   | 6.630  | 30.950 | 10.724 | 15.536 |
According to the extreme difference R, it was found that the primary relationship of the factors influencing the experimental results was build direction > fill rate > fill rate > layer thickness. The test objective was to improve the compression strength, and then the larger k was, the better. Meantime the better level combination was A3B1C1D2 (0.05mm, Upright ,80mm/s, 80%). A graph of the relationship between the factor indicators was shown in Figure 12. 

| Table 10 | Compression test results (b) |
|----------|-----------------------------|
| K1       | 37.677  | 30.953 | 33.030 | 24.233 |
| K2       | 32.297  | 30.830 | 31.430 | 29.767 |
| K3       | 31.520  | 39.710 | 37.033 | 47.493 |
| R        | 6.157   | 8.880  | 5.603  | 23.260 |

According to the extreme difference R, it was found that the primary relationship of the factors influencing the experimental results was infill density > build direction > layer thickness > infill density. The exploratory objective was to increase the compressive strength. The larger k, the better. The better level combination was A1B3C3D3 (0.05mm, Upright ,80mm/s, 80%). A graph of the relationship between the factor indicators was shown in Figure 13. The compressive strength of prism and cylinder specimens with the same process parameters was quite different due to the difference in structure. Firstly, the main influencing factor on the compressive strength of prismatic specimens was the build direction, whereas for cylindrical specimens, it was the infill density. Secondly, the effect of layer thickness on the compressive property of either prisms or cylinders was small, with a slightly more significant on prisms than that on cylinders. Finally, in terms of build direction and infill density, the impact on the compressive strength of prismatic specimens was much greater than that of cylindrical specimens.
4. Conclusions
This paper focused on the variation of four process parameters: layer thickness ($L_t = \{0.05, 0.1, 0.2\} \text{ mm}$), build direction (Flat, On-edge, Upright), filling speed ($F_r = \{20, 40, 80\} \text{ mm/s}$) and infill density (20%, 40%, 80%) under 3D printing by FDM, on the mechanical properties of PLA molded parts.

Among them, the influence of layer thickness on mechanical properties is bending strength $>$ compression strength $>$ tensile strength the order of magnitude. The build direction has a more significant impact on the mechanical properties, especially on the tensile strength, namely tensile strength $>$ bending strength $>$ compression strength in order. The infill density affects the mechanical properties in the order of bending strength $>$ compression strength $>$ tensile strength. The infill density has the greatest effect on the mechanical properties in bending strength $>$ tensile strength $>$ compressive strength.

For the user of a 3D printing system, it is particularly important to ensure the mechanical properties of the part, while also being as efficient and economical as possible. This requires a balance and trade-off in the choice of process parameters. Thus, when the molded part is mainly in tension, a larger layer thickness, a flat build direction, a larger filling speed, and a moderate infill density can be chosen. When the molded part is mainly subjected to bending, a moderate layer thickness, a flat build direction, a moderate filling speed, and a low infill density can be chosen. When the formed part is mainly subjected to compression, a medium layer thickness, a build direction of upright, a medium filling speed, and a low infill density is suggested.

At the same time, the mechanical properties of different colors of the same brand of filament were found to be different in the tests, which will be investigated and confirmed in the subsequent trials to inform better and help the users of 3D printers.

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