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Optimizing PLA Filament Production for Enhanced 3D Printing Performance

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Abstract

This research explores the optimization of polylactic acid (PLA) filament production to improve its performance in 3D printing applications. PLA is a widely used biodegradable polymer known for its eco-friendliness and ease of processing in additive manufacturing. The study investigates various parameters affecting PLA filament production, including material purity, extrusion temperature, filament diameter consistency, and cooling methods. Furthermore, the research evaluates how these fabrication parameters influence the printability of PLA filaments, considering factors such as layer adhesion, surface quality, and dimensional accuracy of printed objects. By fine-tuning the production process based on these findings, manufacturers can enhance the overall quality and reliability of PLA filaments for 3D printing, thereby advancing the capabilities of additive manufacturing technology.

Keywords: PLA Filaments, 3D Printing, fused deposition modelling, biodegradable polymer, additive manufacturing

INTRODUCTION

The advancement of additive manufacturing (AM), particularly 3D printing, has revolutionized various industries by enabling the fabrication of intricate three-dimensional (3D) objects with precision and efficiency [1–5]. Among the different materials utilized in 3D printing, polylactic acid (PLA) has emerged as a prominent choice due to its biodegradability, renewable nature, and ease of processing. PLA filaments are widely used in fused deposition modelling (FDM), a prevalent 3D printing technique known for its low cost, high reliability, and simplicity of operation [6–10]. While PLA filaments have gained popularity for their versatility and eco-friendly properties, optimizing their production process is essential to enhance their performance in 3D printing applications further [11–13]. The fabrication of high-quality PLA filaments involves meticulous control of various parameters, including material purity, extrusion temperature, filament diameter consistency, and cooling methods [14–18]. These parameters significantly influence the printability of PLA filaments, affecting factors such as layer adhesion, surface quality, and dimensional accuracy of printed objects [19–23].

Despite the increasing demand for PLA filaments in both industrial and home-based 3D printing applications, there remains a need to explore and refine the production process to achieve optimal performance [24–27]. This research aims to address this gap by investigating and optimizing the fabrication of PLA filaments for enhanced 3D printing performance [28–30]. By systematically analyzing the effects of fabrication parameters on filament quality and printability, this study aims to provide valuable insights into improving the overall reliability and efficiency of PLA filament production [31–35]. Ultimately, the findings of this research are expected to contribute to advancements

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in additive manufacturing technology, facilitating the broader adoption of PLA filaments in various sectors, including manufacturing, biomedicine, and education [36–42].

MANUFACTURING AND TESTING

The production of optimized PLA filaments for enhanced 3D printing performance involves several key steps:

Material Selection: High-quality polylactic acid (PLA) resin is chosen as the primary material for filament production due to its biodegradability, mechanical properties, and processability.

Filament Extrusion: The PLA resin is fed into an extrusion machine equipped with a screw mechanism. The resin is heated to its melting point and forced through a die to form a continuous filament of uniform diameter.

Diameter Control: Precise control of filament diameter is crucial for consistent printing performance. This is achieved by adjusting the extrusion speed and monitoring the filament diameter using laser sensors or calipers.

Cooling and Spooling: The extruded filament is rapidly cooled to solidify its shape and then wound onto spools for storage and transportation. Proper cooling ensures dimensional stability and prevents deformation during storage.

Fabrication of PLA Filaments

Commercially purchased PLA (4032D type) with an average particle size of 3.5 mm was utilized. Initially, the PLA particles underwent crushing into powders using a WL-A type grinder. These powders were then dried in vacuum conditions at 60°C for 8 hours before being introduced into a B-type desktop extruder for filament production [43–46]. The study explored the impact of varying extrusion temperatures (ranging from 190°C to 220°C in increments of 5°C) and screw rates (ranging from 2 to 8 rpm in increments of 2 rpm) on the quality of the extruded filaments.

3D Printing Filament

To assess the printability of the resulting filaments, a cuboid plate measuring 25 mm (L) × 25 mm (W) × 6 mm (H) was printed using a desktop 3D printer [47–50]. The typical printing parameters are outlined in Table 1.

Table 1. 3D Printer Parameters.

S.N.	Parameters	Values
1	Temperature of Extruder	220
2	Block Temperature	70
3	Speed of Extruding (With)	70
4	Speed of Extruding (Without)	140
5	Gap of Nozzle and Layer	0.2
6	Fill ratio	100

Characterization and Testing of Material

Diameter Measurement: The diameter of the monofilament was measured using a digital vernier caliper. Five monofilaments were tested, and ten measurements were taken for each monofilament. Measurements were conducted every 0.5 meters along the filament, and the results were averaged. Ultimate Tensile Stress Measurement: All tests were conducted at room temperature (T=25°C) using a Sansi stretcher. The stretching speed was set to 2 mm/s. The ultimate tensile stress (σ) was calculated according to Equation (1):

$$\sigma = \frac{F}{A} \tag{1}$$

Where:

- F represents the ultimate tensile force measured by a force meter,
- A denotes the fractured cross-sectional area of the filament.

During the test, the stretcher moves upward at a speed of 4 mm/s until the filament breaks. The maximum force (F) is automatically recorded, and the fractured cross-sectional area (A) of the filament is measured manually. The results from five samples were averaged. For reference, the ultimate tensile stress of a commercial sample of PLA filament was tested to be 59.1±4 MPa.

DISCUSSION ON RESULTS

Exploring the Influence of Extrusion Temperature and Screw Speed on Filament Diameter

The uniformity of filament diameter is crucial for its various applications. the diameter data of filaments produced under different processing conditions. It is evident that with a constant screw speed ranging from 2 rpm to 6 rpm, the filament diameter gradually decreases with increasing extrusion temperature, a trend also supported by Figure 1. This phenomenon aligns with the known principle that higher temperatures reduce melt viscosity, leading to improved melt flow and reduced die swelling effect. However, it was observed that PLA powders fail to completely plasticize when the extrusion temperature falls below 180°C, resulting in unsatisfactory filament formation. Moreover, Table 2 reveals that with a constant extrusion temperature, filament diameter increases as screw speed rises. This is attributed to the greater volume of melt extruded from the die at higher screw speeds, causing significant die swelling and resulting in a larger filament diameter during the subsequent cooling process.

Investigating the Impact of Extrusion Temperature and Screw Speed on Ultimate Tensile Stress

The ultimate tensile strength of the filaments is crucial for their applications. If the filament is too fragile, it risks fracturing during the deposition process, which severely disrupts the printing continuity. As illustrated in Table 3, the ultimate tensile stress of the filaments significantly exceeds 59.1±4 MPa when extrusion temperatures are set at 180°C or 200°C. The value slightly decreases for filaments fabricated under 200°C, while it diminishes considerably for those produced at 195°C. The lower mechanical properties observed in filaments obtained at 185°C or 200°C may be attributed to poor plasticization or defects within the filaments.

Table 2. Data of Extrusion process for temperature and Screw speed.

Speed	180°C	190°C	195°C	220°C
2Rpm	1.805	1.712	1.720	1.421
4Rpm	1.824	1.795	1.798	1.674
6Rpm	-	1.801	1.842	1.812
8Rpm	-	1.982	1.901	1.901

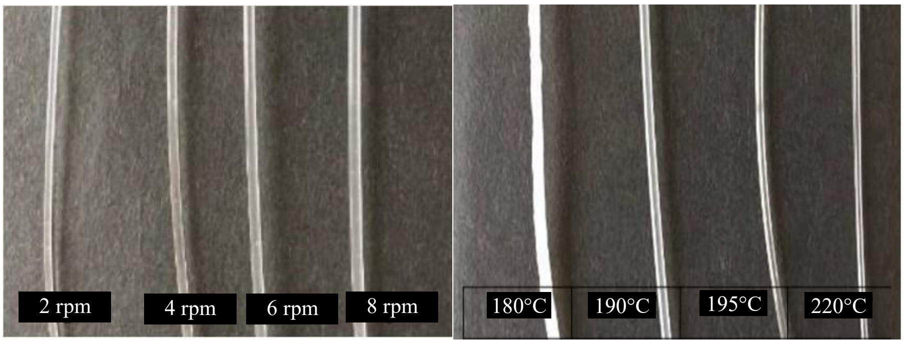

Figure 1. Image of filaments Manufactured a) Constant speed, b) Constant extrusion temperature.

Table 3. Tensile Stress for extrusion temperature and speed

Speed	180°C	190°C	200°C	220°C
2Rpm	6.12	59.12	51.87	53.12
4Rpm	5.98	58.45	54.45	54.78
6Rpm	--	59.78	55.12	55.17
8Rpm	--	59.32	54.12	53.14

Table 4. Printed part Quality with varying layer.

Diameter in mm	0.1	0.2	0.3
Error	0.02	0.024	0.051
Density	1.4	1.71	1.90
Roughness	5.4	9.2	12.14
Tensile Strength	51.8	50.12	49.12

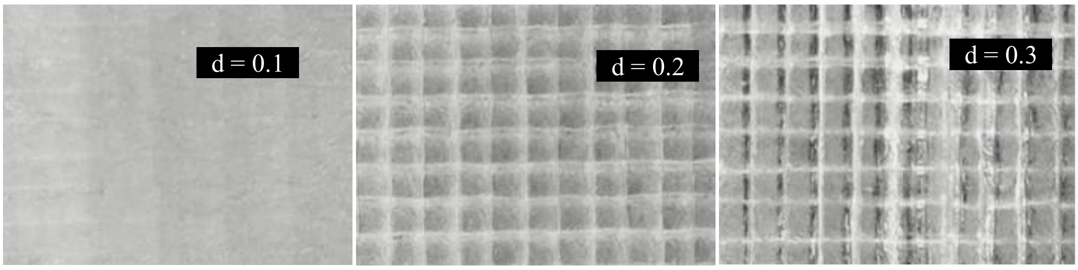

Figure 2. Surface Image of the printed part at different diameters.

Assessing the Printability and Performance of Certified PLA Filaments

The Influence of Build Layer on Part Quality: A Comprehensive Analysis

The build layer is a critical parameter for controlling the quality of printed parts. Typically, as the build layer decreases, the quality of the part improves. Through varying the build layer (d) from 0.1 to 0.3 mm with a 0.1 mm increment while keeping other printing parameters constant (as specified in Table 1), a series of samples were printed and subjected to tests for dimensional accuracy, surface roughness, density, and tensile strength [51–54]. As shown in Table 4, the experimental findings clearly demonstrate that the relative dimensional error of printed parts increases with an increase in the build layer. This is attributed to the higher printing accuracy achieved with more printing layers. Additionally, the surface roughness of parts increases with an increase in the build layer (as depicted in Figure 2). The surface traces of parts become more pronounced with a larger build layer due to the increased gap between the nozzle tip, resulting in greater printing roughness [55–58]. Furthermore, the density of parts increases with a decrease in the build layer. This is because a smaller gap between the nozzle tip leads to greater printing compactness. Regarding the tensile strength of parts, it increases with a decrease in the build layer. This can be attributed to the increased bond between layers with more printing layers, resulting in greater cohesive force [59–65]. Based on the data presented in Table 4, it can be concluded that the quality of printed parts is relatively higher when the build layer is set to 0.1 mm.

Exploring Temperature Optimal Parameters for Enhanced Performance

Extruder temperature is another crucial factor in controlling the quality of printed parts as it significantly influences the plasticization of the polymer filament [66]. By adjusting the extruder temperature (Te) from 200 to 230°C in 10°C increments while keeping other printing parameters constant as specified in Table 1, a series of samples were printed and subjected to tests for dimensional accuracy, surface roughness, density, and tensile strength. The data presented in Table 5 reveal that the relative dimensional error and surface roughness of parts decrease with an increase in extruder temperature within the range of 200 to 220°C. This trend is further confirmed by Figure 3. It is well understood that the liquidity of PLA increases with higher extruder temperatures, resulting in improved spreading and rebonding between PLA droplets when extruded through the nozzle. However, it should be noted that when the temperature exceeds 220°C, it becomes challenging to control the dimensional accuracy and surface roughness of printed parts due to the heightened liquidity of the material. Additionally, the observed density of parts increases with an increase in extruder temperature, attributed to the greater liquidity of PLA resulting in more material being deposited on the cuboid model. Furthermore, the tensile strength of parts also increases with an increase in extruder temperature. Nonetheless, temperatures above 220°C may initiate thermal degradation of the PLA filament, leading to the deterioration of material properties. Based on the data provided in Table 5, it can be concluded that the quality of printed parts is relatively higher when the extruder temperature is set to 220°C.

Speed Optimizing Parameters for Enhanced Performance

The speed while extruding (Ve) is another significant factor that greatly influences the quality of parts. Accordingly, by adjusting Ve from 30 to 120 mm/s in 30 mm/s increments while keeping other printing parameters constant as specified in Table 1, cuboid samples were printed and relevant properties were measured. The experimental findings presented in Table 6 indicate that the relative error (ε) and surface roughness (Ra) increase with an increase in Ve when it exceeds 60 mm/s. Notably, it becomes challenging to control the dimensional accuracy and surface roughness of printed parts at higher extruding speeds. However, it was also observed that when Ve is only 30 mm/s, the relative error value is somewhat larger than that at 60 mm/s. This could be attributed to 30 mm/s being relatively low, leading to more material deposition during part fabrication. As depicted in Figure 4, the surface traces of parts also confirm the results regarding surface roughness. On the other hand, the density and tensile

Table 5. Printed part Quality with different temperature.

	200°C	210°C	220°C	230°C
Error	0.04	0.19	0.012	0.04
Density	1.01	1.13	1.18	1.3
Roughness	9.21	8.7	5.4	8.7
Tensile Strength	41.9	46.1	52.1	49.1

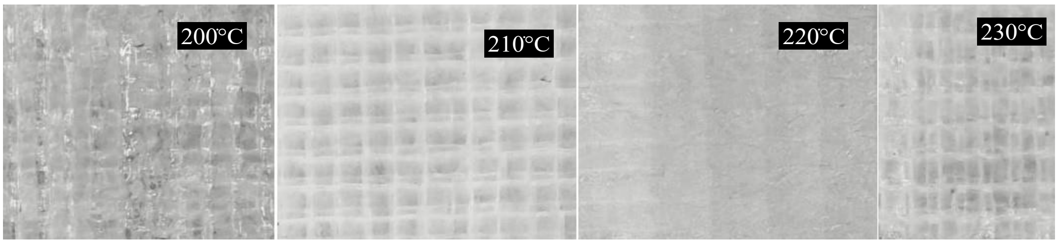

Figure 3. Surface Image of the printed part at different temperatures.

Table 6. Printed part Quality with different extruding speed

Ve Speed	30	60	90	120
Error	0.01	0.02	0.03	0.05
Density	1.2	1.19	1.02	0.91
Roughness	8.8	5.4	6.9	8.1
Tensile Strength	54.1	52.8	48.12	45.1

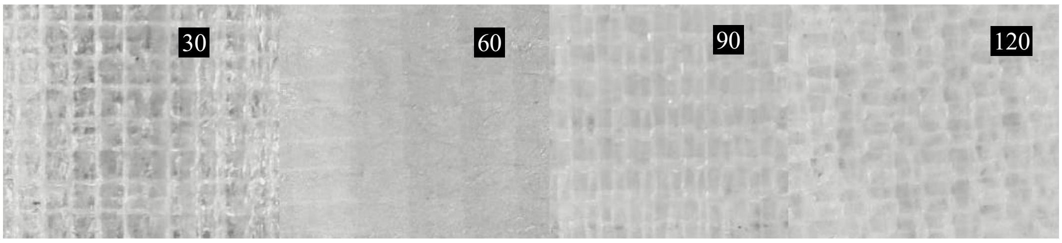

Figure 4. Surface Image of the printed part at different Speeds.

strength of parts were found to increase with a decrease in the speed while extruding. This is because faster speeds may result in more internal defects in parts. Based on the data provided in Table 6, it can be concluded that the quality of printed parts is relatively higher when the speed while extruding is set to 60 mm/s.

CONCLUSION

The preparation of PLA filaments for FDM 3D printing was thoroughly investigated using a desktop extruder specifically designed for household users. The study systematically examined the effects of extrusion temperature and screw speed on the filaments' diameter and ultimate tensile stress. It was determined that qualified filaments could be produced under conditions of extrusion temperature ranging from 180°C to 200°C and screw speed from 2 to 5 rpm. Furthermore, the printable performance of the obtained filaments was explored using a desktop 3D printer. It was discovered that the best printing effect, characterized by a relative dimensional error of 0.011, surface roughness of 5.2 μm, density of 1.16 g/cm3, and tensile strength of 51.7 MPa, could be achieved when the build layer was set to 0.1 mm, extruder temperature to 220°C, and speed while extruding to 60 mm/s. These findings are expected to be valuable for the 3D printing community, particularly for enthusiasts and small enterprises involved in 3D printing.

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