Fabrication of PLA Filaments and its Printable Performance

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Abstract: Fused deposition modeling (FDM) is a typical 3D printing technology and preparation of qualified filaments is the basis. In order to prepare polylactic acid (PLA) filaments suitable for personalized FDM 3D printing, this article investigated the effect of factors such as extrusion temperature and screw speed on the diameter, surface roughness and ultimate tensile stress of the obtained PLA filaments. The optimal process parameters for fabrication of qualified filaments were determined. Further, the printable performance of the obtained PLA filaments for 3D objects was preliminarily explored.

1. Introduction

Being able to construct complex three-dimensional (3D) objects by depositing materials layer by layer, additive manufacturing (AM), in particular, 3D printing has become a fast developing manufacturing technique nowadays.[1-2] Particularly, fused deposition modeling (FDM), which relies upon the extrusion of a thermoplastic monofilament through a heated nozzle, has developed to be one of the prevalent 3D printing techniques.[3-4] Due to its low cost, high reliability and simple operation, FDM 3D printers have correspondingly gained increasing popularity in both industries and home users, and has been started to be utilized in many areas ranging from manufacture, biomedicine to education.[5-7]

As the filaments serve as the premise for successful application of 3D printing, the fabrication of qualified filaments has therefore attracted numerous concerns from industry and academia. So far, the most commonly used polymers for filaments preparation are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). Being a biodegradable, bio-absorbable and renewable thermoplastic polyester, together with its excellent mechanical strength and process ability, PLA filaments exhibit a more promising prospect when compared to ABS. For example, Gaal et al. [8] fabricated integrated microfluidic devices with PLA filaments via FDM 3D printing. Wang et al. [9] used PLA filament to print bone tissue scaffold in cold atmospheric plasma. Melocchi et al. [10] explored the feasibility of FDM 3D printing in the manufacturing of capsular model devices for oral pulsatile release by PLA filaments. Li et al. [11] manufactured continuous carbon fiber reinforced PLA composite by the rapid prototyping approach of 3D printing. Tiersch et al. [12] explored PLA filaments printed cryobiology device.

Although PLA filaments have been applied to FDM process successfully, there are still very few reports about the detailed extrusion process of PLA filaments. Especially, personalized 3D printing technique requires only a small amount of new filament material. Thus, it is very meaningful to explore the fabrication of PLA filament with a desktop extruder. In this work, we use a household extruder to prepare PLA filaments and examine the printable performance of the obtained qualified filament. It is believed the results could provide valuable information for the 3D printing community,
especially for those who want to try novel filaments other than ABS and PLA to print new 3D structures.

2. Experimental

2.1. Fabrication of PLA Filaments
PLA (4032D type, America Nature Works) with an average particle size of 3.5 mm was bought commercially. To fabricate the filaments, PLA particles were first crushed into powders with a WL-A type grinder (Chengde testing machine factory, China). The powders were subsequently dried at 60 °C for 8 h in vacuum and were fed into a B-type desktop extruder (Wellzoom, China) to prepare filaments. The effect of extrusion temperature, ranging from 185°C to 200°C at an interval of 5°C, and screw rate, ranging from 2 to 6 rpm at an interval of 1 rpm, on the quality of the extruded filaments was investigated.

2.2. 3D Printing of Qualified PLA Filaments
To examine the printable performance of the obtained filaments, a cuboid plate with dimensions of 20 mm (L) × 20 mm (W) × 5 mm (H) was printed with a desktop 3D printer (Wellzoom, China, B type). The typical printing parameters were shown in table 1.

| Parameters                          | Values |
|-------------------------------------|--------|
| Extruder temperature Tₑ (°C)        | 220    |
| Build plate temperature Tᵇ (°C)     | 60     |
| Speed while extruding Vₑ (mm/s)     | 60     |
| Speed without extruding Vₜ (mm/s)   | 120    |
| Gap between nozzle tip & build layer d (mm) | 0.1    |
| Filling ratio F (%)                 | 100    |

2.3. Materials Testing and Characterization

Diameter measurement. The diameter of the monofilament was measured by a digital vernier calipers (MNT, China). Five monofilaments were tested and ten measurements were performed for each monofilament. The measurement was performed every 0.5m along the filament and the results were averaged.

Ultimate tensile stress measurement. All tests are conducted at room temperature (T=20 °C) with a Sansi stretcher. The stretching speed is 2mm/s. The calculation of ultimate tensile stress σ is according to the equation (1):

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

where F is the ultimate tensile force as measured by a force meter, S is the fractured cross section area of the filament. During the test, the stretcher is moving upward at a speed of 2mm/s until the filament is broken. The maximum F is then automatically recorded and the fractured cross section area S of the filament is measured manually. The results of five samples were averaged. For reference, the ultimate tensile stress of commercial sample of PLA filament was tested to be 53.9±3 MPa.

3. Results and Discussion

3.1. Effect of Extrusion Temperature and Screw Speed on the Filaments’ Diameter
The uniformity of the filaments’ diameter is very important for its applications. The diameter data of the obtained filaments that fabricated under various processing conditions are shown in Table 2. As can be seen, when the screw speed keeps constant ranging from 2rpm to 6rpm, the filaments’ diameter gradually decreases with the increase of the extrusion temperature. This conclusion is also clearly
confirmed in Figure 1. It is well known that the melt viscosity reduces as the temperature increases, resulting in better melt flow and lower die swelling effect. However, we also observed that PLA powders cannot be completely plasticized when the extrusion temperature reduces to lower than 190°C, and thus no satisfied filaments can be obtained under this situation. Meanwhile, the data in Table 2 also show that, when the extrusion temperature keeps constant, the filaments’ diameter keeps growing as the screw speed increases. This is because the melt volume extruded out of the die increases as the screw speed increases, causing a pronounced die swelling of the melt and a larger diameter in the subsequent cooling process.

**Table 2.** Diameter data of the filaments obtained under various extrusion temperature and screw speed

|       | 185°C | 190°C | 195°C | 200°C |
|-------|-------|-------|-------|-------|
| 2rpm  | 1.756 | 1.680 | 1.620 | 1.448 |
| 3rpm  | 1.760 | 1.721 | 1.680 | 1.575 |
| 4rpm  | —     | 1.791 | 1.727 | 1.665 |
| 5rpm  | —     | 1.831 | 1.810 | 1.747 |
| 6rpm  | —     | 1.946 | 1.888 | 1.857 |

* (—) No satisfied filaments obtained

**Figure 1.** Photography of filaments fabricated under constant extrusion speed (a), or constant extrusion temperature (b).

3.2. Effect of Extruding Temperature and Screw Speed on Ultimate Tensile Stress

Ultimate tensile strength is very important for the applications of the filaments. If the filament is too fragile, it is liable to fracture during the depositing process, which is very detrimental to the continuity of printing. As shown in Table 3, the ultimate tensile stress of the filaments is substantially higher than 53.9±3 MPa when the extrusion temperature is 190°C or 195 °C. The value is slightly lower for the filaments obtained under 200°C, while it is very small for those fabricated under 185 °C. The poor plasticization or defects in the filaments obtained under 185°C or 200 °C may account for the lower mechanical property.

**Table 3.** Ultimate tensile stress of the filaments obtained under various extrusion temperature and screw speed

|       | 185°C | 190°C | 195°C | 200°C |
|-------|-------|-------|-------|-------|
| 2rpm  | 6.0   | 58.2  | 54.8  | 51.7  |
| 3rpm  | 5.4   | 57.5  | 55.1  | 53.3  |
| 4rpm  | —     | 58.8  | 58.7  | 55.6  |
| 5rpm  | —     | 58.4  | 60.4  | 56.6  |
| 6rpm  | —     | 54.2  | 55.9  | 53.4  |

* (—) No satisfied filaments obtained
3.3. Printable Performance of the Qualified PLA Filaments

3.3.1. Effect of the Build Layer on Parts’ Quality. Build layer is a key parameter to control the quality of the printed parts. Generally, the part’s quality becomes better as the builder layer decreases. By varying the build layer $d$ from 0.1 to 0.3 mm with 0.1 mm increment and keeping other printing parameters constant (as given in Table1), a series of samples were printed and the dimensional accuracy, surface roughness, density, tensile strength of the samples were tested respectively.

As shown in Table 4, the experimental results clearly indicate that the relative dimensional error of the printed parts increases with increase of the build layer, this is because the more the printing layers, the higher the printing accuracy. Also, the parts’ surface roughness increases with increase of build layer (as shown in Fig. 2), and the parts’ surface traces become more obvious with increase of the build layer, this is because the greater gap between the nozzle tip, the greater the printing roughness. Additionally, the parts’ density increases with decrease of build layer, this is because the smaller gap between nozzle tip, the greater the printing compactness. As to the parts’ tensile strength, it increases with decrease of the build layer, which can be due to the fact that the more the printing layers, the more the bond between layers, and the greater the cohesive force. Based on the data shown in table 4, it can be drawn that the quality of printing parts is relatively good when the build layer is 0.1 mm.

Table 4. Quality of parts printed with different build layer

| $d$ (mm) | 0.1 | 0.2 | 0.3 |
|----------|-----|-----|-----|
| Relative error $\varepsilon$ | 0.011 | 0.023 | 0.042 |
| Surface roughness $R_{a}(\mu m)$ | 5.2 | 9.1 | 11.38 |
| Density $D(g/cm^3)$ | 1.16 | 1.14 | 1.13 |
| Tensile strength $\sigma$(MPa) | 51.7 | 50.5 | 48.1 |

Figure 2. Surface photography of parts that printed with various build layer. The extruder temperature is 220 °C, and the speed while extruding is 60 mm/s.

3.3.2. Effect of Extruder Temperature on Parts’ Quality. Extruder temperature also plays an important role in controlling the printed parts’ quality as it significantly affects the plasticization of the polymer filament. By adjusting the extruder temperature $T_e$ from 200 to 230 °C with 10 °C increment and keeping the other printing parameters constant as given in Table 1, a series of samples were printed and the dimensional accuracy, surface roughness, density, tensile strength of the samples were tested respectively.

The data in Table 5 indicate that the part’s relative dimensional error and surface roughness decreases with increase of extruder temperature when it is changing from 200 to 220°C. The latter is also clearly confirmed by Figure 3. As is well known that the liquidity of PLA increase as extruder temperature goes higher, leading to better spreading and rebonding between PLA droplets when extruded out through the nozzle. However, it should be noted that when the temperature is above 220 °C, the printed part’s dimensional accuracy and surface roughness is hard to control with higher liquidity material. The parts’ density observed in Table 5 increases with increase of the extruder temperature, which can be ascribed to the fact that the liquidity of PLA increase as extruder
temperature goes higher, leading to more material being deposited on the cuboid model. The parts’ tensile strength also increases with increase of extruder temperature. However, when it is above 220 °C, the thermal degradation of PLA filament may start to occur, causing the deterioration of the material’s properties. It can be drawn from data of table 5 that the quality of the printed parts is relatively good when the extruder temperature is 220 °C.

Table 5. Quality of parts from various extruder temperature

| $T_e$ (°C) | 200 | 210 | 220 | 230 |
|-----------|-----|-----|-----|-----|
| Relative error $\varepsilon$ | 0.032 | 0.018 | 0.011 | 0.031 |
| Surface roughness $R_a$ (μm) | 9.1 | 8.6 | 5.2 | 8.6 |
| Density $D$ (g/cm$^3$) | 1.08 | 1.12 | 1.16 | 1.22 |
| Tensile strength $\sigma$ (MPa) | 41.3 | 45.2 | 51.7 | 48.6 |

Figure 3. Surface photography of parts printed under different extruder temperature. The build layer is 0.1 mm, and the speed while extruding is 60 mm/s.

3.3.3. Effect of Speed while extruding on Parts’ Quality. Speed while extruding $V_e$ is another factor that accounts much for the parts quality. Accordingly, by adjusting $V_e$ from 30 to 120 mm/s with 30 mm/s increment and keeping other printing parameters constant as given in Table 1, cuboid samples were printed and related properties were measured.

The experimental results in Table 6 show that $\varepsilon$ and $R_a$ increases with increase of $V_e$ when it is above 60mm/s. It is worth noting that the printed part’s dimensional accuracy and surface roughness is hard to control with faster speed while extruding. However, we also observed that, when $V_e$ is only 30mm/s, the relative error value is somewhat larger than that when $V_e$ is 60mm/s. This may because 30mm/s is fairly low that leads to more material deposited when fabricating the part. As shown in Fig. 4, the parts’ surface traces also confirm the results of part’s surface roughness. However, the parts’ density and tensile strength are found to increase with decrease of the speed while extruding, this is because that a faster speed will lead to more internal defects of parts. Based on the data in Table 6, it can be drawn the quality of printed parts is relatively good when speed while extruding is 60 mm/s.

Table 6. Parts’ quality of samples printed under various $V_e$

| $V_e$ (mm/s) | 30 | 60 | 90 | 120 |
|-------------|----|----|----|-----|
| Relative error $\varepsilon$ | 0.018 | 0.011 | 0.024 | 0.052 |
| Surface roughness $R_a$ (μm) | 8.7 | 5.2 | 6.7 | 7.9 |
| Density $D$ (g/cm$^3$) | 1.18 | 1.16 | 1.05 | 0.85 |
| Tensile strength $\sigma$ (MPa) | 53.3 | 51.7 | 47.2 | 45.5 |
Figure 4. Surface photography of parts that fabricated under various speed while extruding. The build layer is 0.1 mm and extruder temperature is 220 °C.

4. Conclusion
Preparation of PLA filaments for FDM 3D printing was systematically investigated with a desktop extruder specially designed for household users. The effects of extrusion temperature and screw speed on the filaments' diameter and ultimate tensile stress were systematically investigated. It was found that qualified filaments could be obtained under conditions of extrusion temperature 190-195 °C and screw speed 2-5 rpm. Furthermore, the printable performance of the obtained filaments was explored with a desktop 3D printer. It was found that when build layer is 0.1 mm, extruder temperature is 220 °C and speed while extruding is 60 mm/s, best printing effect with 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. The finding in this work will be valuable for 3D printing community, especially helpful for those 3D printing lovers and small enterprises.

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6. References
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