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Analysis of Extrusion Process Parameters in PLA Filament Production for FFF Technology

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Additive technologies are becoming a common part of not only prototype production, but also piece or small series production. However, the choice of technology and material plays a key role in the applicability of the manufactured parts. The most widespread type of additive technology is FFF technology, which consists of applying a fused plastic string in single layers. The resulting mechanical properties of parts produced using this technology depend not only on the material and structure selected, but also on the process parameters used in the printing process itself. This study deals with the production of filament from PLA, which is the primary material. The advantage is its environmental degradability after the end of the life cycle of PLA products. However, the resulting properties of the printed parts may depend on the way the filament is prepared and in particular on the melt temperature during filament extrusion. This study investigates the effect of the produced filaments on the quality of printed parts. It has been shown that the filament production technology has a significant effect on the quality of printed parts.

Keywords: Extrusion, Filament, PLA, Additive manufacturing

1 Introduction

In the field of additive manufacturing, Fused Filament Fabrication (FFF) is an innovative approach to printing three-dimensional objects. The central element of this technology is the extrusion of thermoplastic filament through a print head that gradually applies thin layers of material to create the desired shape. Although the process appears relatively simple, understanding and selecting the factors affecting the filament extrusion are key aspects of achieving results with good quality and mechanical properties of the printed objects. [1-3]

Filament production at the industrial level takes place on large extrusion lines. Due to the downsizing of production facilities, filament can also be produced in prototype construction, at laboratory level and in the private sector. In the production of filament, virgin polymer or somehow mixed polymer is used. [4-7] Process parameters for pure polymers are provided by the manufacturer in the form of material data sheets. However, these parameters must still be served on a specific machine.

One of the determinants of the FFF printing process that is investigated in detail in this study is the filament processing temperature. [8-10] The temperature of heating the thermoplastic material to the melt state has a significant impact on the material fluidity, which affects the filament quality and final product properties. At the same time, it is crucial to investigate how different processing temperatures affect the specific material used for printing. [11-13]

Another important factor to analyze is the filament diameter. The estimated size of the printed details, the printing accuracy and the properties of the final product are directly linked to the filament diameter. While a wider filament may be associated with faster printing and the ability to produce more robust structures, a narrower filament allows for greater accuracy and detail. [14-16]

In light of these challenges, this study takes a detailed look at the process of printing PLA on 3D printing devices. [17-22] The effect of filament quality on the stability of the printing process was studied with emphasis on determining the most suitable process parameters. The main goal of this study is to identify the factors affecting the quality and consistency of the printing process when using PLA and to propose strategies for identifying process parameters. This study represents a step towards a better understanding of the challenges and opportunities associated with PLA in 3D printing, with an emphasis on improving print quality and process efficiency in the context of sustainable additive manufacturing development.

2 Experimental Part

The aim of this study is to evaluate in detail the effect of processing temperature and filament diameter on the FFF printing process and on the final properties of the produced filament. This investigation will not only provide a deeper understanding of the interactions between these variables, but will also offer practical recommendations for the selection of filament production parameters with respect to specific application and material requirements.

This study will systematically analyse the effect of processing temperature and filament diameter on key printing parameters, strength and overall quality of the filament produced. These experimental procedures and results will then lead to a detailed discussion of the correct extrusion settings depending on the specific requirements and material, which can provide a valuable basis for further development and application of FFF printing technology.

2.1 Material

Polylactic acid (PLA) is a key material in Fused Filament Fabrication (FFF) printing, where it rises above other polymers due to its unique combination of properties. It is based on renewable raw materials, often derived from plant sources, which ensures environmental sustainability. PLA is biodegradable, which means it has the potential to reduce the environmental impact in terms of waste from 3D printing processes. In addition, PLA is easy to print at lower temperatures, making it easier to use in home printers. This feature contributes to seamless printing and ensures the material is widely available to a range of users.

However, the challenges associated with PLA's low heat resistance and specific mechanical properties limit its use in specific industrial applications where high temperatures or significant durability are required. Researchers are exploring ways to modify PLA, including adding glass or carbon fibers, which can improve strength and heat resistance. Scientific efforts are being directed towards further understanding the structure and properties of PLA and innovative processing methods to expand its potential in additive manufacturing and 3D printing. Tested in this study is PLA - SUPLA 018.

2.2 Production

For the production of the printing filament, a machine from the brand 3devo was chosen, which is a complete small production line for the printing filament. The machine is produced in several variants, for high or standard processing temperatures, or with a mixing or precision screw. The variant used was the Composer 450, which features a mixing auger to guarantee better mixing results for the materials being processed and the additives being added. Thanks to its dimensions of 650 x 370 x 650 mm, the machine is very portable.

The extrusion chamber contains 4 heating zones, which are marked H4, H3, H2, H1 (Tab. 1), from the hopper to nozzle direction, these zones reaching temperatures up to 450 °C. A hardened screw is used for extrusion, made of high chromium and molybdenum alloy steel.

The cooling system contains two positionable fans for even air distribution. The fan speed has been set at 55 % of the total speed range. The diameter sensor includes an optical sensor that is designed to measure diameters from 0.5 mm to 3.0 mm. Underneath it is a retraction system that automatically adjusts for precise diameter control.

The filament positioner automatically places the filament on a spool whose size has been pre-set on the extruder according to the parameters of the spool being used, so that a neat uniform winding occurs.

The desired temperature for extrusion of the material, the screw speed, the cooling of the fans and the diameter of the extrusion were set on the machine. A nozzle with a diameter of 4 mm was used. After the 4 temperature zones have been heated to the desired temperature, the working screw is started at the set speed.

The extruded material was pulled through the optical sensor and attached to the extraction system. This was followed by a delay, where the extraction was automatically regulated to reach the set diameter of the extruded material. After calibration of the retraction, the extruded material was pulled through the positioner and the filament was attached to the prepared spool stored in the winding system.

The filament was made from virgin PLA granulate, which was dried for 12 hours at 50 °C in a Binder FD 56 laboratory dryer. The extrusion diameter of filament was set to 1.75 mm, and the speed of the rotating screw was set to 4 rpm.

Tab. 1 *Marking and processing temperatures of materials*

Material	PLA 165	PLA 175	PLA 185
H1 – nozzle [°C]	165	175	185
H2 [°C]	180	190	200
H3 [°C]	175	185	195
H4 – hopper [°C]	165	175	185

2.3 Methods

The tensile test was performed on a LabTest 6.50 universal testing machine. The test was carried out according to EN ISO 6892-1. The crosshead speed during the modulus measurement was 5 mm/min and the crosshead speed during the actual test was 50 mm/min. Each measured value was obtained from 10 measurements, which were then statistically evaluated.

The measurements were carried out at room temperature of 23 °C at 50 % humidity. The distance between the axes of the fixture was 150 mm. Before each measurement, the diameter of the string was remeasured to match the diameter values entered into the software.

The technological reverse bend test of filament was performed according to ISO 7801. This standard is for steel wires, but in principle can be used for plastic wires. The test filament is bent 90° alternately in both directions. One movement is defined as bending the free end of the test body by 90° and returning it to its starting position. The next bend is made in the opposite direction.

Keyence VHX-1000 digital microscope was also used during the inspection. It is a 3D laser confocal microscope with high resolution, down to nanometers. It can be used to scan and measure the surface and evaluate the profile, roughness or film thickness.

Last test was printing test. The filaments were tested on the MiniTest model (Fig. 7). The model was printed on a Zortrax M200 Plus printer. A layer height of 0.19 mm was selected for printing.

There are many parts on the model that can be evaluated. In total, 7 areas were visually smoothed as follows:

- 1) Hole test – here the printing of three circular holes of 4, 3, 2 mm diameter and the printing of three rectangular holes of 10 mm length and 4, 3, 2 mm width were observed. Attention was focused on observing the smooth circular hole walls and the sharp corners of the rectangular holes.
- 2) Diameter test – in this test, the circularity of two cylinders of 8 and 6 mm diameter was evaluated to see if they were deformed and formed a perfect cylinder.
- 3) Stringing test – in this test, the space between the prisms placed in height was observed and the presence of residual material in the form of strings was observed.
- 4) Scale test – the test focused on the shape and dimensions of the prisms and it was observed whether these parameters are the same at different rotations
- 5) Bridging test – bridging of material at 2, 5, 10, 15, 20, 25 mm was observed. Attention was focused on deformation and imperfectly stiffened material which can be seen in the form of loose fibers.
- 6) Support test – in the test, the functionality and stability of the supports that are removed after printing were observed.
- 7) Overhang test – in this test, the correct geometry (angle), quality of printed description and quality of outer and inner surface are checked.

3 Results and Discussion

3.1 Mechanical tensile tests - Ultimate tensile strength

The Fig. 1 shows the tensile property values of PLA polymer at room temperature. The test values showed that the highest strength was achieved by PLA 175 material - 66.2 MPa. Which is more than three percent more than PLA 185 material which has the lowest strength.

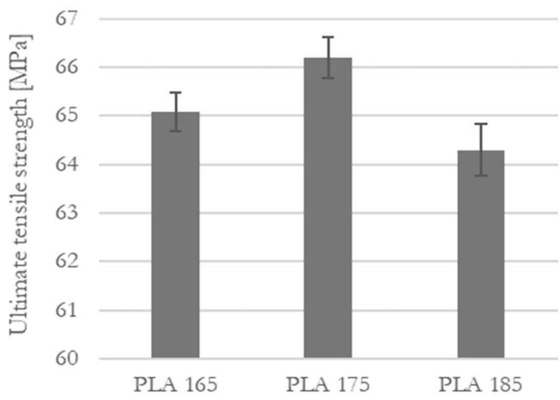

Fig. 1 *Ultimate tensile strength*

3.2 Mechanical tensile tests – Strain

The effect of processing temperatures on the relative elongation in tension (Fig. 2) at room temperature is more evident than in the previous case. The PLA 165 material deformed (20.1%) the most under stress, approximately four percent more than the other materials.

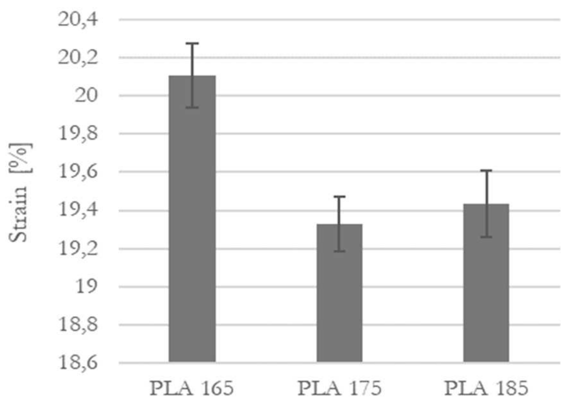

Fig. 2 *Strain*

3.3 Extruded diameter of filament

The Composer 450 extruder can be connected to a computer via USB with the ability to record process conditions. In Fig. 3, the filament diameter measurement for one hour for all three materials can be observed. The PLA 165 and 185 materials crossed the imaginary limit of the large range (±0.1 mm). PLA 175 approached but did not exceed this upper limit. This material also exhibited the longest and steepest average filament diameter of (1.750 ± 0.028) mm. Which is a very more or less ideal diameter. PLA 185 has (1.748 ± 0.030) mm and the PLA 165 material had the worst diameter with the largest variance of values at (1.752 ± 0.047) mm.

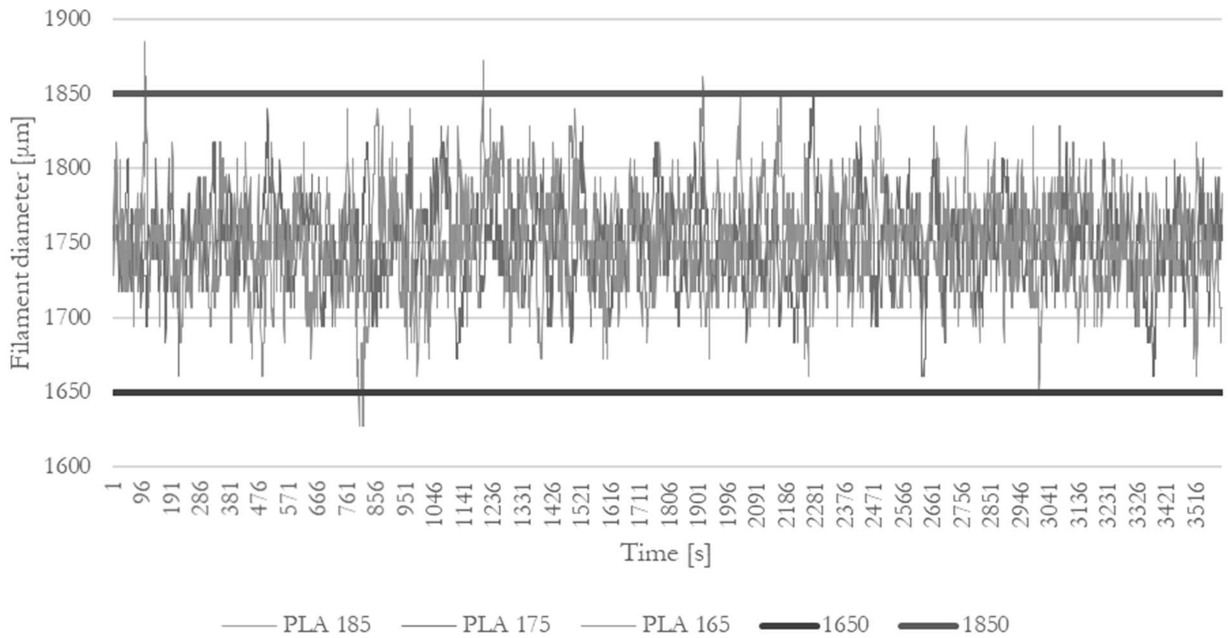

Fig. 3 *Filament diameter in time*

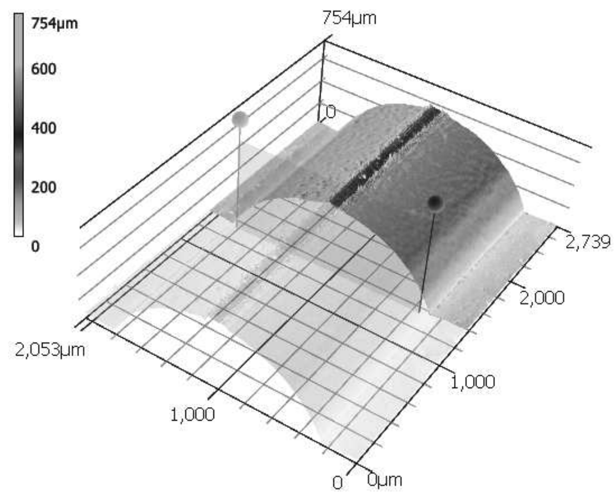

Fig. 4 *Microscope measurements images*

Measurements on the confocal microscope (Fig. 4 and Fig. 5) partially correspond to measurements directly on the extruder. The size of the diameters are approximately similar depending on the extrusion temperatures. Their absolute size is slightly smaller, because the microscope measured the filaments at room temperature, but the extruder measured them at elevated temperature, shortly after the filament solidified. Measurements on the microscope were taken at 10 random locations versus continuous measurements on the extruder over the course of an hour.

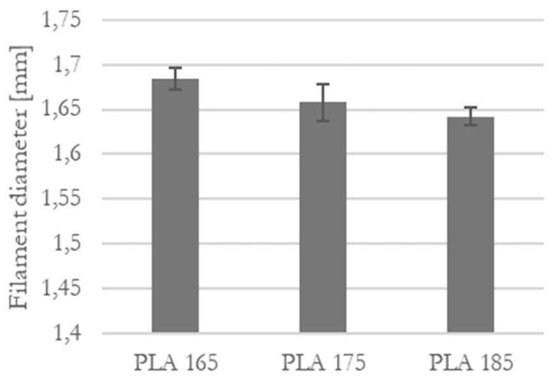

Fig. 5 *Filament diameters*

3.4 Motor current

An interesting Fig. 6 to read from the machine is the motor current. The motor current required to extrude the material at the temperatures tested. The highest consumption is at a low temperature of 165 °C - the average consumption is 1.9 A. By gradually increasing the processing temperature by 10 °C, the consumption decreases by 0.1 A.

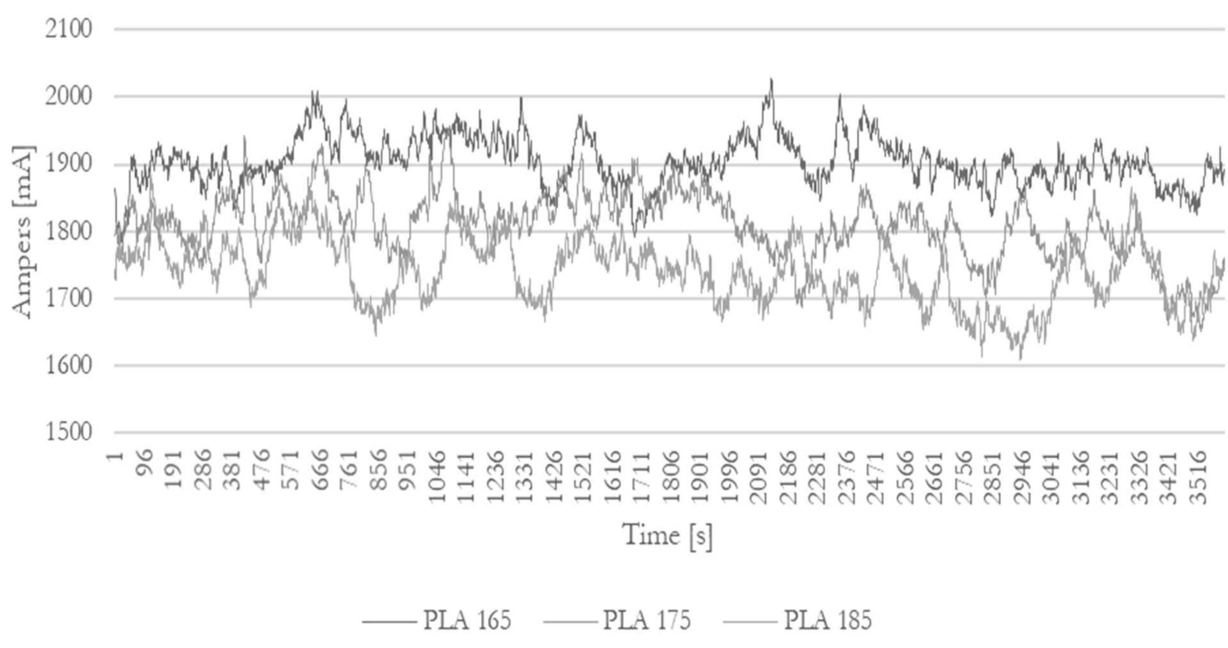

Fig. 6 Motor current in time

3.5 Reverse bend test

The technological test was performed by alternating bending (Fig. 7). When the filament was caught in the fixture and the bending to one side and the other was started and the number of bends before the filament broke was counted. PLA 165 and 175 exhibit similar behavior, breaking at approximately 6.5 bends. But PLA produced at 185 °C will break on average one bend earlier.

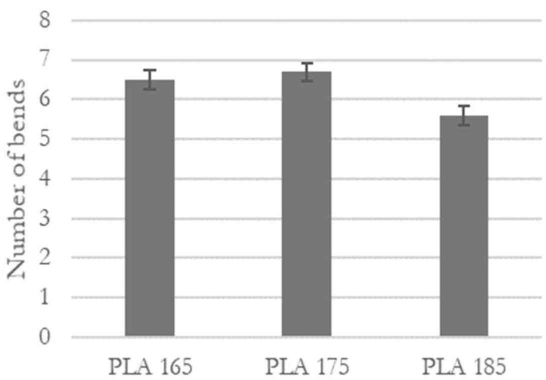

Fig. 7 Reverse bend test

3.6 Printing test

Finally, the filament was tested on the MiniTest model (Fig. 8). The prints were visually inspected and scored. For the evaluation of the samples, scores 1-5 (5 - best, 1 - worst) (Tab. 2) were determined. PLA 175 performed as the best, being able to collect the most of all parts of the tests. It performed similar to PLA 165 material. The worst performer was PLA 185, which, as in other types of tests, has worse results.

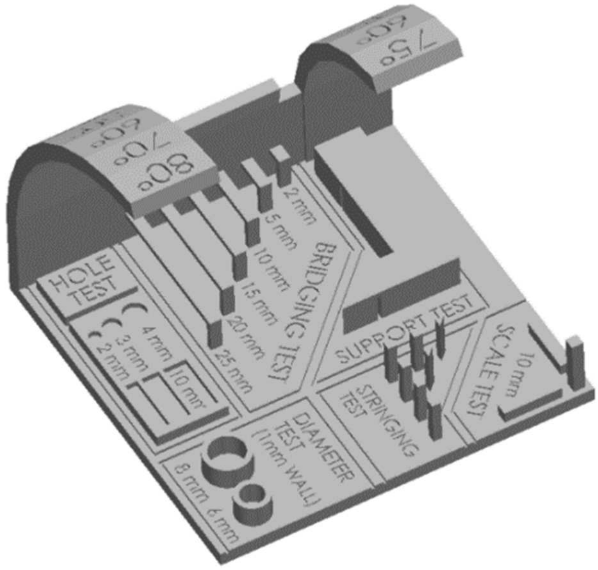

Fig. 8 Printing Mini test

Tab. 2 Mini test points

Mini test	Material		
	PLA 165	PLA 175	PLA 185
Hole test	4	5	4
Diameter test	3	4	3
Stringing test	4	5	3
Scale test	5	4	4
Bridging test	4	4	3
Support test	3	2	2
Overhang test	1	2	1
Result	24	26	20

4 Conclusions

The main objective of the research work is to study filament extrusion for 3D printing with emphasis on the choice of extrusion temperatures. Experiments are performed to investigate the effect of different extrusion temperatures on the physical properties of the filament, in particular on the strength limit, which represents the mechanical resistance of the material. In addition, the stability of the filament diameter is monitored, as precise and uniform dimensions are crucial for the quality and accuracy of printed objects.

The research also includes a comparison of visual printed products created under the same 3D printing conditions. This comparison focuses on the aesthetic and surface properties of the printed objects and their possible influence on the overall visual impression. The goal of the study was to find the most suitable parameters for the production of filament that was extruded on a laboratory extrusion device. The results show that the process conditions of filament production have a significant effect on the quality of printed products.

The results show that the optimum melt temperature for extrusion is 175 °C. At this temperature, the filament cross section was the most consistent, as well as showing the best mechanical properties compared to the other tested filaments. However, as the melt temperature was decreased but also increased by 10 °C, the mechanical properties of the filaments deteriorated. As far as the quality of the prints is concerned, it slightly decreased with decreasing melt temperature, however, there was a significant deterioration in the quality of the 3D printed PLA part with increasing melt temperature. In conclusion, it can be stated that not only the material itself but also the filament production technology has a significant effect on the quality and final behaviour of the 3D printed parts.

The results offer useful information for the production of PLA printing filament and highlight the importance of choosing the right parameters to achieve high quality and consistent printed objects. This study will further investigate the possibility of preparing a filament from modified PLA material that will have increased temperature stability but also maintain its biodegradability. This modified PLA filament is expected to be more sensitive to both the process conditions of the filament and the process conditions of the 3D printing itself.

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