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Production and dimensional analysis of filament from recycled PLA material

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Abstract: This study focuses on the recycling of polylactic acid (PLA) waste generated during 3D printing using Fused Filament Fabrication (FFF) technology and its reuse to produce recycled filament. The main objective was to evaluate the dimensional accuracy of filament produced from recycled PLA material. The recycling process consisted of shredding printed PLA specimens, drying the resulting granulate, and subsequently re-extruding the material using a laboratory-scale filament extrusion system. During the extrusion process, the filament diameter was continuously monitored using an integrated optical sensor with a nominal target diameter of 1.75 mm. The dimensional stability of the produced filament was subsequently evaluated using descriptive statistical analysis. The results demonstrated that most of the measured diameter values remained within the predefined tolerance range of 1.65–1.85 mm, indicating a relatively stable and controlled extrusion process. The average filament diameter reached a value of 1.747 mm, corresponding to the nominal target value. Only a negligible exceedance of the upper tolerance limit was recorded, with the maximum measured diameter reaching 1.851 mm. Statistical analysis revealed slight variability in the diameter values, most likely caused by the inhomogeneity and varying granule size of the recycled material after the shredding process. The findings confirm that recycled PLA material can be successfully reprocessed into filaments suitable for FFF 3D printing applications. The study also highlights the potential of PLA recycling in supporting sustainable and environmentally responsible additive manufacturing while maintaining acceptable filament quality and dimensional stability.

1 Introduction

Additive manufacturing represents one of the most significant technologies in modern industrial production, while Fused Filament Fabrication (FFF) technology is among the most widely used methods of 3D printing. This technology utilizes thermoplastic filaments that are gradually melted and deposited layer by layer into the desired shape of the product [1]. One of the most used materials is polylactic acid (PLA), which is particularly popular due to its biodegradability, low processing temperature, minimal warping during printing, and favorable mechanical properties [2]. PLA is a polymer derived from renewable resources such as corn starch or sugarcane, making it a more environmentally friendly material compared to conventional plastics [3].

However, with the increasing use of 3D printing, the amount of waste generated during filament production, failed prints, and support structures is also growing. This issue has led to increased interest in the recycling of PLA materials and their reuse in the production of new filaments [4]. PLA recycling represents an important step toward the principles of the circular economy and sustainable manufacturing [5]. Mechanical recycling, based on shredding, melting, and re-extrusion of the material, is considered one of the most promising methods for processing waste from 3D printing [6]. Nevertheless, the repeated extrusion process causes degradation of polymer chains, leading to a reduction in the molecular weight of the material and deterioration of its mechanical and rheological properties [7]. Several studies have demonstrated that recycled PLA material exhibits changes in strength, toughness, viscosity, and dimensional stability of the filament [8]. Hidalgo-Carvajal et al. reported that PLA from a controlled source can be re-extruded approximately three times without significant degradation of properties, whereas mixed-source waste shows faster deterioration of parameters [9]. These changes significantly affect the quality of the resulting filament and consequently the quality of 3D printing. One of the most important parameters of a filament is its diameter and dimensional accuracy. The standard

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filament diameter for FFF technology is most commonly 1.75 mm or 2.85 mm, while diameter tolerance significantly affects the stability of material extrusion during printing [10]. An uneven diameter causes fluctuations in the volume of extruded material, leading to product defects, under-extrusion, or over-extrusion [11]. In the production of filaments from recycled PLA, ensuring dimensional stability is more challenging due to the changing rheological properties of the material during repeated processing [12]. Dimensional analysis of the filament therefore represents an important part of evaluating the quality of recycled material. Modern measurement systems use optical sensors and laser measuring devices that enable continuous monitoring of filament diameter during extrusion [13]. Petsiuk and Pearce proposed an open-source optical filament diameter measurement system that allows monitoring of diameter deviations along the entire length of the material and identification of critical points arising during production [14]. Such systems significantly contribute to the optimization of production parameters and improvement of the quality of recycled filaments. An important factor in the production of recycled PLA filaments is also the adjustment of extrusion technological parameters such as melting temperature, extrusion speed, cooling conditions, and filament winding speed [15]. Improperly selected parameters may cause diameter fluctuations or the formation of internal material defects [16]. Research indicates that combining recycled and virgin PLA materials can improve both the mechanical properties and dimensional stability of the filament [17]. Another promising solution is filament coextrusion, in which the core consists of recycled material while the outer layer is made of virgin PLA [18].

Currently, filament recycling is intensively investigated mainly from the perspective of sustainability and economic efficiency of additive manufacturing. Dimensional analysis of filaments represents one of the key indicators of recycled material quality and directly affects the reliability of the 3D printing process [19]. Therefore, research in the field of recycled PLA filaments is focused on optimizing production processes, minimizing material degradation, and ensuring stable dimensional properties of the filament [20]. The aim of this study is to utilize recycled PLA material to produce a new filament and to analyze it from the perspective of dimensional diameter accuracy.

2 Methodology

2.1 Material

As an input material to produce recycled filament, PLA filament (Smart PlastIQs, Slovakia) was used, which had previously been utilized in the fabrication of test specimens intended for mechanical testing. The test specimens were manufactured using the 3D printing process according to the parameters specified in Table 1. The basic physical and mechanical properties of the applied material are presented in Table 1 and are based on the technical documentation provided by the filament manufacturer.

Table 1 Printing parameters of initial objects and basic properties of PLA material

Basic properties of PLA material		**Printing parameters of initial objects**	
Melting temperature (Tm)	150 – 180 °C	Nozzle Temperature	220 °C
Glass transition temperature (Tg)	55 – 65 °C	Bed Temperature	60 °C
Tensile strength	~ 55 MPa	Cooling during extrusion	100%
Density	1.24 g/cm^3	Speed	60 mm/s
Printing shrinkage	0,2 – 0,5 %	Infill	100%

2.2 Material recycling and filament creation

The overall recycling process consisted of the material crushing process, the material drying process, and material extrusion process (see Figure 1).

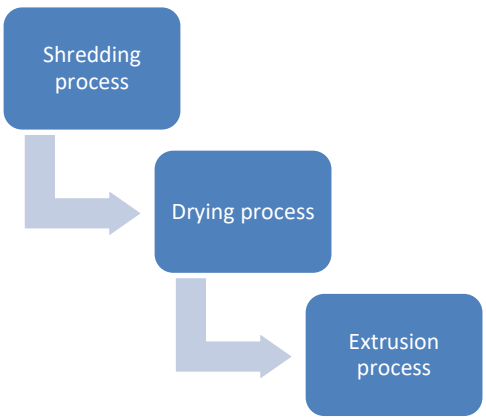
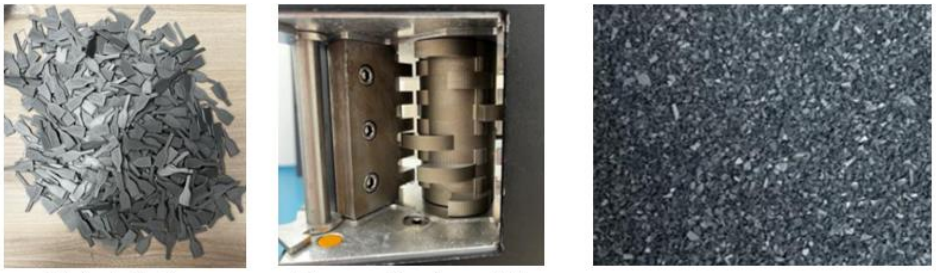


Figure 1 Process diagram of PLA material recycling and filament production

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Shredding process

The first step of the process involved the mechanical shredding of the printed models. For this purpose, a hybrid polymer shredder, SHR3D (3devo, Netherlands), was used, into which the material was manually fed through the upper inlet opening. The shredding process was carried out gradually and at a low material feed rate, as continuous and excessively rapid feeding may lead to increased friction between the material fragments and the shredding mechanism. After completion of the shredding process, the size of the shredded material granules was measured using a caliper. The granule size ranged from 2 mm to 4 mm. Figure 2 illustrates the objects prior to shredding as well as the resulting mixture of PLA material.



Objects before shredding | The mechanism of the shredding device | Final mixture

Figure 2 PLA material shredding process

Drying process

Due to the hygroscopic nature of PLA, which leads to the absorption of moisture from the surrounding air, it was necessary to dry the material again after the shredding process prior to extrusion. The PLA granulate was dried at a temperature of 45 °C for 5 hours in order to remove excess moisture and stabilize the material properties before extrusion processing. The drying process was carried out using dryer F300 (Apium, Germeny) After 150 minutes, the drying process was temporarily interrupted to mix the granulate, thereby ensuring a more uniform heat distribution and improving the efficiency of the drying procedure. Subsequently, the drying process was resumed until the predetermined drying time was completed. The PLA granulate drying process is illustrated in Figure 3.



Placing the granulate in the chamber | Set parameters of the granulate drying process

Figure 3 Drying process

Extrusion process

The production of recycled PLA filament was carried out using the Filament Maker Composer 450 (3devo, Netherlands). This device is designed for laboratory-scale and semi-industrial production of thermoplastic filaments and enables precise control of processing parameters, particularly extrusion temperature and feed rate.

The extrusion unit is equipped with a four-zone heating system, while the material is conveyed to the heating elements by means of a screw-driven mechanism. After passing through the extrusion nozzle, the extruded melt was cooled using two fans positioned directly below the outlet opening of the device. Prior to the production of the recycled filament, an HDPE-based cleaning material was used to purge the extrusion system, remove residual materials from previous processing cycles, and ensure the cleanliness of the extruder. Figure 4 shows the extrusion of recycled PLA material, with the resulting extrusion creating filament for 3D printing. The extrusion parameters are described in Table 2.

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Figure 4 Extrusion process

Table 2 Extrusion parameters of recycled PLA material

Parameter	Value
Heater 1	195 °C
Heater 2	185 °C
Heater 3	185 °C
Heater 4	175 °C
RPM	4 rotation/minute
Cooling intensity	60%

2.3 Measurement of filament diameter

During the extrusion process of the recycled PLA material, the diameter of the produced filament was continuously monitored using an integrated optical sensor with an accuracy of ± 43 µm. The optical sensor was integrated into the Filament Maker device and enabled continuous monitoring of the filament diameter throughout the entire extrusion process. Real-time recording and monitoring of the measured values were performed using the DevoVision software (3devo, Netherlands), with a measurement frequency of one value per second. The optical sensor measured the filament diameter along a single axis, specifically in the horizontal plane. The nominal diameter of the produced filament was set to 1.75 mm. The maximum allowable filament diameter was defined as 1.85 mm, while the minimum allowable diameter was set to 1.65 mm. These limits were selected to ensure sufficient dimensional stability of the filament for subsequent application in the FDM 3D printing process.

3 Results

The analysis of the diameter of filament produced from recycled material represents an important factor in ensuring its dimensional stability, consistent quality, and reliability in the 3D printing process. Recycled polymer materials may exhibit a higher degree of variability in chemical composition and processing properties, which is often reflected in fluctuations of the extruded filament diameter. Variations in filament diameter can negatively affect the stability of material flow during the FFF printing process, lead to irregular material feeding, impair interlayer adhesion, and consequently reduce the geometrical accuracy and overall quality of the printed components. For these reasons, continuous monitoring and control of filament diameter are essential in order to minimize production deviations and ensure stable processing conditions during the manufacturing of filaments from recycled materials.

Furthermore, the control of filament dimensional accuracy represents an important aspect in improving the efficiency of material recycling and supporting environmentally sustainable manufacturing processes. Therefore, the objective of this part of the study was the analysis of the produced filament diameter.

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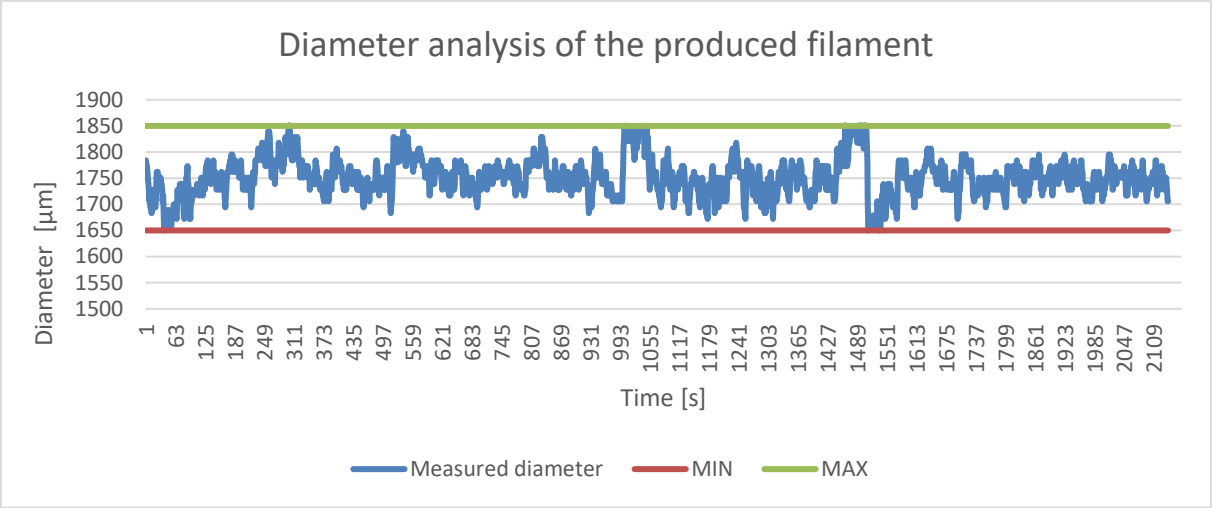


Figure 5 Diameter analysis of the produced filament

Figure 5 illustrates the temporal evolution of the measured filament diameter during the extrusion process of recycled PLA material. The horizontal axis (X-axis) represents the measurement time in seconds, while the vertical axis (Y-axis) shows the filament diameter values expressed in micrometers (µm). The blue curve represents the actual measured filament diameter values throughout the entire production process. The graph also includes upper and lower boundary limits defining the maximum and minimum allowable diameter tolerances of the filament. The measurement results indicate that the majority of the recorded values remained within the defined tolerance limits, demonstrating a relatively stable extrusion process and adequate quality control during filament production. In the initial stage of extrusion, a short-term increase in filament diameter toward the upper tolerance limit can be observed, which is likely associated with the stabilization of thermal and processing conditions after the start of extrusion. Following process stabilization, the diameter values fluctuated only slightly around the nominal value. During the measurement, local deviations in the form of short-term increases and decreases in filament diameter were also recorded, with some values approaching the upper or lower tolerance boundaries. These fluctuations may be attributed to changes in melted viscosity, inhomogeneity of the recycled material, or temporary variations in processing parameters during extrusion. In the second half of the recorded data, a sudden short-term drop or spike in the filament diameter was identified, after which the process stabilized again and continued within the defined tolerance limits. The results obtained confirm that the recycled filament production process was predominantly stable and well-controlled in terms of dimensional stability. Continuous monitoring of filament diameter represents an important quality control tool, as it enables real-time identification of process deviations, analysis of their causes, and optimization of extrusion parameters. Maintaining a stable filament diameter is essential for ensuring a reliable FFF 3D printing process, since even minor dimensional deviations may negatively affect printing accuracy, surface quality, and the mechanical properties of the final components. Overall, the analysis indicates that despite the natural fluctuations associated with the dynamics of the extrusion process, the control limits were appropriately defined, and the produced filament met the required quality criteria for subsequent processing.

Another method used for the analysis of the filament produced from recycled PLA material was the statistical evaluation of the measured diameter values using descriptive statistical methods. To assess the dimensional stability of the filament, the following basic statistical parameters were analyzed: arithmetic mean ($\bar{x}$), standard deviation (SD), median (MED), variance (s^2), skewness, kurtosis, minimum value (MIN), and maximum value (MAX). These statistical indicators enable a comprehensive assessment of the variability, distribution, and stability of the measured filament diameter values during the extrusion process. The calculated values of the individual parameters are presented in Table 3.

Table 3 Filament diameter analysis – descriptive statistics

Parameter	Value
Mean	1.747
Standard deviation	34.86
Median	1.746
Variance	1215.17
Skewness	-0.52
Kurtosis	0.17
Minimum value	1.65
Maximum value	1.851

The statistical results obtained indicate that, within the predefined filament diameter tolerance range (1.65 mm to 1.85 mm), the lower limit was not exceeded. A slight exceedance was recorded only for the maximum diameter value, which reached 1.851 mm. However, this exceedance represents a deviation of only 0.001 mm, which can be considered negligible in terms of FFF technology and without a significant effect on the quality of the 3D printing process.The average measured filament diameter during the production process reached a value of 1.747 mm, which corresponds, after rounding to the nominal diameter of 1.75 mm set prior to the extrusion process. This result confirms the appropriate adjustment of the processing parameters and the ability of the extrusion system to produce filaments with the required dimensional accuracy. Nevertheless, higher values of standard deviation (34.86) and variance (1215.17) were recorded during the extrusion process, indicating the presence of variability in the measured filament diameter values. This phenomenon may be associated with the inhomogeneity of the recycled feedstock material, particularly the varying granule sizes after the shredding process. Differences in granule size may influence the homogeneity of the melt and its rheological properties, especially viscosity, during the transition of the material from the solid to the viscous state, which may subsequently lead to minor fluctuations during the extrusion of the PLA material.

4 Conclusions

The aim of this study was to analyse the possibilities of recycling PLA material through a process involving mechanical shredding followed by filament extrusion for FFF 3D printing technology. The experimental results demonstrated that recycled PLA material can be successfully processed into filament with a diameter meeting the standard requirements for FFFprinting. The analysis of filament diameter and the results of descriptive statistics confirmed a relatively stable extrusion process, with most of the measured values remaining within the predefined tolerance limits. The observed deviations were minimal and were most likely related to the inhomogeneity of the input material and the varying granule sizes after the shredding process. The results of this study highlight the potential of recycling PLA waste for the re-production of filaments, thereby supporting material efficiency and environmentally sustainable approaches in the field of additive manufacturing. Future research could focus on the optimization of extrusion process parameters and the evaluation of the mechanical properties of recycled filament after multiple recycling cycles.

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