

Article

Effect of Filament Material and Printing Temperature on 3D Printing Extrusion Force

Daša Krapež ¹, Muhammed Jusufagić ², Murčo Obučina ², Manja Kitek Kuzman ¹ and Mirko Kariž ^{1,*} 

¹ Biotechnical Faculty, University of Ljubljana, Jamnikarjeva 101, 1000 Ljubljana, Slovenia; dasa.krapez@bf.uni-lj.si (D.K.); manja.kitekkuzman@bf.uni-lj.si (M.K.K.)

² Department of Wood Technology, Faculty of Mechanical Engineering, University of Sarajevo, 71000 Sarajevo, Bosnia and Herzegovina; muhammedjusufagic97@gmail.com (M.J.); obucina@mef.unsa.ba (M.O.)

* Correspondence: mirko.kariz@bf.uni-lj.si

Featured Application: The results of this study demonstrate a practical application for improving the performance and reliability of 3D printing systems. By integrating a load cell-based force measurement system into the 3D printer, this approach can be used to dynamically monitor and optimize printing parameters. This is particularly beneficial for preventing nozzle clogging and ensuring the uniform extrusion of composite filaments containing, for example, wood particles. The proposed system could be used as part of an effective tool for real-time quality control in additive manufacturing, especially for materials with a variable composition.

Abstract: In this study, a modified 3D printer hotend equipped with a load cell, attached to the feeding system, was used to evaluate the effects of filament material composition and printing parameters on the extrusion force required. Four different materials (commercial PLA, pure PLA, wood-PLA with different ratios of wood particles, and wood-PLA with different ratios of thermally modified wood particles) were used for 3D printing, and the feeding resistance was measured. The filament feeder was connected to the extruder hotend via a load cell, which measured the forces required to push the filament through the extruder and the nozzle. Three printing nozzle temperatures of 200, 210, and 220 °C were used. The results show that the printing temperature and the material influence the required extrusion forces, which varied between 1 and 8 N, but the variation was high. With proper optimization and integration into the printer firmware, this setup could also be used to detect nozzle clogging during printing, modify printing parameters during the process, and prevent the uneven extrusion of composite filaments.

Keywords: FFF; wood-PLA filament; wood content; extrusion force; printing parameters



Academic Editor: Thang Quyet Tran

Received: 17 January 2025

Revised: 7 February 2025

Accepted: 12 February 2025

Published: 15 February 2025

Citation: Krapež, D.; Jusufagić, M.; Obučina, M.; Kitek Kuzman, M.; Kariž, M. Effect of Filament Material and Printing Temperature on 3D Printing Extrusion Force. *Appl. Sci.* **2025**, *15*, 2046. <https://doi.org/10.3390/app15042046>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Fused filament fabrication (FFF) is a widely used 3D printing technology. Variability in part quality, influenced by dimensional tolerances, surface roughness, and occasional defects (e.g., porosity, layer delamination), has traditionally limited this technology to non-load-bearing applications. However, advancements have already demonstrated its potential for high-end use. Much of this variability could be improved by proper in-process measurement, real-time control of additive manufacturing [1,2], and process modelling [3] to improve the process, monitoring printer health [4] and the properties of the printed parts. However, true in-line monitoring of material flow and real-time print correction is

still lacking [5]. Unfortunately, newer industrial systems offer limited, if any, capability for inline control and correction of the nozzle temperature, surrounding temperature, and filament feed rate, although studies with older systems have provided some important insights into their influence [5].

Irregularities during extrusion can be detected by analyzing data obtained from various sensors on the 3D printer: the thermocouple at the hotend, a non-contact infrared (IR) temperature sensor to measure the deposited molten polymer, a borescope camera, three-axis miniature MEMS accelerometers to measure vibrations on the table and extruder head, thermocouples to measure the temperature of the table bed [6], and pressure sensors in the hotend. Different methods are used to measure the extrusion forces and the condition of the printer and monitor the flow through the print nozzle during the printing process—from measuring the forces that occur when the filament is pushed into the hotend to measuring the vibrations—using acoustic emission (AE) sensors, accelerometers, infrared thermometers, and visual cameras to monitor the parameters of the extruder motor [4]. By integrating modern methods like digital twins, in situ monitoring with machine vision, applying machine learning algorithms, and utilizing real-time analysis powered by artificial intelligence, product quality and productivity can be significantly enhanced [7–9].

The rheology of the polymer melt in the extruder could also be measured using pressure drops in several measurements in specially developed novel online rheometers used for measuring the extensional viscosity [10]. Thus, the combination of measuring power to drive the filament in the hotend, pressure measurement in the nozzle, IR temperature measurement, and modeling could be used to estimate the pressure drop in the nozzle [11]. Pressure values from 140 to 6900 kPa were measured over a range of ABS filament feed rates at 230 °C, 235 °C, and 240 and a flow rate of 5 mm³/s. The in situ pressure measurements were higher than the theoretical predictions using a power-law fluid model, suggesting that the assumptions used for the theoretical calculations may not fully capture the dynamics in the FFF liquefier [12].

Coogan and Kazmer developed a special in-line rheometer by designing a modified nozzle with a customized pressure transducer and a thermocouple to measure the temperature of the processed melt [13]. After applying the appropriate corrections, the inline rheometer provided an accurate viscosity measurement that could be used for real-time monitoring and process control.

FFF printers use feeding rollers to feed the filament into the hot end. Feeding is usually performed by an electric motor-controlled pinch roller mechanism. If the resistance in the hot end is too high (for various reasons, such as clogging of the nozzle, inhomogeneous material, or incorrect temperatures), slippage can occur. Slippage can also occur if the filament diameter is not constant, the knurled feeding roller does not rest on the surface, or the rollers are worn. Non-constant feeding also occurs if the control of the stepper motor with an open control loop is too weak, and skipping steps occur due to suddenly occurring high extrusion forces (a blocked nozzle, a temperature drop in the nozzle, impure materials with particles, etc.). Various solutions are used to ensure a constant feed, from knurled rollers to springs that ensure the correct contact between the feed roller and the thread to double feed rollers to avoid underflow of material from the liquefier nozzle and underextrusion in the printed part [14]. In order to achieve good printing accuracy and resolution, a tight tolerance in filament diameter is required for the filament feed [14]. Nozzle clogging in FFF 3D printing can also be monitored by measuring the current of the filament feed motor. The extrusion process is optimized by selecting suitable closed-loop stepper motors [15]. Chen and Smith use a modified extruder in which the hotend is connected to the stepper motor of the direct extruder via a load cell and thus measures the required extrusion force. Assuming that the pressure of the polymer melt at the nozzle

outlet is zero, the feeding force in the filament is related to the pressure drop through the nozzle and the inlet area (filament cross-section) [16].

The feeding irregularities due to filament slippage or nozzle clogging can also be measured by measuring the speed difference between the filament feed gear speed and the filament speed using an inexpensive USB microscope video camera and image processing [17]. This also allows us to estimate the volumetric flow rate in real time and, together with the stepper motor control, correct the feeding if necessary.

The print quality also depends on the materials selected. Filaments with different fillers, like wood–polymer composites (WPC), place higher demands on the print. Higher filler contents in WPC significantly increase the viscosity of the polymer melt due to filler–filler and filler–polymer interactions, which makes flowing and molding more difficult. This could be improved via the incorporation of additives, such as lubricants, which promote sliding against the walls, thereby reducing the energy required for production. The usual strategy of increasing the temperature to reduce the viscosity of the melt is impractical due to the thermal degradation of wood and even polymers [18]. When 3D printing and extruding wood–polymer composites through small capillary nozzles, the sieve effect can occur. The wood particles accumulate in clusters at the entrance of the narrow part of the nozzle, which leads to their sieving and separation from the polymer matrix at the capillary entrance [18]. The filler particle size, aspect ratio, and distribution also affect extruding. As the size of the wood particles decreases, the apparent viscosity increases. This phenomenon can be explained by the fact that finer particles, which have a larger surface area compared to coarser ones, form more additional chemical bonds with the matrix [18]. Researchers are also investigating the effects of chemical or thermal pretreatments on wood fibers prior to compounding. Rheologically, these treatments could slightly reduce both the complex viscosity and the storage modulus [18].

The aim of this study was to develop a method for measuring the required extrusion forces for different materials and to determine the effects of different wood particles in different particle ratios in wood–polymer composite filaments on the extrusion forces required for 3D printing. The influence of the printing temperature was also investigated. The proposed measurement setup could also be used to continuously monitor the printing process and material changes and to detect nozzle clogging and, thus, possible defects in printed parts. The goal at this stage was to use these force measurements to manually adjust printing parameters, optimizing factors such as the nozzle diameter, printing temperature, printing speed, and retraction speed for the best possible print quality with the selected wood–polymer composite filaments. With the right feedback loop and printer control, it could be used to control the inline feed rate, flow ratio, and forces to ensure a homogeneous material flow.

2. Materials and Methods

2.1. Filaments

Eight different 1.75 mm filaments were used in research (Table 1):

- Commercially available white PLA filament (basic polymer: PLA Ingeo™ 4043D).
- Pure PLA filament (PLA Ingeo™ 2003D).
- Wood-PLA filament with 10 and 20% wood particles (PLA Ingeo™ 2003D, beech wood particles, unmodified).
- TM180 wood-PLA filament with 10 and 20% wood particles (PLA Ingeo™ 2003D, beech wood particles, thermally modified at 180 °C).
- TM200 wood-PLA filament with 10 and 20% wood particles (PLA Ingeo™ 2003D, beech wood particles, thermally modified at 200 °C).

Table 1. Filaments composition and marking.

Formulation Code	PLA (wt%)	Beech (wt%)	TM Beech at 180 °C (wt%)	TM Beech at 200 °C (wt%)
White PLA	100	-	-	-
PLA	100	-	-	-
B10	90	10	-	-
B20	80	20	-	-
TM_180_10	90	-	10	-
TM_180_20	80	-	20	-
TM_200_10	90	-	-	10
TM_200_20	80	-	-	20

Pure PLA and wood-filled PLA filaments were produced in Kompetenzzentrum Holz GmbH, Linz, Austria, from PLA Ingeo™ 2003D (NatureWorks, Blair, NE, USA) granules and different beech wood particles. Thermally modified wood particles were produced via thermal modification using Silvapro procedure in semi-anoxic conditions [19]. Further information on the properties of these filaments can be found in an earlier study [20].

2.2. Extrusion Force Measuring Setup

The measurements were carried out using an FFF Creality CR10-V3 3D printer (Creality 3D Technology Co., Ltd, Shenzhen, China) with a modified extruder with a 1 mm nozzle. A load cell, integrated between the extruder and feeder (Figure 1), measures the force induced by backpressure within the extruder as the filament is driven forward. The load cell is connected to an HX711 amplifier (SparkFun, Boulder, CO, USA), which conditions the signal before transmitting it to an Arduino Uno board (Arduino S.r.l., Arduino Uno, Scarmagno, Italy). The Arduino processes the data and sends it to a PC for real-time monitoring and subsequent analysis.

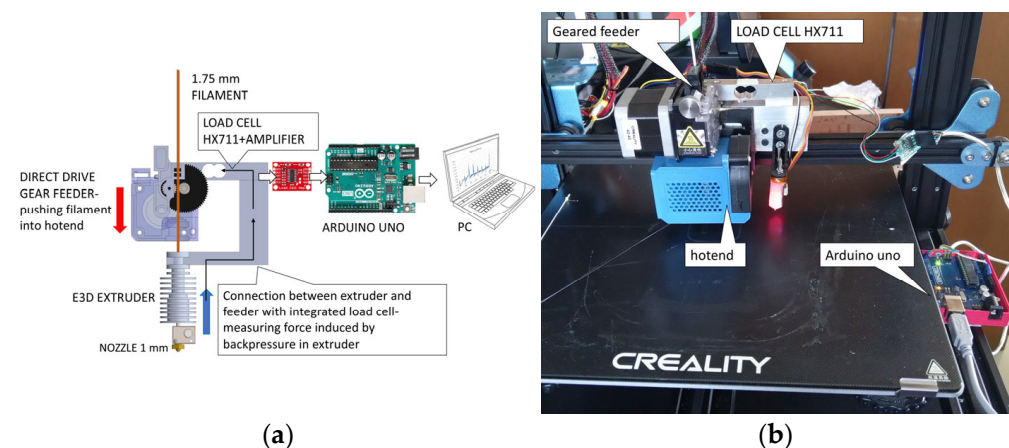


Figure 1. (a) Extrusion force measuring setup on modified extruder head on 3D printer—schematic, (b) working setup right.

A 500 g weight was used for calibration of HX711 load cell and Arduino measurements. After calibration, a plug-in was installed that logs the Arduino serial output to CSV/Excel file. To effectively monitor the progression of feedback force during 3D printing, it is essential to incorporate a timestamp into the output data from the load cells. This timestamp allows precise identification of the layer and specific region within the layer associated with a given feedback force. A simple Arduino program was employed to zero (tare) the load cell prior to printing and to continuously measure the forces exerted during filament feeding into the hotend. The printer was controlled with OctoPrint software. The OctoLapse

plug-in (version 0.4.2) was used to precisely determine the start of each layer. Before the start of each layer, the camera took a photo, and the timestamp of the photo was used to synchronize the force measurements obtained from the load cell and the Arduino board with the start of the layer [21].

Simple cuboid parts measuring $(125 \times 12.7 \times 3.2)$ mm were modeled in SolidWorks and saved in STL format. The model was then sliced using CURA Slicer version 5.3.0. The aim of the investigation was to determine the differences in the extrusion forces of the various materials and not the strength of the printed parts. Therefore, the print lines always ran parallel to the length of the sample (unidirectional infill pattern) to ensure long print movements with a uniform/steady flow. In addition, the retraction was limited to the movements of the Z-axis when moving up to the next layer. As a result, the printed parts did not exhibit significant strength as the print lines did not intersect/cross to form a cohesive structure.

Printing parameters were determined on the basis of previous experience with the materials used [20,22]. A printing nozzle with a diameter of 1 mm was used to prevent the nozzle from clogging with wood particles in the filament. Three different extrusion temperatures were used: 200, 210, and 220 °C. The bed temperature was set to 50 °C. The printing speed was 20 mm/s for all layers. A low printing speed of 20 mm/min was selected based on previous experiments using laboratory-prepared wood-filled filaments. Due to the presence of larger wood particles, a reduced speed was necessary to achieve higher-quality printed samples. In contrast, PLA can be printed at significantly higher speeds, with modern 3D printers capable of reaching 150–200 mm/min. Printing speed also influences backpressure, which could be an important parameter for future research.

The first layer thickness was 0.3 mm to ensure adhesion to the bed surface, and the next 6 layers were 0.5 mm thick. The calculated volumetric flow rate was, according to [23], $5.96 \text{ mm}^3/\text{s}$ for 1st layer, and for the rest of the layers, it was $8.93 \text{ mm}^3/\text{s}$.

When switching to the next tested filament, the previous filament was cold-pulled to remove as much residual material from the hotend as possible. The new filament was then loaded and extruded to further purge any remaining traces of the previous material from the nozzle. To measure the effect of the previous layer, which includes the backpressure created by pressing the molten polymer either onto the surface of the bed or onto the previously partially solidified polymer, an initial measurement was always performed in air. To accomplish this, the printer ran the same G-code with the nozzle 20 mm offset from the bed, and the material was printed in air without contact with the surface. Subsequent printing was carried out normally, with the nozzle in contact with the printer bed.

2.3. Rheology

Solid discs with a diameter of 25 mm and a thickness of 1 mm were 3D-printed to measure rheological properties. An ARES G2 rheometer (TA Instruments, New Castle, DE, USA) with parallel plates was used to measure complex viscosity at 200 °C. The discs were placed in the rheometer on preheated plates at 100 °C, pressed together with an axial force of 0.01 N to ensure proper contact, and then heated to 200 °C. At this temperature, an oscillation frequency sweep test was performed, ranging from 0.0628 to 628 rad/s, with the oscillation amplitude set to 0.004 rad. Two samples of each material were tested, and the average complex viscosity at 100 rad/s was calculated.

3. Results and Discussion

A typical measurement is shown in Figure 2. The force data were recorded during the entire printing process. The first peak in the force graph corresponds to the nozzle cleaning phase, in which the printer extruded two short lines on the left side of the printer bed to

clean the nozzle, remove material residue, and establish a constant flow; in this step, the extrusion speed and layer thickness were controlled by the printer firmware. The print head then moved to the center of the bed and began printing using configured settings. In this stage, the force increased as the molten polymer was forced through the nozzle onto the bed surface. When printing in air (blue curve), the recorded forces were lower as the material was able to flow freely through the nozzle without any backpressure from previously deposited material.

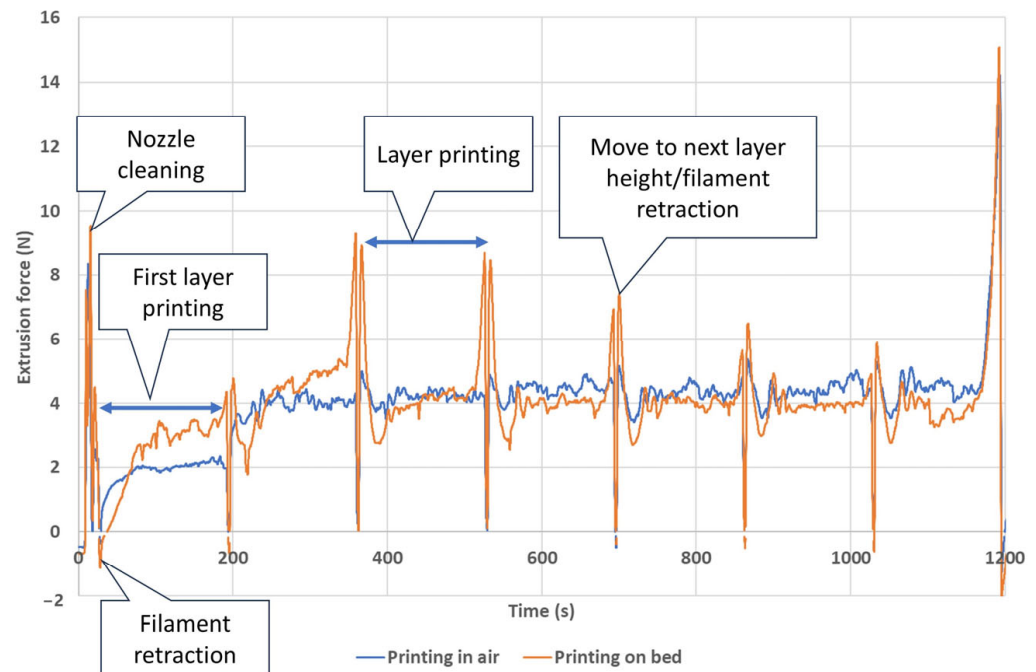


Figure 2. Typical measurement of extrusion forces for PLA filament ($T = 200\text{ }^{\circ}\text{C}$, printing speed 20 mm/s).

The force values during the first layer of printing were lower than those of the subsequent layers. This difference is probably due to the material flow: The first layer had a thickness of 0.3 mm , while the subsequent layers were 0.5 mm thick. As a result, about 50% more material had to be pushed through the nozzle in the second and subsequent layers (with a volumetric flow rate from $5.96\text{ mm}^3/\text{s}$ to $8.93\text{ mm}^3/\text{s}$).

The last part of the extrusion on each printing line always showed a short increase (Figure 3) because a little material is extruded into the wall overlap of the printing lines to ensure a better connection of the current printing line with the existing lines and a better strength of the printed parts. This parameter was set in the Cura Slicer and was 0.3 mm —the nozzle prints 0.3 mm into the walls. After finishing one layer, the nozzle moves upwards to print the next layer. To prevent the material from oozing during the Z-movement to the next layer height, the filament is retracted—this is indicated by a sudden drop in force. The filament is pulled back 5 mm by the feeding roller, followed by an increase in force as the feeding roller begins to push the filament into the nozzle and extrude the next layer. During each layer, the forces are relatively constant with small fluctuations due to material inhomogeneity, deceleration and acceleration in printer movement as the printer changes direction (e.g., across the nine longitudinal infill lines—Figure 4), and likely some contribution from vibrations of the printer head during movement. Lastly, with printing on the last layer, the increase in force is greater again as the extruded material overlaps the outer surface more to ensure closed solid surface.

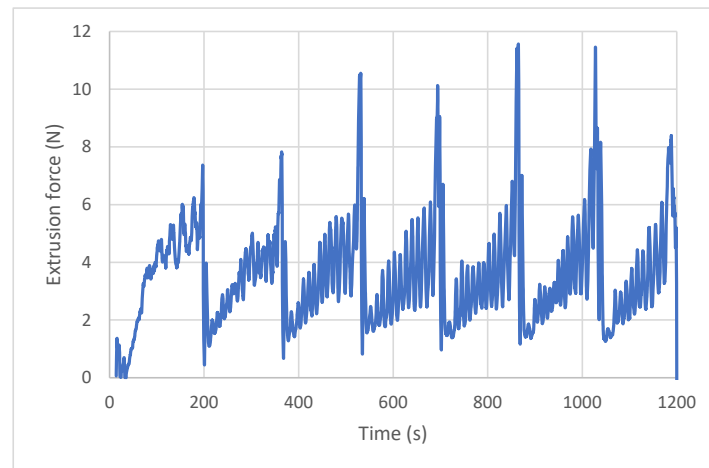


Figure 3. Force measurements—example of PLA-beech with 20% wood, 200 °C.

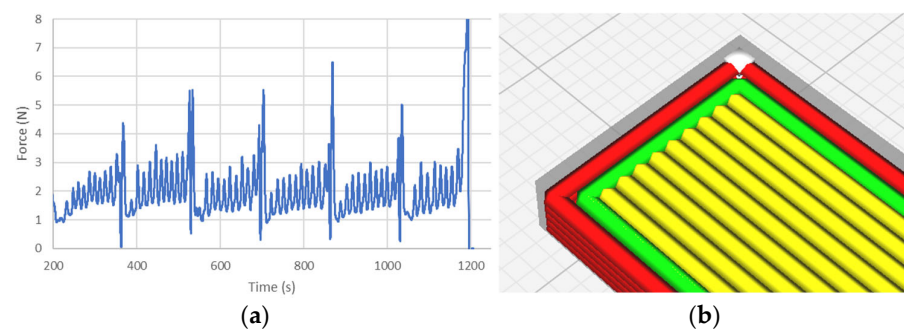


Figure 4. (a) Force measurements—small peaks in each printing layer—B20, T200 s20, (b) schematic of printing layers in slicer software right-red and green lines present outer walls printing lines, yellow are infill printing lines.

One of the conditions for steady extrusion is constant temperature in hotend. The power required to maintain a constant temperature can be calculated from

$$P = \frac{q \times C_p \times (T_m - T_{amb})}{efficiency} \quad (1)$$

where the following apply:

P = Power (in watts).

q = Flow rate (in mm^3/s).

C_p = Specific heat capacity (in $\text{J/g}^\circ\text{C}$).

T_m = Melting temperature of PLA (in $^\circ\text{C}$).

T_{amb} = Ambient temperature (in $^\circ\text{C}$).

efficiency = efficiency (as a fraction, 1 for 100% efficiency).

The specific heat capacity of PLA is about $1.9 \text{ J/g}^\circ\text{C}$, and the extruding temperature of PLA is 220°C . Max flow rate (q) is $8.93 \text{ mm}^3/\text{s}$. PLA filament typically has a density of around 1.24 g/cm^3 . Assuming 100% efficiency, meaning all electrical energy is used to heat the filament, the required power for heating the hot end is

$$P = 8.93 \times 1.24 \times 1.9 \times 0.001 \times (220-25) = 4.1 \text{ W}$$

The actual cartridge heater (rated 40 W) should be capable of heating the material to the desired T even at the highest used material volumetric flow. In addition, the heater cartridge is mounted in an aluminum block, which ensures thermal inertia to minimize temperature fluctuations. This means that the temperature variations could not be the

reason for the different extrusion forces needed. The actual nozzle temperature/melt temperature was not measured directly (except for the printer's temperature sensor in the heating block), which could be a possible limitation and considered in future studies to improve accuracy and process control.

During measuring forces in one printing layer, there are noticeable small fluctuations in force (Figure 4a)—probably because of different backpressure when extruding on edges or the inside of walls. Part of these small increases includes the overlapping of the printing lines inside to walls. In some cases, the force slightly increases from the beginning of the layer to the end of the layer, increasing pressure in the melt zone behind the nozzle (Figure 3). After retraction of the filament at the end of the layer, this force decreases, and the pattern is repeated in the next layer. This is particularly evident with some filaments with a higher proportion of wood particles (beech with 20% wood).

This could be an effect of the sieving of particles in the nozzle. According to [18], during WPC extruding, clogging of the particles in the thin capillary nozzle can occur and affect sieving—the polymer separates from particles and is first extruded, and when enough pressure is formed before this clog, the particles are pushed through the nozzle, and the process repeats. This could result in an uneven distribution of the wood particles in the printed part, despite the filament having an even distribution of the particles. Due to the unidirectional infill printing pattern, there were 13 printing lines in the longitudinal direction (two for walls on each side and nine for the infill) (Figure 4). These peaks in the saw profile in one layer represent each print line and overlap on the extrusion lines running parallel to the longitudinal direction with perpendicular lines at the end, where the nozzle attempts to extrude material into the already deposited material to join the extrusion lines with those previously deposited.

In order to compare different materials extruded at different temperatures, the average extrusion force was calculated for each material. In these calculations, the protruding forces at the end and beginning of the layer (due to retraction) and the initial part with nozzle cleaning were eliminated from the calculation. The average forces calculated are shown in Figure 5. The average force serves as a basis for comparing different materials, while these protruding forces represent peak values that could lead to printing errors, such as the filament slipping in the feeder or buckling before entering the hotend. Identifying and analyzing these peaks provides valuable insight into the extrusion behavior of wood-polymer composite filaments and allows parameter adjustments to minimize the risk of defects and optimize the printing process.

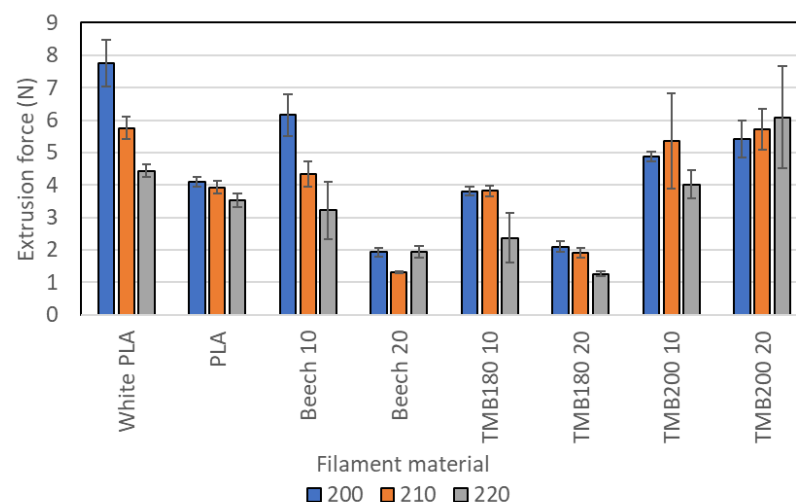


Figure 5. Average extrusion forces for different materials and three printing temperatures: 200, 210, and 220 °C.

For example, high force peaks caused by filament retraction at the end of each layer could likely be reduced by decreasing the retraction speed/acceleration in the slicer settings. While this adjustment may slightly lengthen the printing process, it would help prevent filament slippage and ensure a more stable and reliable extrusion.

The highest average extrusion forces were measured for white PLA filament at the lowest extrusion temperature (200 °C). The type of colorant used for white commercial PLA is not evident from the manufacturer's data sheet, but typically, titanium dioxide (TiO₂) is used in white filaments in the range of 5 to 20% by weight, depending on the manufacturer and any other fillers involved. This high proportion of colorant could be the reason for the higher extrusion forces required. In addition, the white filament is a commercial filament, the exact formulation of which is unknown and could contain some additives. Compared to pure PLA filament, the extrusion forces were almost half higher (7.8 vs. 4.1 N). The differences between white PLA and pure PLA could also lie in the PLA granules used—for white PLA, Ingeo 4043D (NatureWorks, Minneapolis, MN, USA) is used, and pure PLA filament is from 2003d, but according to the manufacturer, both PLAs have the same melt flow rate of 6 g/10 min (ASTM 1238 [24]). Chen and Smith measured lower extrusion forces of about 2 N but with a different nozzle (0.4 mm) and a volume flow rate three times smaller (1.7 mm³/s) [16]. White colorant is commonly in powder form, small sizes, and with a more uniform distribution; thus, it differs from wood particles, which are bigger and with higher variability in sizes. In this research, we used only a 1 mm diameter nozzle and a relatively low printing speed. In future studies, it would be beneficial to investigate the effects of different nozzle diameters and printing speeds (i.e., varying volumetric flow rates). Possible measurement inaccuracies could also be caused by the experimental setup. We acknowledge that the feeder in the current setup is not completely rigidly connected to the hotend as it was in the original printing condition, and that there is some flexibility in the attachment of the load cell, which could lead to slight variations in the dynamics of the filament feed. In addition, the PTFE guide tube in the hotend is not rigidly fixed between the hotend and the feeder, so it may shift slightly due to back pressure. As a result, molten polymer could momentarily accumulate in the gap between the hotend and the PTFE tube, creating a swirling flow and potentially affecting the overall extrusion conditions. These factors could lead to deviations from the actual extrusion forces measured. Future improvements could include a stiffer mounting system with a different load cell to further increase measurement accuracy and the use of an all-metal extruder to avoid PTFE tubes.

A higher extrusion temperature should reduce the viscosity of the melted polymer and thus require a lower extrusion force. This was evident for printing with white PLA, pure PLA, PLA with untreated beech wood particles (10%), and thermally treated wood particles TMB180 (Figure 5). This was not so obvious for samples with TMB200 wood. The decrease in extrusion force with higher temperature could be quite high, e.g., for white PLA, from 7.8 N at 200 °C to 4.4 N at 220 °C, and for filament with 10% beech particles, from 6.2 to 3.2 N. There was no clear trend for the TMB200 samples, but this was probably due to the fact that the nozzles often clogged during printing, and therefore, an accurate measurement of the average force was not possible.

According to the literature, the higher proportion of wood particles in wood–plastic composites increases the viscosity of the melted mixture of wood and particles. The measurement of the average forces did not show this trend (Figure 6). The measured average extrusion forces were even lower at higher loadings. Even compared to pure PLA, where the average extrusion force was 4.1 N, some of the filaments with wood particles have even lower extrusion forces. At higher temperatures, the trends are similar, but with lower extrusion forces.

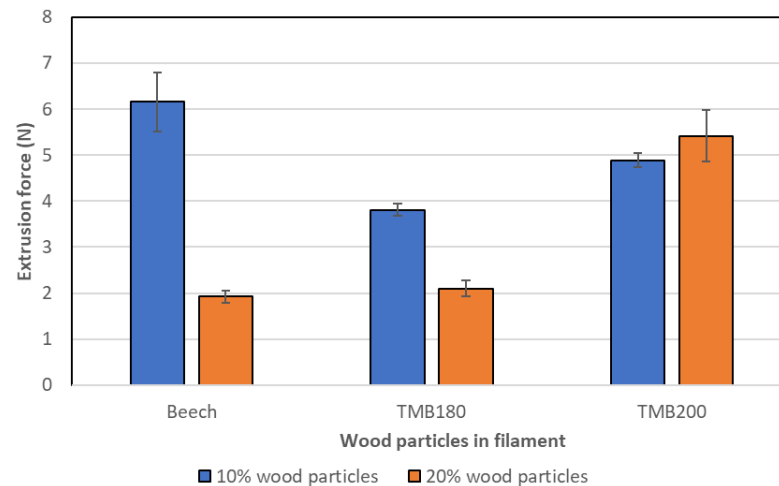


Figure 6. Comparison of average extrusion forces for wood-PLA filaments with different wood ratios during printing at 200 °C.

At the same loading, the filament with unmodified beech showed higher extrusion forces than filaments with TM wood. The reason could be due to the particle size and the distribution of the particle sizes. The size of the wood particles was studied in previous research [25]. Using a particle analyzer with computer-controlled laser alignment, significant differences were found between particles of beech and thermally modified (TM) beech ground with a 250 µm sieve. TM beech particles were smaller and more uniform, which is due to the increased brittleness of the wood after modification. The brittleness of TM wood resulted in smaller particles, as the exposure to temperatures between 150 °C and 200 °C damaged the cell wall. The fineness of the particles contributed to a larger surface area and greater slenderness of the particles.

The density of beech wood (623 kg/m³) and TM beech wood (602 kg/m³) is lower than that of PLA (1240 kg/m³). Consequently, incorporating wood decreases the density of the filaments [25]. An earlier study [20] showed that 3D-printed specimens from wood-PLA filament containing 10% TM180 had a 13.6% lower density than specimens from filament with 10% beech wood and a 7.7% lower density than specimens with 10% TMB200. The density of specimens with 20% TMB180 had a similar density to those with 20% beech wood. In contrast, specimens with 20% TMB200 wood had an 11% higher density than the TMB180 and beech wood specimens. This difference may be attributed to a lower void content or porosity in TMB200 specimens, which is possibly due to the improved encapsulation of wood particles with PLA. Again, the higher density observed in PLA composites with TMB200 wood could be related to the wood's characteristics. Wood modified at higher temperatures tends to be more brittle, resulting in smaller and more uniform particles compared to TMB180 and non-modified wood.

The porosity of the filaments could also affect the extrusion forces. Filaments with more wood particles exhibit more voids in the cross-section, which could affect the heating and flow of the material. In an earlier study [20], the lowest porosity (8.4%) had specimens 3D printed from B10, followed by 20% TMB200 (11.5%) and 10% TMB200 (15.3%). Specimens with B20 and 10% TMB180 had similar porosity (19.8 and 19.9%, respectively), and the highest porosity was in specimens with 20% TMB180 (20.6%). However, it should be noted that the porosity and density of 3D-printed specimens depend on many parameters such as printing settings, the moisture content of filaments, etc. Nevertheless, most of the variables occurring in 3D printing influenced the filament loading in this experiment—the density of raw materials, the density of filaments (possible voids in filament cross-sections), and anomalies that occur during printing (nozzle clogging, uneven material flow, the formation

of gasses at higher extrusion temperatures, moisture in filament, etc.). There is a correlation between the density/porosity of the filaments and the extrusion force—the higher the density, the higher the extrusion force, since higher-density composites exhibit a greater resistance to flow [26].

The actual temperature of the melted polymer also affects the viscosity and extrusion forces, but the temperature of the melted material in the nozzle was not measured. The melting temperature of the wood-PLA filament measured with DSC was 155.5 °C [27], while the extrusion temperature varied between 200 and 220 °C. The printing speed was set to 20 mm/s, and the length from feeding roller to exit from hotend was approx. 70 mm, which means that the filament was heated for a max of 3.5 s.

It is assumed that the filament does not slip on the feeding rollers and that the feeding motors are strong enough to overcome the required force. If the feeding stepper motor is not strong enough and starts skipping steps, the measurement would reflect these force fluctuations. This could also be used to predict possible spots with material under-extrusion and weak points in the structure of the printed parts.

Rheology

Wood particles can considerably influence the rheology of wood-PLA composite material [18]. The amount, type, and morphology of the particles and their pretreatments can have a significant effect. The rheological properties were measured at a temperature of 200 °C on 3D-printed discs. The discs were 3D-printed with a solid infill, but even with these settings, there were still voids in the printed material, which could affect the rheological properties. The average complex viscosity, measured at an oscillation frequency of 100 rad/s, is shown in Figure 7. This speed correlates with speeds used during extrusion and 3D printing, where shear rates between 5 and 500 s^{−1} are expected [28,29]. It is evident that the viscosity increases for wood-PLA filaments with a higher wood content for beech and TMB180 and TMB200. One of the expected results is the complex viscosity of pure PLA, which is the highest measured among all materials tested. This might be related to the porosity and density of the material.

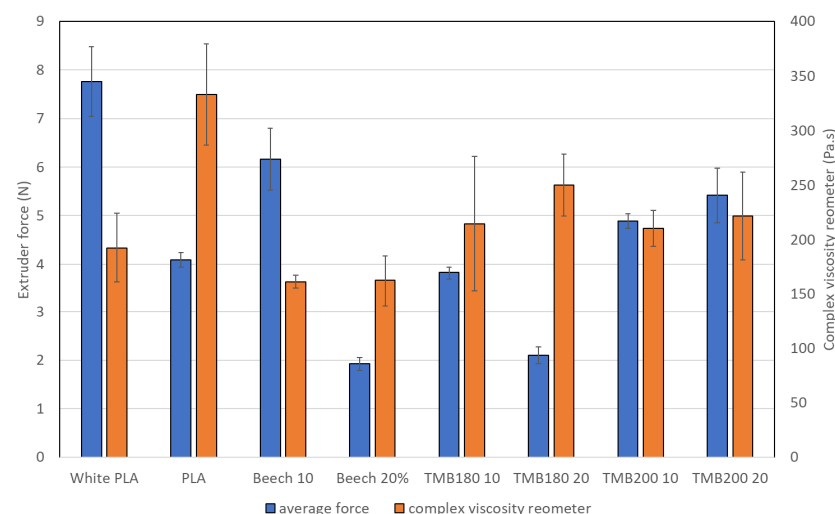


Figure 7. Comparison of average complex viscosity for different materials at oscillation frequency of 100 rad/s and 200 °C, measured with parallel plate rheometer and average extrusion force at 200 °C.

Beech with a higher wood content (20%) has the same—slightly bigger viscosity as B 10% but lower viscosity than PLA. The same applies to TMB180 and TMB200.

Materials with thermally modified wood particles exhibit higher viscosity than materials with unmodified beech wood particles. It is reported that various thermal modifications

of wood fillers increase the viscosity of melted WPC [30,31]. Modified wood also has more hydrophobic properties, which could contribute to better adhesion between polymer and wood particles. The reason for this could be in particle size dimensions and connections/bonds between particles and polymers. The wood particles were obtained using the same grinding procedure, but since TM wood is more brittle, we obtain smaller particles and a larger proportion of these small particles compared to unmodified beech wood [25] with a hydrophobic PLA polymer. In general, the apparent viscosity increases as the dimensions of the wood particles decrease [18] since fine particles have a larger surface area than bigger particles and can, therefore, form more chemical bonds with the polymer matrix.

The layer thickness for printing of the first layer was set to 0.3 mm to achieve better adhesion to the printer bed, the remaining layers were 0.5 mm thick. According to the measurements, the forces for the extrusion of the first layer were equal to or greater than the second layer (Figure 8).

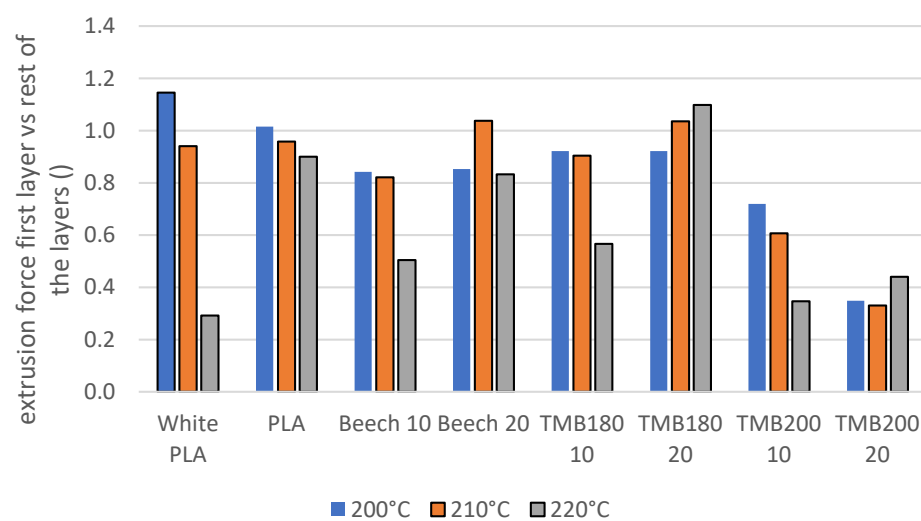


Figure 8. Extrusion force—first layer vs. rest of the layers (ratio) for different materials and printing temperatures.

During 3D printing, a certain amount of backpressure is always present, regardless of whether depositing material onto the printer bed or onto a previously printed layer. This backpressure directly impacts the extrusion force required to push the material through the nozzle. When printing the first layer, the material is pressed against a solid, non-compliant surface, such as the printer bed. In contrast, subsequent layers are deposited onto the partially hardened material of the previous layer, which offers some compliance as the new hot, molten material is pressed into it. If we compare printing in the air with printing on the previous layer, we see that extrusion in the air is almost always easier (about 1 to even 4 times bigger forces) (Figure 9), which suggests the existence of backpressure from the previous layer material.

The backpressure created by the printing (too) near the previous layer causes several effects in the hotend. The material does not flow freely through the nozzle and can stagnate in the hotend. The filament, which acts as a piston to drive the melted polymer material out of the nozzle, is typically not flush with the liquefier wall. This inadequate fit causes the heated polymer to flow back into the annular area between the filament and the liquefier wall, creating additional backpressure in the nozzle and further impeding the flow of material [32].

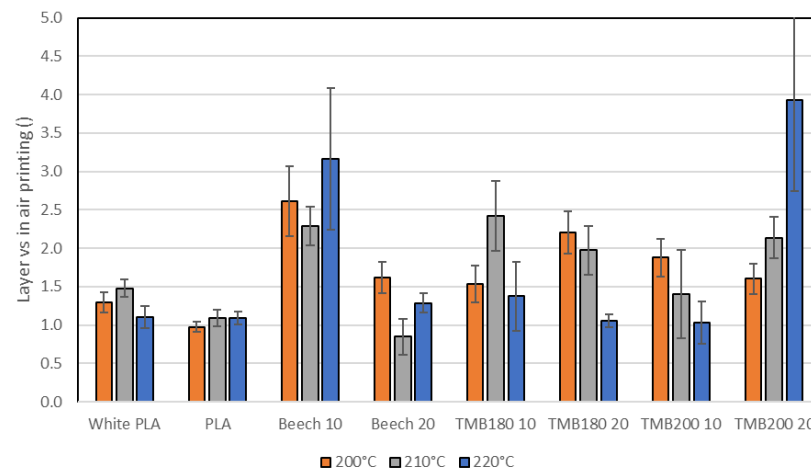


Figure 9. Extrusion force—printing on previous layer vs. printing in air (ratio between forces) for different materials and printing temperatures.

Filaments with wood particles showed higher differences between printing in air and printing on the previous layer. Printing on the previous layer exhibited higher forces. The reason for this could be small backpressure from pushing material in the previous layer, which causes uneven flow through the nozzle and possible clogging.

If the extrusion force required to push the filament through the nozzle is too high, the filament may buckle and disrupt the material flow, or the feeding rollers may slip or tear off the filament material. Buckling occurs when the required extrusion pressure is higher than the critical buckling load that the filament can withstand [33]. The load-bearing capacity of the filament depends on the compressive elastic modulus of the material and the guide tube in the extruder head. The extrusion resistance (or extrusion pressure) depends on the viscosity of the feedstock, the nozzle geometry, the nozzle size, the printing layer thickness, and the volumetric flow rate [34]. The critical buckling force for our filaments can be calculated according to Venkataraman et al., 2000, and is about 58 N, so the force we measured (up to 10 N) is far from buckling.

Another problem when feeding filaments is the slipping or tearing of the material at the feeding system. The feed force that the feeding system is capable of depends on the contact pressure/pinch force between the rollers and the surface of the rollers (often toothed or knurled surface). The feeding system in the printer consists of a driven toothed roller and counterrotating roller. The pinch force is adjustable. The teeth on the roller are used to permanently deform the filament, creating a rack-like and pinion style gearing and increasing friction [35]. According to [35], the feeding system with straight-toothed gear with flat flanks can provide between 25 and 120 N of feeding force, depending on the pinch roller force. The forces we measured were below these values, so we should avoid slipping if the nozzle does not clog.

4. Conclusions

This research presents a method that determines the feed force required to feed filaments into the hotend and extrude material. It detects variations in the feed force (between 1 and 8 N) and distinguishes between materials with and without wood particles and at different printing temperatures.

Detecting extrusion forces can serve as a valuable method for optimizing the printing process, as high feed forces indicate the risk of filament slipping in the feed rollers, leading to uneven extrusion or possible nozzle clogging. Corrective action can be taken to address these issues, such as cleaning the nozzle, adjusting the process parameters (e.g., reducing the print speed, increasing the extrusion temperature, and changing feeding acceleration),

or using a larger-diameter nozzle. Conversely, if the extrusion forces are low, the force can be increased to an optimum level by increasing the printing speed, thus ensuring a stable material flow and increasing productivity at the same time. This study provides valuable insights by measuring the extrusion forces in wood–polymer composites with different wood contents and different modification methods. By analyzing these parameters, this study contributes to a deeper understanding of wood–polymer extrusion behavior, complements existing monitoring techniques, and enhances process optimization to improve material performance.

This study found that between tested materials, white PLA filament requires the highest average extrusion force at the lowest extrusion temperature (200 °C). This higher force is probably due to the high content of titanium dioxide (TiO₂) in white filaments, which is usually between 5 and 20 percent by weight. Compared to pure PLA filament, almost twice the extrusion force was required for white PLA, which may partly be due to differences in the PLA base polymer type.

A higher extrusion temperature generally reduced the polymer viscosity, which lowered the extrusion forces. This trend was observed for white PLA, pure PLA, PLA with untreated beech wood particles (10%), and TMB180. However, it was less consistent for filaments with TMB200 wood particles, likely due to nozzle clogging during the printing process, which affected accurate force measurements. The literature indicates that a higher wood particle content generally increases the viscosity of wood–plastic composites, although this was not observed in the average forces measured, which unexpectedly decreased at higher particle loads.

Filaments with untreated beech wood required lower extrusion forces than those with thermally modified (TM) wood. This discrepancy could be due to differences in the particle size and distribution, as previous research has shown that TM wood particles are smaller and more uniform because they have become more brittle due to exposure to 150–200 °C. The smaller size and larger surface area of the TM wood particles probably contribute to these differences.

When printing on a previous layer or the print bed, the back pressure increases the extrusion forces, especially for filaments with wood particles. For wood-containing filaments, greater differences were observed between extrusion in air and extrusion on the previous layer, likely due to backpressure causing uneven flow and possible nozzle clogging.

Despite these results, the significant variability of the measurements indicates that the method needs to be further optimized. Future improvements should focus on real-time force measurement and analysis during printing. Modern technologies such as computer vision, machine learning, and artificial intelligence [7] could detect nozzle clogging and dynamically adjust printing parameters inline to ensure a consistent print quality. Assumptions about the stability of filament flow, such as the absence of slippage on the transport rollers and sufficient strength of the transport motor, also need to be verified. Such improvements could help predict potential under-extrusion zones and identify weak points in 3D-printed structures.

Author Contributions: Conceptualization, M.K.; methodology, M.K. and M.J.; software, M.K. and M.J.; validation, M.K. and M.J.; formal analysis, M.K., D.K., M.J. and M.O.; investigation, M.J. and M.K.; resources, M.O., M.K.K. and D.K.; writing—original draft preparation, D.K. and M.K.; writing—review and editing, D.K., M.K., M.J., M.O. and M.K.K.; visualization, D.K., M.K. and M.J.; supervision, M.K.; project administration, M.O. and M.K.K.; funding acquisition, M.O. and M.K.K. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the financial support from the Slovenian Research Agency (research core funding No. P4-0015).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original data presented in the study are openly available at the RUL, Repository of the University of Ljubljana, PID 20.500.12556/RUL-166731, accessible at <https://repozitorij.uni-lj.si/IzpisGradiva.php?id=166731&lang=eng> (accessed on 31 January 2025).

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Mani, M.; Lane, B.; Donmez, A.; Feng, S.; Moylan, S.; Fesperman, R.; Pritzker, P.; May, W.E. *Measurement Science Needs for Real-Time Control of Additive Manufacturing Powder Bed Fusion Processes*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2015. [CrossRef]
- Oleff, A.; Küster, B.; Stonis, M.; Overmeyer, L. Process Monitoring for Material Extrusion Additive Manufacturing: A State-of-the-Art Review. *Prog. Addit. Manuf.* **2021**, *6*, 705–730. [CrossRef]
- Stavropoulos, P.; Foteinopoulos, P. Modelling of Additive Manufacturing Processes: A Review and Classification. *Manuf. Rev.* **2018**, *5*, 2. [CrossRef]
- Fu, Y.; Downey, A.; Yuan, L.; Pratt, A.; Balogun, Y. In Situ Monitoring for Fused Filament Fabrication Process: A Review. *Addit. Manuf.* **2021**, *38*, 101749. [CrossRef]
- Turner, B.; Strong, R.; Gold, S. A Review of Melt Extrusion Additive Manufacturing Processes: I. Process Design and Modeling. *Rapid Prototyp. J.* **2014**, *20*, 192–204. [CrossRef]
- Rao, P.K.; Liu, J.; Roberson, D.; Kong, Z.; Williams, C. Online Real-Time Quality Monitoring in Additive Manufacturing Processes Using Heterogeneous Sensors. *J. Manuf. Sci. Eng.* **2015**, *137*, 061007. [CrossRef]
- Goh, G.D.; Yeong, W.Y. Applications of Machine Learning in 3D Printing. *Mater. Today Proc.* **2022**, *70*, 95–100. [CrossRef]
- Goh, G.D.; Bin Hamzah, N.M.; Yeong, W.Y. Anomaly Detection in Fused Filament Fabrication Using Machine Learning. *3D Print. Addit. Manuf.* **2023**, *10*, 428–437. [CrossRef]
- Kantaros, A.; Piromalis, D.; Tsaramirsis, G.; Papageorgas, P.; Tamimi, H. 3D Printing and Implementation of Digital Twins: Current Trends and Limitations. *Appl. Syst. Innov.* **2021**, *5*, 7. [CrossRef]
- Köpplmayr, T.; Luger, H.J.; Burzic, I.; Battisti, M.G.; Perko, L.; Friesenbichler, W.; Miethlinger, J. A Novel Online Rheometer for Elongational Viscosity Measurement of Polymer Melts. *Polym. Test.* **2016**, *50*, 208–215. [CrossRef]
- Phan, D.D.; Swain, Z.R.; Mackay, M.E. Rheological and Heat Transfer Effects in Fused Filament Fabrication. *J. Rheol.* **2018**, *62*, 1097–1107. [CrossRef]
- Anderegg, D.A.; Bryant, H.A.; Ruffin, D.C.; Skrip, S.M.; Fallon, J.J.; Gilmer, E.L.; Bortner, M.J. In-Situ Monitoring of Polymer Flow Temperature and Pressure in Extrusion Based Additive Manufacturing. *Addit. Manuf.* **2019**, *26*, 76–83. [CrossRef]
- Coogan, T.J.; Kazmer, D.O. In-Line Rheological Monitoring of Fused Deposition Modeling. *J. Rheol.* **2019**, *63*, 141–155. [CrossRef]
- Turner, B.N.; Gold, S.A. A Review of Melt Extrusion Additive Manufacturing Processes: II. Materials, Dimensional Accuracy, and Surface Roughness. *Rapid Prototyp. J.* **2015**, *21*, 250–261. [CrossRef]
- Tlegenov, Y.; Lu, W.F.; Hong, G.S. A Dynamic Model for Current-Based Nozzle Condition Monitoring in Fused Deposition Modelling. *Prog. Addit. Manuf.* **2019**, *4*, 211–223. [CrossRef]
- Chen, J.; Smith, D.E. Filament Rheological Characterization for Fused Filament Fabrication Additive Manufacturing: A Low-Cost Approach. *Addit. Manuf.* **2021**, *47*, 102208. [CrossRef]
- Greeff, G.P.; Schilling, M. Closed Loop Control of Slippage during Filament Transport in Molten Material Extrusion. *Addit. Manuf.* **2017**, *14*, 31–38. [CrossRef]
- Mazzanti, V.; Mollica, F. A Review of Wood Polymer Composites Rheology and Its Implications for Processing. *Polymers* **2020**, *12*, 2304. [CrossRef]
- Rep, G.; Pohleven, F.; Kosmerl, S. Development of the Industrial Kiln for Thermal Wood Modification by a Procedure with an Initial Vacuum and Commercialisation of Modified Silvapro Wood. In Proceedings of the 6th European Conference on Wood Modification, Ljubljana, Slovenia, 17–18 September 2012; pp. 11–17.
- Krapež Tomec, D.; Schöflinger, M.; Lešlhuber, J.; Žigon, J.; Humar, M.; Kariž, M. Effect of Thermal Modification of Wood on the Rheology, Mechanical Properties and Dimensional Stability of Wood Composite Filaments and 3D-Printed Parts. *Wood Mater. Sci. Eng.* **2024**, *19*, 1251–1265. [CrossRef]
- Jusufagić, M. Properties and Application of Wood-Plastic Composites Obtained by 3D Printing. Master's Thesis, Univerzitet u Sarajevu-Mašinski Fakultet, Sarajevo, Bosnia and Herzegovina, 2023.
- Krapež Tomec, D.; Balzano, A.; Žigon, J.; Šernek, M.; Kariž, M. The Effect of Printing Parameters and Wood Surface Preparation on the Adhesion of Directly 3D-Printed PLA on Wood. *J. Renew. Mater.* **2022**, *10*, 1787–1796. [CrossRef]

23. Slic3r Manual—Flow Math. Available online: <https://manual.slic3r.org/advanced/flow-math> (accessed on 7 February 2024).
24. ASTM 1238; Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer. American Society for Testing and Materials: West Conshohocken, PA, USA, 2013.
25. Krapež Tomec, D.; Schwarzkopf, M.; Repič, R.; Žigon, J.; Gospodarič, B.; Kariž, M. Effect of Thermal Modification of Wood Particles for Wood-PLA Composites on Properties of Filaments, 3D-Printed Parts and Injection Moulded Parts. *Eur. J. Wood Wood Prod.* **2023**, *82*, 403–416. [[CrossRef](#)]
26. Lv, X.; Hao, X.; Ou, R.; Liu, T.; Guo, C.; Wang, Q.; Yi, X.; Sun, L. Rheological Properties of Wood–Plastic Composites by 3D Numerical Simulations: Different Components. *Forests* **2021**, *12*, 417. [[CrossRef](#)]
27. Krapež Tomec, D.; Schöflinger, M.; Leßlumer, J.; Gradišar Centa, U.; Žigon, J.; Kariž, M. The Effects of Microcrystalline Cellulose Addition on the Properties of Wood–PLA Filaments for 3D Printing. *Polymers* **2024**, *16*, 836. [[CrossRef](#)] [[PubMed](#)]
28. Arrigo, R.; Frache, A. FDM Printability of PLA Based-Materials: The Key Role of the Rheological Behavior. *Polymers* **2022**, *14*, 1754. [[CrossRef](#)] [[PubMed](#)]
29. Mackay, M.E. The Importance of Rheological Behavior in the Additive Manufacturing Technique Material Extrusion. *J. Rheol.* **2018**, *62*, 1549–1561. [[CrossRef](#)]
30. Hong, H.; Guo, Q.; Zhang, H.; He, H. Effect of Interfacial Modifiers and Wood Flour Treatment on the Rheological Properties of Recycled Polyethylene/Wood Flour Composites. *Prog. Rubber Plast. Recycl. Technol.* **2020**, *36*, 31–46. [[CrossRef](#)]
31. Askanian, H.; Verney, V.; Commereuc, S.; Guyonnet, R.; Massardier, V. Wood Polypropylene Composites Prepared by Thermally Modified Fibers at Two Extrusion Speeds: Mechanical and Viscoelastic Properties. *Holzforschung* **2015**, *69*, 313–319. [[CrossRef](#)]
32. Gilmer, E.L.; Miller, D.; Chatham, C.A.; Zawaski, C.; Fallon, J.J.; Pekkanen, A.; Long, T.E.; Williams, C.B.; Bortner, M.J. Model Analysis of Feedstock Behavior in Fused Filament Fabrication: Enabling Rapid Materials Screening. *Polymer* **2018**, *152*, 51–61. [[CrossRef](#)]
33. Venkataraman, N.; Rangarajan, S.; Matthewson, M.J.; Harper, B.; Safari, A.; Danforth, S.C.; Wu, G.; Langrana, N.; Guceri, S.; Yardimci, A. Feedstock Material Property—Process Relationships in Fused Deposition of Ceramics (FDC). *Rapid Prototyp. J.* **2000**, *6*, 244–252. [[CrossRef](#)]
34. Rangarajan, S.; Qi, G.; Venkataraman, N.; Safari, A.; Danforth, S.C. Powder Processing, Rheology, and Mechanical Properties of Feedstock for Fused Deposition of Si₃N₄ Ceramics. *J. Am. Ceram. Soc.* **2000**, *83*, 1663–1669. [[CrossRef](#)]
35. Nienhaus, V.; Spiehl, D.; Dörsam, E. Investigations on Roller-Based Filament Drives. *J. Manuf. Mater. Process.* **2021**, *5*, 53. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.