engineering proceedings

MDPI

Proceeding Paper

Additive Manufacturing of Inflatable Thermoplastic Extrudates Using a Pellet Extruder †

Md Ahsanul Habib and Mohammad Abu Hasan Khondoker *

Industrial Systems Engineering, University of Regina, Regina, SK S4S0A2, Canada; mhy407@uregina.ca
* Correspondence: mohammad.khondoker@uregina.ca; Tel.: +1-306-585-4289

† Presented at the 1st International Conference on Industrial, Manufacturing, and Process Engineering (ICIMP-2024), Regina, Canada, 27–29 June 2024.

Abstract: Additive manufacturing (AM) has emerged as one of the core components of the fourth industrial revolution, Industry 4.0. Among others, the extrusion AM (EAM) of thermoplastic materials has been named as the most widely adopted technology. Fused filament fabrication (FFF) relies on the commercial availability of expensive filaments; hence, pellet extruder-based EAM techniques are desired. Large-format EAM systems would benefit from the ability to print lightweight objects with less materials and lower power consumption, which is possible with the use of hollow extrudates rather than solid extrudates to print objects. In this work, we designed a custom extruder head and developed an EAM system that allows the extrusion of inflatable hollow extrudates of a relatively wide material choice. By incorporating a co-axial nozzle–needle system, a thermoplastic shell was extruded while the hollow core was generated by using pressurized nitrogen gas. The ability to print using hollow extrudates with controllable inflation allows us to print objects with gradient part density with different degrees of mechanical properties. In this article, the effect of different process parameters, namely, extrusion temperature, extrusion speed, and gas pressure, were studied using poly-lactic acid (PLA) pellets. Initially, a set of preliminary tests was conducted to identify the maximum and minimum ranges of these parameters that result in consistent hollow extrudates. Finally, the parameters were varied to understand how they affect the core diameter and shell thickness of the hollow extrudates. These findings were supported by analyses of microscopic images taken under an optical microscope.

Keywords: additive manufacturing; extrusion additive manufacturing; hollow extrudates; pellet extrusion; fused filament fabrication

check for updates

Citation: Habib, M.A.; Khondoker, M.A.H. Additive Manufacturing of Inflatable Thermoplastic Extrudates Using a Pellet Extruder. *Eng. Proc.* **2024**, *76*, 59. https://doi.org/10.3390/engproc2024076059

Academic Editors: Golam Kabir, Sharfuddin Khan and Hussameldin Ibrahim

Published: 30 October 2024

Copyright: © 2024 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

Additive manufacturing (AM), often referred to as 3D printing, has emerged as a groundbreaking technology with the potential to revolutionize the way we create and manufacture objects [1,2]. Unlike traditional manufacturing methods that involve subtracting material, AM builds objects layer by layer, offering unprecedented design flexibility and efficiency [3]. Extrusion-based additive manufacturing (Material Extrusion) is one of the seven additive manufacturing processes that creates objects layer by layer using materials that are pushed or squeezed through a nozzle [4]. This method involves depositing material in a controlled manner, allowing it to solidify and form the desired shape. It is commonly used in 3D printing and offers advantages such as versatility, cost-effectiveness, and the ability to work with a variety of materials. When thermoplastic polymers are used in extrusion manufacturing processes, it is called FDM (Fused Deposition Modeling) or FFF (Fused Filament Fabrication). In FDM/FFF, a filament of thermoplastic material is heated until it melts, and then extruded through a nozzle onto a build platform. The nozzle moves in a controlled manner, depositing the melted material layer by layer to build up the final object [5]. Once each layer is deposited, it quickly solidifies to form a solid part. FDM/FFF is known for its simplicity, affordability, and versatility, making it widely used in various industries and applications [6]. But FDM/FFM is not free from limitations. What if we want to manufacture a product with variable density? FDM/FFM has the "infill" option to create a lighter or less dense product but this option creates a product with uniform density, which does not solve our mentioned issue. Inflatable extrusion can be a solution to this. If we can create an inflatable extrusion and control the inflation rate at different positions of the product, it will help us to create a product with different density. Therefore, we developed a method to create an inflatable extrudate and control the rate of inflation and in this paper, we will discuss how different extrusion parameters affect the degree of inflation rate.

2. Experimental Set-Up and Material

2.1. Extruder Design

In our experiment to extrude inflatable thermoplastic instead of solid material, we engineered a custom hot-end extruder tailored to our needs. The unique design incorporated a needle, allowing the controlled flow of nitrogen gas to hollow out the extrudate. To maintain the necessary temperature for this process, we affixed a (120 V, 50 W) heater to the extruder. The needle was connected to an air pressure regulator, enabling us to fine-tune the pressure and observe the outcomes under various air pressure settings. This setup shown in Figure 1 facilitated our exploration of creating hollow structures, offering a novel dimension to traditional 3D printing.

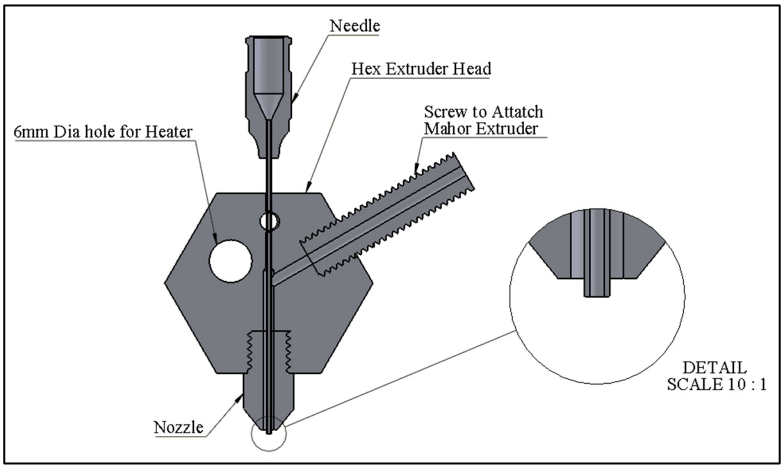

Figure 1. Extruder head for the inflatable additive manufacturing process.

2.2. Printer Set-Up

In our experiment, we worked with an extrusion 3D printer (Model: Ender-5 S1, Make: Creality 3D Technology Co. Ltd., Shenzhen, China). This printer has a build volume of 220 × 220 × 280 mm, meaning it can create objects within those dimensions, and a printing accuracy of ±0.1 mm for precise prints [7]. To operate the printer and prepare our 3D models for printing, we used Repetier Host V2.3.2, which served as both the printer controller and the slicing software. For the experiment's purposes, we modified the printer's hot end to accommodate a pellet extruder (Model: V4, Make: Mahor XYZ, Madrid, Spain). This required crafting our own bracket to securely attach the Mahor Pellet extruder and hex extruder to the hot end. Additionally, we added a hopper to guide the pellets toward the Mahor extruder during the printing process. These adjustments allowed us to explore the possibilities of using pellet-based materials in our 3D printing experiments.

2.3. Material

In our research, we opted for PLA as our testing material. PLA, a widely used polymer in the additive manufacturing industry, stands out for its lower melting temperature, excellent surface finish, and cost-effectiveness. Renowned for its user-friendly nature, PLA is often regarded as the most beginner-friendly material. Its derivation from corn starch or sugarcane not only contributes to its biodegradability but also makes it less toxic, adding to its popularity among users. The combination of ease of use, eco-friendliness, and versatility positions PLA as a preferred choice for various 3D printing applications [8,9].

3. Result and Discussion

3.1. Volumetric Flow Rate

To calculate the volumetric flow rate, we first let the PLA extrude freely for a certain period of time, and then measured the mass and flow time. This provided us with the mass flow rate. We used the following equation to convert the mass flow rate to the volumetric flow rate.

$$\rho = \frac{m}{V},\ v = \frac{m}{\rho} \quad (1)$$

where

ρ is the density of PLA.

m is the mass of the extrudate for a certain period of time.

V is the volume of that extrudate [10].

For each set of parameters (nozzle diameter, air pressure, temperature), we collected three samples and calculated the average volumetric flow rate. From our experiment, we found that with the increments in temperature or air pressure, the volumetric flow rate for PLA increased.

The volumetric flow rate of a polymer tends to increase with temperature due to the polymer's enhanced mobility and reduced viscosity at higher temperatures. The Vogel–Fulcher–Tammann (VFT) equation is commonly used in the field of rheology to describe the temperature dependence of viscosity in amorphous materials, such as glass-forming liquids or polymers [11,12]. The VFT equation is shown below.

$$\eta = \eta_0 exp\left(\frac{B_{VFT}}{T - T_0}\right) \quad (2)$$

where

η is the value of the viscosity at temperature T.

η_0 is the value of the viscosity at the high temperature limit.

B_{VFT} is the activation energy for viscous flow.

T is the absolute temperature.

T_0 is the so-called "Vogel temperature", which represents the temperature at which the viscosity would become infinite.

In this next section, we analyze how the VFT equation shows that an increase in temperature (T) results in a decrease in viscosity (η).

The key factor in understanding the temperature dependence is the exponential term $exp(B_{VFT}/(T - T_0))$. As temperature increases, the denominator $(T - T_0)$ becomes larger, making the exponent more negative; as the exponent becomes more negative, the entire term approaches zero. This means that at higher temperatures, the exponential term tends to make the viscosity term smaller.

We found that the highest volumetric flow rate was 5.07 mm^3/s at 205 °C. Beyond this flow rate, the extrusion motor no longer functioned. However, at 220 °C, the maximum flow rate was 10.06 mm^3/s, as with a higher temperature, PLA became less viscous, and hence our extrusion motor could handle the higher flow rate in our experiment.

3.2. Effect of Extrusion Parameters

We changed our extrusion parameters like volumetric flow rate, air pressure, and temperature and observed how it affects our inflated extrudates' outer diameter, core diameter and shell thickness shown in Table 1.

Table 1. Data collection for different extrusion parameters.

Nozzle Diameter	Extrusion Speed (mm/s)	Air Pressure (psi)	Average Mass (g)	Average Time (s)	Average Volumetric Flow Rate (mm³/s)	Average Outer Diameter (D) (mm)	Average Core Diameter (d) (mm)	Average Shell Thickness (t) (mm)
Temperature 220 °C, PLA Density 0.00118 mm³/s								
1.5	0.5	2	0.21 ± 0.006	100.52 ± 0.11	1.74 ± 0.05	1.36 ± 0.05	0.72 ± 0.06	0.32 ± 0.055
		2.5	0.21 ± 0.01	100.63 ± 0.07	1.77 ± 0.09	1.39 ± 0.07	0.77 ± 0.07	0.31 ± 0.07
1.5	1.5	2	0.42 ± 0.021	67.49 ± 0.21	5.23 ± 0.26	1.46 ± 0.06	0.82 ± 0.02	0.32 ± 0.04
		3.5	0.44 ± 0.023	67.44 ± 0.12	5.57 ± 0.3	1.64 ± 0.08	1.02 ± 0.02	0.31 ± 0.05
1.5	2.5	2	0.38 ± 0.006	40.32 ± 0.26	7.92 ± 0.17	1.55 ± 0.07	0.85 ± 0.04	0.35 ± 0.055
		4	0.43 ± 0.017	40.30 ± 0.07	9.04 ± 0.37	1.79 ± 0.10	1.09 ± 0.03	0.35 ± 0.065
1.5	3	2	0.35 ± 0.045	33.90 ± 0.16	8.75 ± 0.21	1.60 ± 0.07	0.87 ± 0.04	0.37 ± 0.055
		4	0.4 ± 0.01	33.68 ± 0.13	10.06 ± 0.24	1.95 ± 0.02	1.23 ± 0.02	0.36 ± 0.02
Temperature 205 °C, PLA Density 0.00118 mm³/s								
1.5	0.5	2	0.21 ± 0.015	100.52 ± 0.13	1.74 ± 0.13	1.35 ± 0.06	0.68 ± 0.03	0.33 ± 0.045
		4	0.21 ± 0.006	100.60 ± 0.1	1.80 ± 0.05	1.56 ± 0.04	0.93 ± 0.07	0.31 ± 0.055
1.5	1.5	2	0.4 ± 0.026	67.51 ± 0.22	5.02 ± 0.32	1.44 ± 0.09	0.74 ± 0.03	0.35 ± 0.06
		4	0.4 ± 0.012	67.45 ± 0.10	5.07 ± 0.15	1.59 ± 0.07	0.93 ± 0.04	0.33 ± 0.055

A graph was plotted for air pressure 2.0 psi, and the changes in outer diameter (OD), core diameter (CD) and shell thickness (ST) alongside the changes in volumetric flow rate and temperature are shown below in Figure 2.

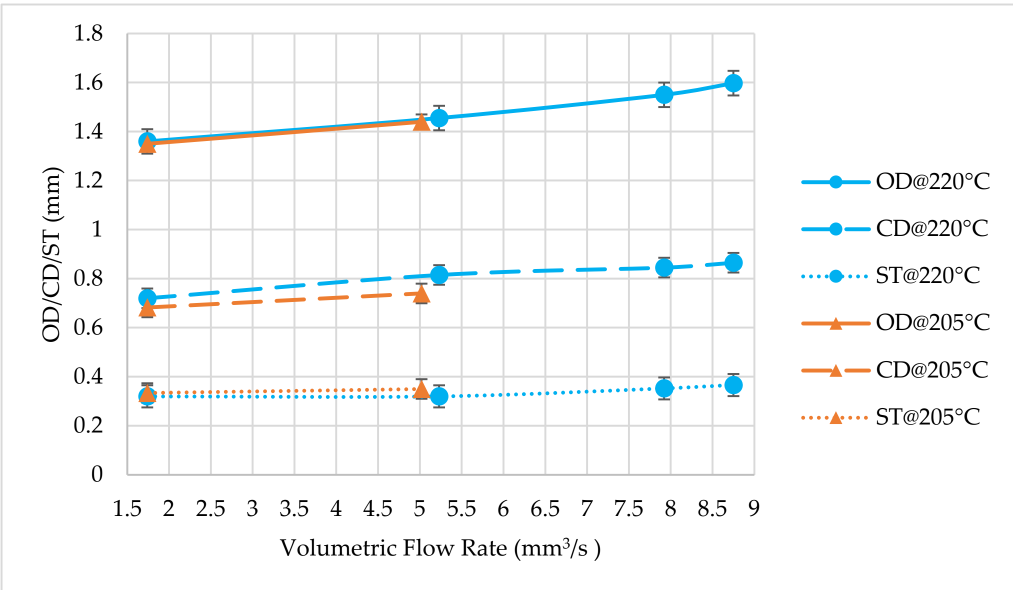

Figure 2. Changes in extrudate's outer diameter (OD), core diameter (CD) and shell thickness (ST) with the change in volumetric flow rate and temperature at 2.0 psi air pressure.

For a constant temperature and air pressure, if we change the volumetric flow rate, we see that with the increases in volumetric flow rate, all the parameters like outer diameter, core diameter and shell thickness increase. We carried out our experiment at two different temperatures, (220 °C, 205 °C) and in both cases, we found that with the increase in flow rate, all the above-mentioned parameters increase.

At the same time, we observed that, with the increase temperature from 205 °C to 220 °C for the same flow rate, the outer diameter and core diameter increased but the shell thickness decreased.

An increase in temperature leads to a decrease in viscosity of the polymer. As the viscosity decreases, the polymer becomes less resistant to flow. This, in turn, may result in a larger inner diameter of the extrudate. The inert gas passing through the polymer may also expand with the temperature increase, contributing to a larger inner diameter.

The decrease in viscosity with increasing temperature may lead to a thinner extrudate wall, affecting the outer diameter. Lower viscosity allows the polymer to flow more easily, potentially resulting in a larger outer diameter.

Increasing air pressure influences both the inner and outer diameters of the extrudate, shown in Figure 3, leading to a larger inner diameter and potentially a thinner extrudate wall. The flow also increases with a higher air pressure, shown in Figure 4, given that the other factors remain constant. We controlled our flow rate using the extrusion speed and found that for a certain temperature and extrusion speed, if we increase the air pressure, the flow rate increases. At the same time, the inner and outer diameter increase with air pressure and the shell thickness decreases.

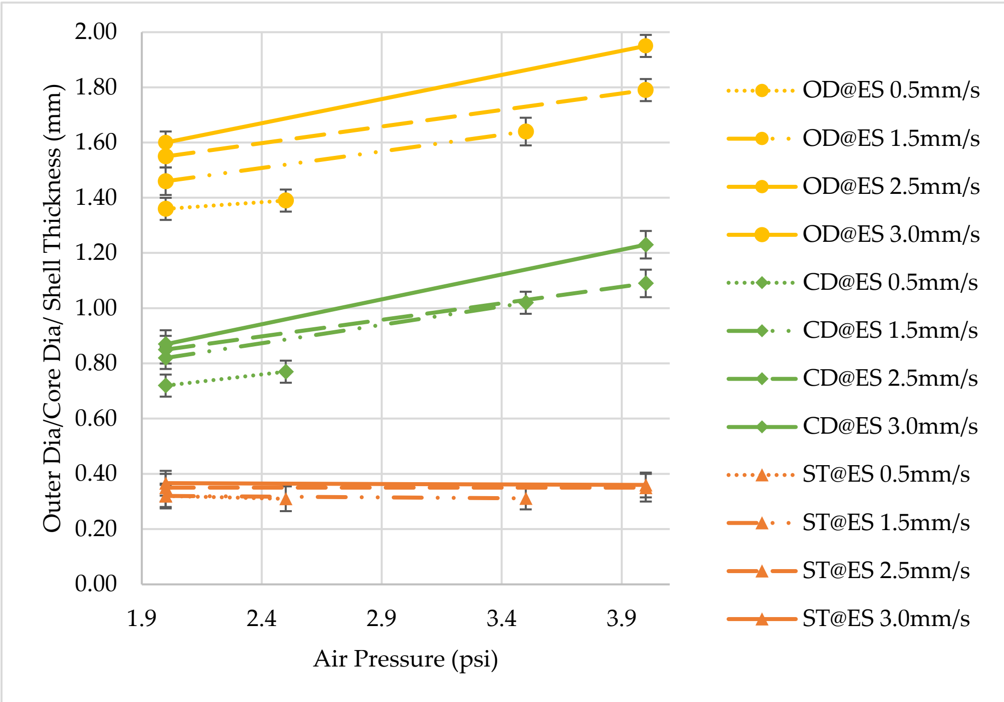

Figure 3. Change in extrudate's outer diameter (OD), core diameter (CD) and shell thickness (ST) with the change in air pressure at 220 °C.

In our experiment, we changed the flow rate, temperature, and air pressure and observed the impact on outer diameter, inner diameter and shell thickness, which is summarized below.

We also captured microscopic images under various conditions, as illustrated below. In Figure 5a, the notation '1.5_205_0.5_2.0' signifies that the sample was obtained using a 1.5 mm diameter nozzle, at a temperature of 205 °C, with an extrusion speed of 0.5 mm/s, and an air pressure of 2.0 psi.

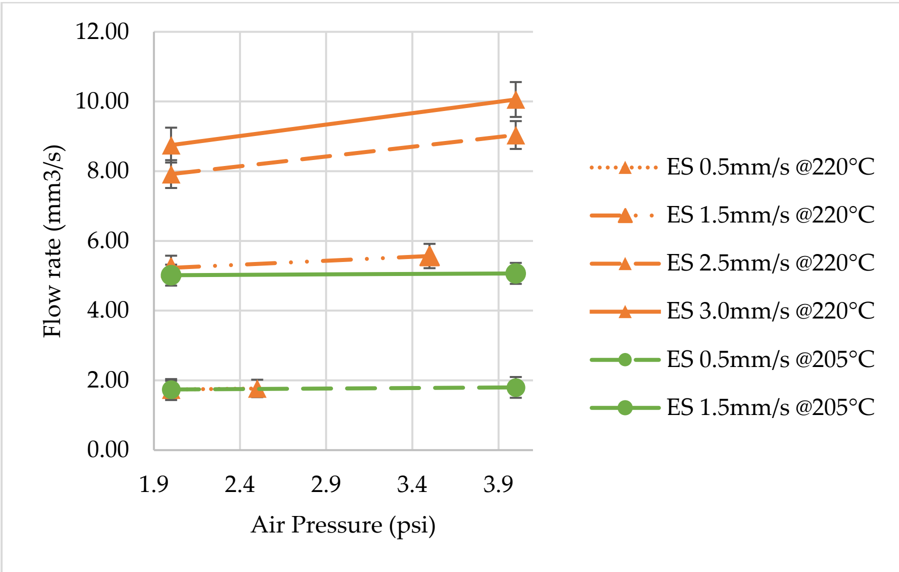

Figure 4. Change in volumetric flow rate with the change in air pressure.

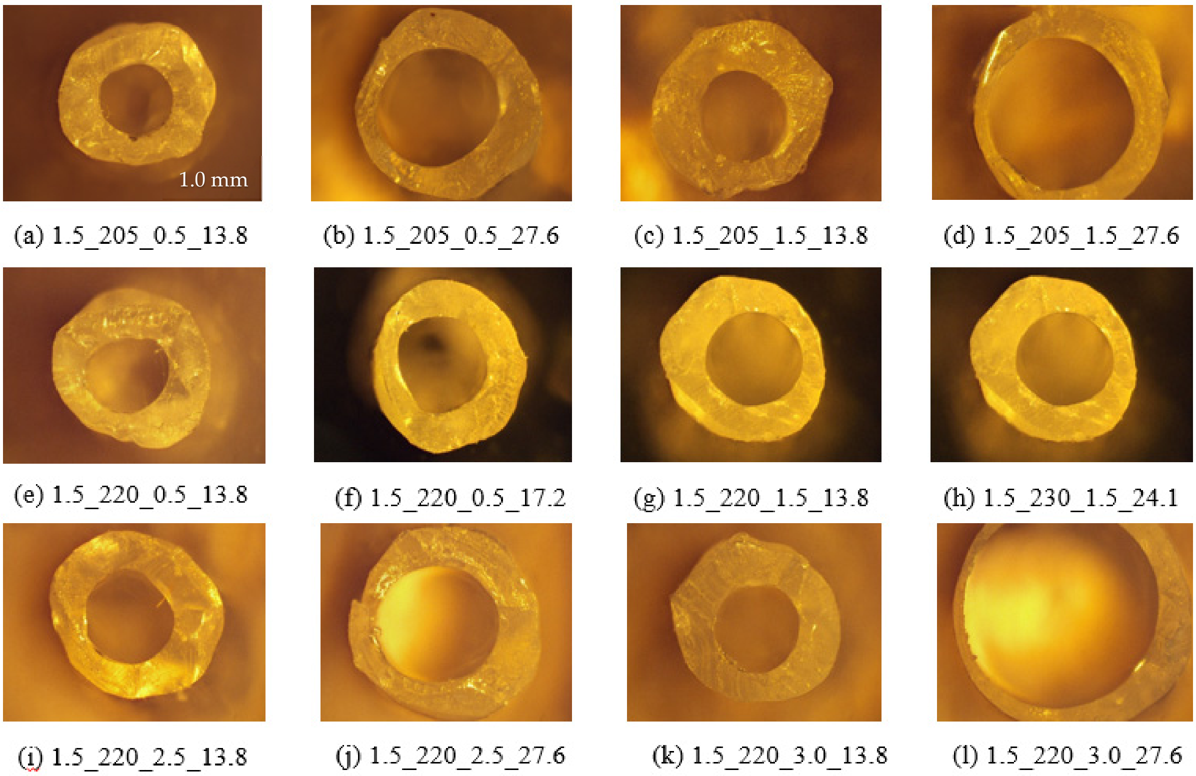

Figure 5. Microscopic images of extrudate cross sections for different extrusion conditions.

4. Conclusions

In summary, our exploration revealed exciting possibilities in the realm of 3D printing. By passing inert gas through melted polymers, we created hollow structures that could be used in 3D printing. Our experiments showed that adjusting factors like temperature, air pressure, and flow rate played a crucial role in determining the size and thickness of our extrudate. Achieving the right balance allowed us to produce extrudates that were not only visually interesting but also functionally versatile.

Moreover, our findings open up new avenues for innovation and applications across various industries. The lightweight nature, customizable design possibilities, and rapid prototyping capabilities of inflatable thermoplastic extrudates offer immense potential for addressing diverse manufacturing challenges and creating novel solutions. For instance, in prosthetics, varying densities could enhance comfort while maintaining stability. In automotive design, it could lead to the creation of safer, energy-absorbing components. Overall, the combination of inflatable FDM and differential density printing opens doors to innovative designs across numerous industries, promising heightened efficiency, comfort, and safety in various applications.

Author Contributions: Conceptualization, M.A.H.K.; methodology, M.A.H. and M.A.H.K.; validation, M.A.H.K.; formal analysis, M.A.H. and M.A.H.K.; investigation, M.A.H.; resources, M.A.H. and M.A.H.K.; data curation, M.A.H. and M.A.H.K.; writing—draft, M.A.H.; writing—review, M.A.H.K.; visualization, M.A.H. and M.A.H.K.; supervision, M.A.H.K.; project administration, M.A.H.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the Natural Sciences and Engineering Research Council of Canada.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the manuscript. For further inquiries, please contact the corresponding author (mohammad.khondoker@uregina.ca).

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

References

1. Wang, S.; Daelemans, L.; Fiorio, R.; Gou, M.; D'hooge, D.R.; de Clerck, K.; Cardon, L. Improving mechanical properties for extrusion-based additive manufacturing of poly (lactic acid) by annealing and blending with poly(3-hydroxybutyrate). *Polymers* **2019**, *11*, 1529. [CrossRef] [PubMed]
2. Terekhina, S.; Skornyakov, I.; Tarasova, T.; Egorov, S. Effects of the Infill Density on the Mechanical Properties of Nylon Specimens Made by Filament Fused Fabrication. *Technologies* **2019**, *7*, 57. [CrossRef]
3. Gibson, I.; Rosen, D.; Stucker, B.; Khorasani, M. Additive manufacturing technologies. In *Additive Manufacturing Technologies*; Springer International Publishing: Berlin/Heidelberg, Germany, 2020. [CrossRef]
4. Sakib-Uz-Zaman, C.; Khondoker, M.A.H. A Review on Extrusion Additive Manufacturing of Pure Copper. *Metals* **2023**, *13*, 859. [CrossRef]
5. Khondoker, M.A.H.; Sameoto, D. Design and Characterization of a Bi-Material Co-Extruder for Fused Deposition Modeling. In Proceedings of the ASME 2016 International Mechanical Engineering Congress and Exposition, Phoenix, AZ, USA, 11–17 November 2016. Volume 2: Advanced Manufacturing. V002T02A060. [CrossRef]
6. Altıparmak, S.C.; Yardley, V.A.; Shi, Z.; Lin, J. Extrusion-based additive manufacturing technologies: State of the art and future perspectives. *In Journal of Manufacturing Processes* **2022**, *83*, 607–636. [CrossRef]
7. Ender-5 S1 3D Printer. Available online: https://store.creality.com/ca/products/ender-5-s1-3d-printer?spm=..collection_f54d010d-3006-4cd2-bbe0-f4803f859154.albums_1.1&spm_prev=..index.products_display_nav_1.1 (accessed on 8 May 2024).
8. A Comprehensive Guide to PLA Melting Point and How It Influences 3D Printing. Available online: https://www.wevolver.com/article/a-comprehensive-guide-to-pla-melting-point-and-how-it-influences-3d-printing (accessed on 28 May 2024).
9. Introduction to the Most Common Materials Used for 3D Printing. Available online: https://www.3ds.com/make/solutions/blog/most-common-materials-3d-printing (accessed on 28 May 2024).
10. Density. Available online: https://en.wikipedia.org/wiki/Density (accessed on 28 May 2024).
11. Darabi, L.; Zare, M. High correlate simple equations for temperature and pressure dependence of the viscosity of ionic liquids. *Chem. Phys.* **2020**, *539*, 110933. [CrossRef]
12. Ikeda, M.; Aniya, M. Understanding the Vogel-Fulcher-Tammann law in terms of the bond strength-coordination number fluctuation model. *J. Non-Cryst. Solids* **2013**, *371–372*, 53–57. [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.