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Optimization in Extrusion Process for Polypropylene and High-Density Polyethylene Pellets in Additive Manufacturing of 3D Printing Filament

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ABSTRACT: The increasing demand for sustainable and cost-effective materials in additive manufacturing has driven research into optimizing the extrusion process for creating 3D printing filament from Polypropylene (PP) and High-Density Polyethylene (HDPE) pellets. This study explores the critical parameters in the extrusion process, including temperature, and screw speed, to enhance the quality and consistency of the resulting filament. Through a series of controlled experiments, we analyze the effects of these parameters on the filament's diameter, mechanical properties, and printability. Our findings demonstrate that by optimizing these variables, it is possible to produce high-quality 3D printing filament with excellent mechanical strength and dimensional accuracy, meeting industry standards. This research not only contributes to the broader adoption of PP and HDPE in 3D printing but also supports the development of more sustainable manufacturing practices by utilizing recyclable materials.

KEYWORDS: Extrusion Process, 3D Printing Filament, Polypropylene (PP), High-Density Polyethylene (HDPE), Additive Manufacturing.

I. INTRODUCTION

Manufacturing (AM) has transformed the production of customized products by reducing costs, shortening lead times, lowering energy consumption, and minimizing waste. As AM technology matures, it is expected to become standard across various industries [1]. Widely adopted for its efficiency in fabricating 3D parts, AM is particularly effective in methods like Fused Deposition Modelling (FDM), which typically uses materials like Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). Polypropylene (PP), a promising alternative to PLA, offers potential cost reductions and enhanced material properties [2][3]. Additionally, the emphasis on sustainability in manufacturing underscores the importance of High-Density Polyethylene (HDPE), valued for its environmentally friendly properties and recyclability [4].

With increasing awareness of the environmental impact of plastic waste, a significant portion of recycled waste consists of PP and HDPE. Utilizing these materials in 3D printing not only addresses the issue of plastic waste but also leverages their beneficial properties. However, challenges such as consistent filament diameter, optimal mechanical properties, and compatibility with FDM systems have limited the broader adoption of PP and HDPE in 3D printing. This paper aims to optimize the extrusion process for these materials by analyzing key parameters, such as temperature and screw speed, to produce filaments with superior quality. The findings are expected to support the wider use of PP and HDPE in 3D printing, promoting sustainable and efficient manufacturing practices.

II. LITERATURE REVIEW

Additive manufacturing (AM) has evolved significantly since its introduction, offering potential for environmentally friendly and sustainable production [5][6]. Among the various AM techniques, Fused Deposition Modelling (FDM) stands out for its simplicity and cost-effectiveness. However, despite these advantages, FDM still faces challenges related to the mechanical properties of the printed parts, which require further optimization to fully realize the potential of this technology [7].

Polypropylene (PP) emerges as a viable alternative to PLA, providing benefits in terms of cost and material properties. Nevertheless, challenges such as dimensional accuracy and warpage continue to hinder its printability [3]. Chong et al. (2020) demonstrated that recycled HDPE and PP filaments offer enhanced thermal stability and improved elongation properties, highlighting their potential for 3D printing applications [8]. This observation aligns with Devicharan et al. (2019) who emphasized the necessity of optimizing extrusion processes to improve filament quality and consistency [9].

Setiawan et al. introduced a double extruder system for HDPE, achieving notable success with a PID control system and optimal extrusion at 200°C. This underscores the potential of advanced extrusion techniques in enhancing filament performance [10][11]. Similarly, Freeman et al. explored methods to recycle HDPE, including converting materials from end-of-life boats into 3D printing filaments using screw-assisted extrusion. Their findings demonstrate effective methods for producing durable materials from recycled HDPE, addressing challenges related to waste accumulation and material sustainability [12].

The utilization of recycled materials in 3D printing, including the performance and cost implications of PP and HDPE, has been discussed extensively [13][14]. Romanenko et al. provide a comparative analysis of FDM with other AM techniques, emphasizing the ongoing need for optimization to address mechanical limitations and enhance the overall efficacy of the technology [15].

III. METHOD

To optimize the extrusion process for 3D printing filaments from polypropylene (PP) and high-density polyethylene (HDPE) pellets, a comprehensive literature review was conducted to identify key challenges and effective solutions. This review focused on critical parameters including temperature control, extrusion speed, and material properties.

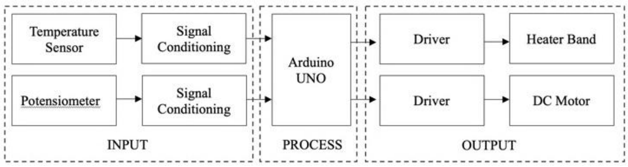

Figure 1. Extruder Control System

The design phase involved the integration of advanced control systems, incorporating an Arduino microcontroller, a heater band, and a thermocouple for precise thermal regulation as shown figure 1. A BTS7960 driver was employed to control motor speed, enhancing the accuracy and reliability of the extrusion process.

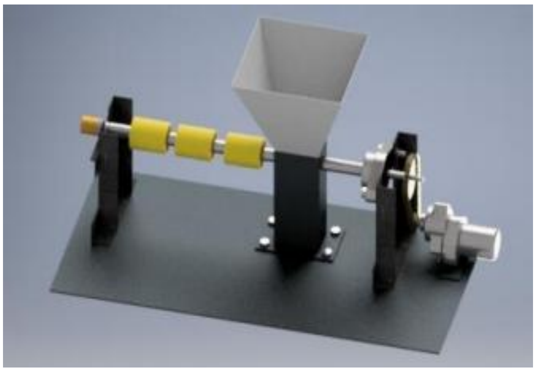

Figure 2. Extruder Design

Figure 2 shows an extruder design. The mechanical and electrical designs were converted into a physical prototype. The manufacturing process entailed assembling the extrusion components, integrating the temperature control system, and installing the motor control system. Emphasis was placed on the robustness and alignment of components to ensure effective filament production from PP and HDPE pellets, as shown in figure 3.

Figure 3. PP and HDPE Pellets

The extruder was subsequently tested for mechanical stability and structural integrity, electrical functionality of sensors and actuators, and overall integration to ensure seamless operation of the mechanical and electrical systems. To evaluate the optimization process, data on filament dimensions, extrusion speeds, and thermal values were collected. The results were presented in graphical formats to facilitate easy interpretation and comparison.

IV. RESULT AND DISCUSSION

No more than three levels of headings should be used. All headings must be in 10pt font. Every word in a heading must be capitalized except for short minor words as listed in Section III-B.

The results from the extrusion process and subsequent tests provide critical insights into the performance of the developed system for producing 3D printing filaments from PP and HDPE pellets. This section discusses the effectiveness of the temperature control system, motor speed adjustments, and the quality of the produced filaments, highlighting the key factors that influence the extrusion process. To evaluate the extruder's performance, two sets of data were analyzed: motor control data for the extruder machine operating without load and motor control data for the extruder machine under load with plastic pellets. These analyses reveal the operational efficiency of the extruder system and the characteristics of the resulting filaments under different conditions.

A. Extruder Machine without Load

The first test involved evaluating the extruder machine without a load by connecting the motor control to the gearbox to produce minimum and maximum rotational speeds. These speeds were controlled by adjusting the PWM (Pulse Width Modulation) output from the Arduino, which regulates the motor's rotation and speed. This test aimed to assess the stability of the motor's rotation, with the results presented in the following table.

Table I. Stability Motor Test Without Load

No	Motor Speed (PWM)	Operation Time (minutes)	Stability
1	10 (PWM)	10	Unstable
2	20 (PWM)	10	Unstable
3	30 (PWM)	10	Unstable
4	40 (PWM)	10	Unstable
5	50 (PWM)	10	Stable
6	60 (PWM)	10	Stable
7	70 (PWM)	10	Stable

As shown in Table 1, the motor test without a load was conducted within a rotational speed range of 10-70 PWM with an operational time of 5-10 minutes. The results indicate that the motor rotation stabilizes at speeds exceeding 50 PWM.

Table II. Stability Temperature Test Without Load

No	Set Point Temp. (°C)	Settling Time (minutes)	Stable Temp. (°C)	Stability
1	110	15	112	Stable
2	120	20	122	Stable
3	130	25	131	Stable
4	140	30	142	Stable
5	150	35	152	Stable
6	160	40	162	Stable
7	170	45	171	Stable

Subsequently, an unloaded extruder temperature test was conducted, as detailed in Table 2. The findings demonstrate that the extruder exhibits commendable temperature stability, with an average deviation of less than 3°C from the target temperature.

The data from the two tables indicate that the motor maintains stable operation at speeds exceeding 50 PWM, demonstrating consistent performance in this range. Moreover, the temperature control system for the heater band is functioning effectively, with temperature deviations kept within a narrow range of less than 3°C. These findings underscore the successful integration of both motor speed and temperature control, affirming their role in ensuring the reliable operation of the extruder machine.

B. Extruder Machine with Plastic Pellets Load

The performance of the extruder was tested with plastic pellets to evaluate its handling of real-world conditions. This assessment focused on how motor speed and temperature settings affect filament quality. This section reviews the results, highlighting the impact of loading on motor control and filament production.

Table III. Extruder Temperature Testing With PP Plastic Pellets

Temperature (°C)	Filament Length (cm/minutes)	Result
130	0	Temperature too low, the filament cannot be extruded
140	0	Temperature too low, the filament cannot be extruded
150	0	Temperature too low, the filament cannot be extruded
160	29	
170	0	 The temperature is too high, the filament doesn't form

Based on Table 3, the temperature test for the extruder with PP pellets shows that the optimal temperature for producing filament is 160°C. Below this temperature, the filament does not extrude due to insufficient heat. This data was obtained using a PWM setting of 60.

Table IV. Extruder Temperature Testing With HDPE Plastic Pellets

Temperature (°C)	Filament Length (cm/minutes)	Result
150°C	0	Temperature too low, the filament cannot be extruded
160°C	7	
170°C	12,5	

180°C	13,5	
190°C	0	The temperature is too high, the filament doesn't form

The temperature test for the extruder with HDPE pellets, as shown in Table 4, indicates that filament does not extrude at temperatures below 160°C due to insufficient heat, while temperatures above 180°C result in no filament formation because the heat is too high. The optimal temperature range for HDPE pellets is between 160°C and 180°C. This data was collected using a PWM setting of 60.

Subsequently, data were collected on the melting performance of both PP and HDPE pellets under the optimized temperature settings and motor speeds. This step involved analyzing how well the pellets melted and formed filaments at the specified conditions, providing a comprehensive assessment of the extrusion process efficiency.

Table V. 3D Printing Filaments From Pp And Hdpe Pellets

Material/gram	**PWM**	**Temp. (°C)**	**Diameter (mm)**	**Homogeneity**	**Strength**	**Filament Result**
1 minute extruder machine operation						
PP 145 gr	60	160	1,75	Adequate	Adequate	
HDPE 150 gr	70	170	2,05	Insufficient	Good	
2 minutes extruder machine operation						
PP 145 gr	60	160	1,25	Good	Adequate	
HDPE 150 gr	70	175	1,77	Adequate	Good	
3 minutes extruder machine operation						
PP 145 gr	60	160	1,35	Adequate	Insufficient	
HDPE 150 gr	80	180	1,70	Adequate	Good	
4 minutes extruder machine operation						
PP 145 gr	60	160	1,15	Adequate	Insufficient	
HDPE 150 gr	80	190	1,10	Insufficient	Adequate	

The standard diameter for 3D printing filament is generally 1.75 mm. The table illustrates that PP plastic pellets melted effectively and formed 3D printing filament with an input of 145 grams at a temperature setting of 160°C and a motor speed of 60 PWM. During a one-minute data collection, the resulting filament had a diameter of 1.75 mm, exhibiting adequate homogeneity and mechanical strength.

In contrast, HDPE pellets also melted effectively and formed 3D printing filament with an input of 150 grams at a temperature setting of 175°C and a motor speed of 70 PWM. Over a two-minute data collection period, the filament had a diameter of 1.77 mm, demonstrating adequate homogeneity and good mechanical strength.

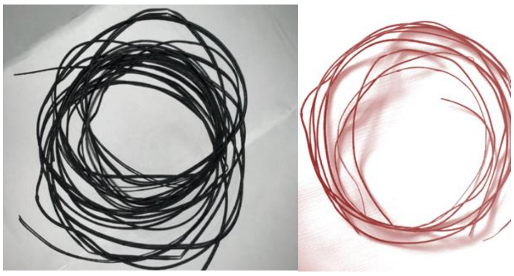

Figure 4. PP and HDPE Filament

Figure 4 shows the filament produced under the most optimal settings. The resulting filament closely aligns with the standard 1.75 mm diameter, exhibiting optimal levels of homogeneity and mechanical strength. The temperature and motor speed settings in this scenario proved to yield a stable and consistent filament quality, making it an excellent choice for 3D printing applications using PP and HDPE plastic pellets.

CONCLUSIONS

The results from the extrusion process and subsequent tests provide critical insights into the performance of the developed. The results demonstrate that the extruder effectively produces 3D printing filaments from polypropylene (PP) and high-density polyethylene (HDPE) pellets. The system achieved a filament diameter of 1.75 mm for PP at a production speed of 410 mm/min and 1.77 mm for HDPE at 130 mm/min. The filaments from PP showed adequate homogeneity and mechanical strength, while HDPE filaments exhibited adequate homogeneity and good mechanical strength., making them suitable for 3D printing applications. Optimal temperatures for filament production were found to be 160°C for PP and 175°C for HDPE, with heating times of 35-45 minutes and 40-50 minutes, respectively. The Arduino-based temperature control system proved effective in maintaining accurate and stable temperatures, with real-time adjustments based on feedback from temperature sensors. This research introduces a practical approach to filament production by combining advanced temperature control with a robust extrusion system, contributing to more efficient and reliable 3D printing processes.

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