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Construction of an extrusion machine for converting recycled PET plastics into filament for 3D printing

Harold Alberto Rodríguez-Arias[1]; Daniel Andrés Yepes Tapia[2]; Carmen Daniela Diaz Durango[3]
[1,2,3]Universidad Tecnológica de Bolívar, Colombia, harias@utb.edu.co

***Abstract*– This paper presents the design, development, and implementation of an extrusion machine for converting recycled polyethylene terephthalate (PET) plastics into filament for 3D printing. The project's main objective is to provide the community of the Universidad Tecnológica de Bolívar (UTB) with a tool that promotes the reuse of plastic waste, thus contributing to the reduction of environmental impact and supporting the realization of sustainable student projects. The extrusion machine supports the principles of the circular economy by promoting recycling and material reuse, fostering the use of post-consumer materials as raw materials for new processes and encouraging eco-friendly production methods.**

The machine is designed for laboratory use and allows the production of recycled PET filament from plastic bottles. Its design includes three main modules: a drag system that drives the filament, a positioning system that ensures the correct movement of the filament, and a winding system that collects the filament on a spool in an orderly manner. In addition, the extrusion nozzle's temperature is controlled by a PID system, with a clamp-type heater used as the heating element to ensure consistent extrusion performance.

This project also serves as an educational tool, fostering hands-on learning in areas such as recycling, manufacturing processes, and 3D printing technologies. It offers an opportunity for students to engage with real-world applications, contributing to the growing field of sustainable manufacturing and the transformation of recycled materials into functional products for 3D printing, reinforcing the importance of sustainable design and technology.

***Keywords* – Filament, Extrusion, Plastic, Recycling, 3D Printing.**

I. Introduction

The mass production of plastics for use in single-use products such as containers and packaging has led to a significant increase in plastic waste worldwide. In Colombia, around 700,500 tons of plastic containers and packaging are produced annually, of which only 30% are reused [1]. Of this amount, less than one-third of the plastic bottles consumed are recycled, despite being made of PET (Polyethylene Terephthalate), a 100% recyclable material [2].

In 2023, the Universidad Tecnológica Bolívar (UTB) generated a total of 83,346 kg of solid waste, of which 14% was recovered through the Integrated Solid Waste Management Plan [3]. Given this situation, the possibility arises of using non-recycled waste for alternative purposes.

At the same time, students at UTB are increasingly turning to 3D printing technology for the fabrication of components, which allows them to reduce the production costs of their projects. However, obtaining raw material can be complicated at times, resulting in higher expenses and time loss. In this context, the reuse of PET plastics can become useful in 3D printing.

II. Objective of the Research

The main objective of this research is the design, construction, and implementation of a prototype of a recycled plastic filament (PET) extrusion machine, intended for use as a laboratory tool at the Universidad Tecnológica Bolívar (UTB). This prototype not only aims to convert plastic waste into usable filament for 3D printing but will also serve as a multidisciplinary platform for research and learning. In particular, chemistry students will be able to use the machine to conduct material tests, analyzing the mechanical, thermal, and processability properties of filaments produced from recycled PET. In addition, the prototype will foster innovation in the field of circular economy, allowing engineering and design students to explore new applications for recycled materials.

III. Theoretical Framework

A. 3D printing

Additive manufacturing, commonly known as 3D printing, is a manufacturing process that allows the creation of three-dimensional objects through the successive layering of material, typically thermoplastic polymers, from a digital model [4]. This technology has revolutionized the industry due to its ability to reduce costs, production times, and material waste compared to traditional methods [5].

1) 3D Printing Technologies:

FDM (Fused Deposition Modeling): This is the most used technique in 3D printing. It involves the fusion and deposition of thermoplastic filaments layer by layer to build the object. It is valued for its low cost and ease of use [6].

SLA (Stereolithography): It uses liquid resins that are solidified by ultraviolet light. This technique offers high precision and quality surface finishes, making it ideal for applications that require fine details [7].

SLS (Selective Laser Sintering): It uses powder materials (such as nylon) that are fused using a laser. It is suitable for the manufacturing of functional and complex parts, without the need for supports [8].

2) Materials for 3D Printing:

PLA (Polylactic Acid): A biodegradable and easy-to-print material, ideal for rapid prototyping. However, it has lower mechanical and thermal resistance compared to other materials [9].

ABS (Acrylonitrile Butadiene Styrene): Known for its high strength and durability, it is widely used in industrial applications. It requires higher printing temperatures and a heated bed to prevent warping [10].

PET (Polyethylene Terephthalate): It offers a balance between mechanical strength, ease of printing, and sustainability. It is recyclable and commonly used in the manufacturing of containers and bottles [11].

3) Advantages of 3D Printing:

Customization: It allows the manufacturing of customized parts adapted to specific needs, which is especially useful in sectors such as medicine and aeronautics [12].

Waste Reduction: Unlike subtractive methods, additive manufacturing generates less waste, as only the necessary material is used to build the part [13].

Speed: It facilitates the rapid production of prototypes and final parts, reducing product development times [14].

B. Extrusion Process.

Extrusion is a continuous manufacturing process in which a thermoplastic material is melted and forced through a nozzle to create profiles with specific cross-sectional shapes. This method is widely used in industry to produce filaments, pipes, sheets, and other plastic products [15].

Some of the stages of the extrusion process are:

1. Feeding:

The material in the form of pellets or granules is introduced into the extruder’s hopper.

2. Melting:

The material is heated and melted in the extruder barrel by using electrical heaters and the friction generated by the screw.

3. Compression:

The screw compresses the molten material and pushes it toward the nozzle.

4. Shaping:

The molten material passes through the nozzle, where it acquires the desired shape.

5. Cooling:

The extruded material is cooled and solidified, retaining the obtained shape [16].

C. Polyethylene Terephthalate (PET)

PET is a thermoplastic polymer widely used in industry due to its excellent mechanical, chemical, and thermal properties. It is strong, transparent, and recyclable, making it an ideal material for the manufacture of packaging, bottles, and textile fibers [17]

1. Mechanical Properties:

Tensile Strength: Between 55 MPa and 75 MPa. Young's Modulus: Between 2800 MPa and 3100 MPa [18].

Hardness: High resistance to wear and abrasion, making it suitable for high-performance applications [19].

2. Thermal Properties:

Melting Temperature: Approximately 260 °C. Glass Transition Temperature: Between 70 °C and 80 °C, indicating its stability at moderate temperatures [20].

D. Regulations and standards.

1. ISO 527:

It specifies the test methods for determining the mechanical properties of plastics, such as tensile strength [21].

2. ISO 178:

It sets out the methods for evaluating the bending properties of plastics [22].

3. ISO 11357:

It describes methods for thermal analysis of plastics, including the determination of melting temperature and glass transition [23].

IV. Methodology

The methodology is detailed through a flowchart shown in Fig. 1, which illustrates the complete process for the design, development, and validation of a machine intended for the production of recycled PET filament. The process begins with the design of the machine's morphology, focusing on key systems such as extrusion, filament advancement, positioning, and winding. Next, a simulation of the thermal behavior is carried out to identify possible unwanted overheating. If detected, adjustments are made to elements that may affect it, such as sensors, controllers, or actuators. Subsequently, in the production phase, the necessary parts are designed, the non-designed parts are acquired, and the components are integrated. In parallel, a PID control system with an interface is programmed to ensure proper control of the machine [24]. The system validation includes checking critical parameters such as temperature, extrusion speed, filament advancement synchronization, and positioning. If the results are unsatisfactory, adjustments are made; otherwise, the produced PET filament is used.

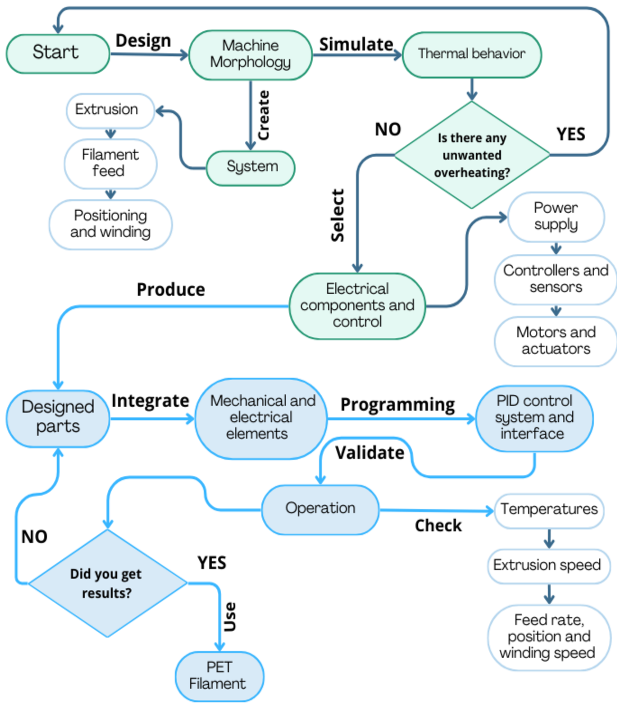

Fig. 1 Flow diagram of the methodology used.
Own elaboration.

The conceptual design of a plastic extruder involves the initial planning and structuring of the key elements of the system before its manufacturing. This process defines the operational principles, the main components, and the appropriate materials for the correct functioning of the equipment. In Fig. 2, the essential components of the extruder machine and a preview of the assembly are shown.

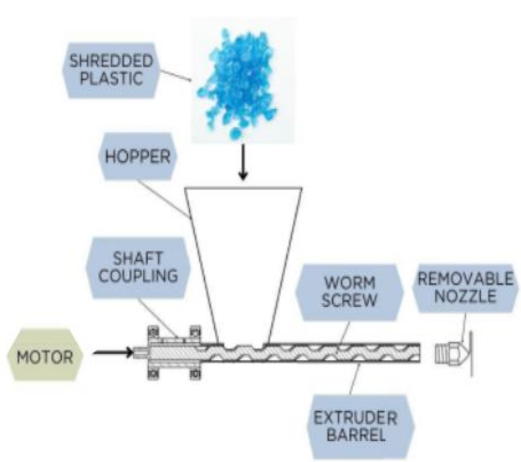

Fig. 2 Conceptual design of extruder machine.

In Fig. 3, the cooling system that thermally stabilizes the filament after extrusion is shown. Subsequently, the drive system regulates the speed and tension of the filament. Next, the filament positioning system manages the alignment and homogeneous distribution of the material, and the winding system organizes the filament into a spool, facilitating its storage and subsequent use.

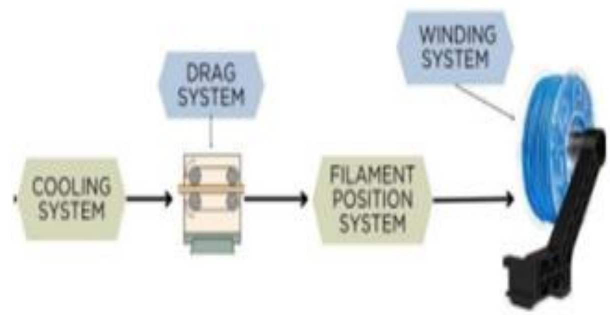

Fig. 3 Conceptual design for the winding phase
Own elaboration.

V. Results

The extrusion system was put into operation using PET (see Fig. 4) and PLA (see Fig. 5) pellets. During the initial tests, nozzle leakage problems caused by the high temperature extrusion speed were resolved. This allowed the system to be calibrated to determine the optimal temperatures and speeds for each material.

Additionally, a guide support was implemented in the drive section, which proved to be effective in preventing filament deviation and ensuring a more uniform flow.

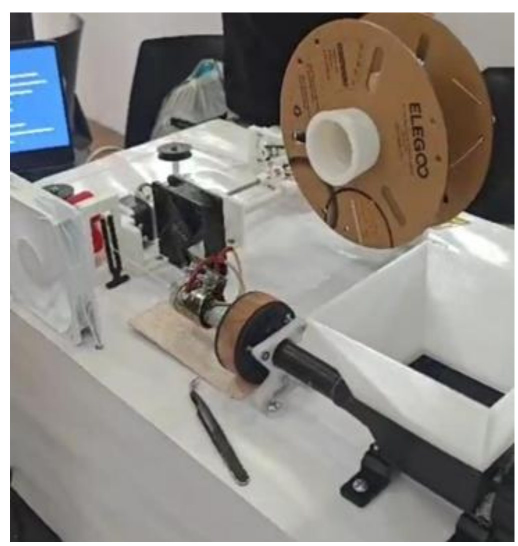

Fig. 4 PET functional tests.

Pulleys were incorporated to guide the material toward the winding section (see Fig. 5), optimizing the space occupied by the machine and facilitating its operation in laboratory environments with area limitations.

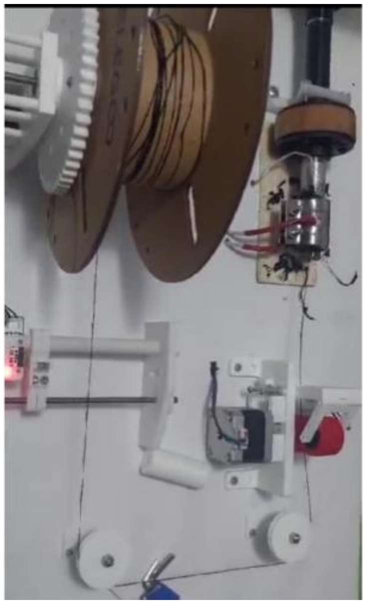

Fig. 5 Functional tests with PLA.

The filament can be obtained in solid form by operating between temperatures of 240 and 260 °C (see Table 1). At higher temperatures, it becomes too fluid, which prevents it from getting into the form of a thread and being wound. Within this range, at 260 °C, the material remains quite fluid, and although it can start to be wound, the diameter becomes very irregular. Additionally, as it is close to its melting point, it tends to evaporate inside the barrel, generating air bubbles within it (see Fig. 6). If kept at this temperature for too long, thermal degradation begins, causing the material to lose quality and become unsuitable for 3D printing.

TABLE I
EXTRUSION TESTS AT DIFFERENT TEMPERATURES AND SPEEDS

Test	Temperature (°C)	Speed (%)	Results
1	270	30	High fluidity, trapped air, and evaporation.
2	270	50	High fluidity, less evaporation, and air.
3	260	50	Trapped air, lower fluidity, high fragility, and variable diameter.
4	250	50	Higher viscosity, lower fragility, variable diameter, and less air.
5	245	30	Flexible, slight diameter fluctuation, moderate air, and clogging.
6	245	50	Flexible, slight diameter fluctuation, little trapped air.
7	245	70	Flexible and irregular diameter due to high speed.
8	240	50	Flexible, stable diameter, little trapped air.
9	<230	50–100	Clogging that stops the flow.

Fig. 6 PET filament with trapped air.

At 240°C and with an extrusion speed of 50%, the filament exhibits better mechanical properties, such as higher viscosity, improved flexibility, and less trapped air (see Fig. 7). However, as the temperature drops, the fluidity also decreases, which may cause blockages in the barrel area due to the resistance to movement created by the material. In this regard, it is considered necessary to use a motor with higher torque to ensure a constant flow of shredded material and reduce clogging.

Since low temperatures cause blockages and reduce the quality of the filament, it is determined that for the process, it is suitable to maintain a temperature between 240 and 260°C and a medium extrusion speed. This is because, when the speed is increased too much, the filament's diameter quality is lost, whereas decreasing the speed increases the frequency of blockages and the presence of trapped air in the material.

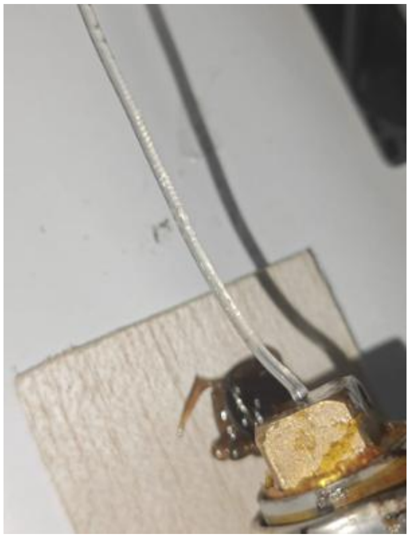

Fig. 7 PET filament.

For the printing test with this material, it is recommended to use the parameters in Table 2.

TABLE II
RECOMMENDED PRINT PARAMETERS AND TEST VALUES.

Parameter	**Recommended value**	**Value used in the test (Anycubic Kobra 2 Neo)**
Extruder Temperature	260 °C	260 °C
Bed temperature	100 °C	100 °C
Print Speed	80 mm/s	150 mm/s

The object to print was a "Benchy" (see Fig. 8), which allows assessing the properties of the material being used, since it contains overhangs, retractions, and small details that make it the perfect test candidate. The size was reduced to 50% to test the pressure, which shows that the material performs well with small parts.

Fig. 8 Printing with PET filament "Benchy".

Based on the results obtained, PET emerges as a recycled option with good potential for 3D printing applications. However, further testing is still necessary to improve its behavior, particularly regarding ease of processing. Although a direct experimental comparison with commercial PET filaments was not made, their technical properties were used as a reference to guide the evaluation of the recycled filament, which provides a preliminary estimate of its viability compared to market standards. It is also recommended to explore the idea of making blends to enhance its properties and achieve better results in 3D printing.

Preliminary tests were conducted with PLA shredding (see Fig. 9), which, requiring less temperature than PET, showed better consistency. However, due to the size of the shredded material and the frequent clogs in the machine, it was not possible to carry out prints with this material.

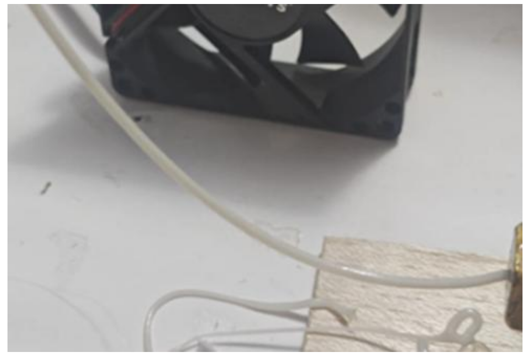

Fig. 9 Filament extrusion with PlA shredding.

VI. DISCUSSION

Among the issues detected during extrusion, the low quality of the filament, the presence of trapped air, and the clogs stand out.

A. Low quality of the filament.

PET (polyethylene terephthalate) is a semicrystalline material, which allows it to adopt either an amorphous or crystalline structure depending on the processing conditions [25]. In the case of bottles, the degree of crystallinity varies across different areas (see Fig. 10); for the body of the bottle, it ranges between 25.9% and 33.8% [25].

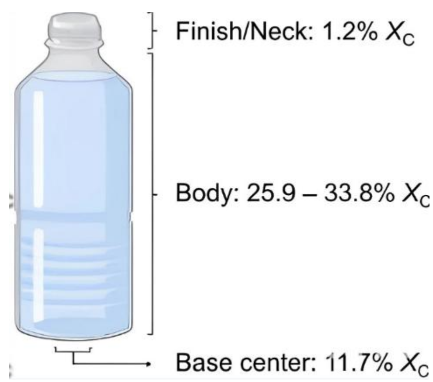

Fig. 10 Crystallinity degrees of a bottle [25].

The crystalline state in PET filament improves properties such as toughness, stiffness, tensile strength, and hardness [25]; however, it also increases brittleness. The crystallization peak of PET occurs at 175°C [26], a temperature at which the glass transition temperature (Tg) has already been surpassed, but it has not yet reached the melting point (260°C).

For this process, at temperatures ranging from 240 to 260 °C, it is located within the melting zone (Tm) (see Fig. 11), where PET (partially crystallized polymer) shows lower resistance to deformation. For this reason, it is necessary to conduct tests at lower temperatures to assess filament quality. The possibility of mixing with other materials to reduce crystallinity during the extrusion process is also considered.

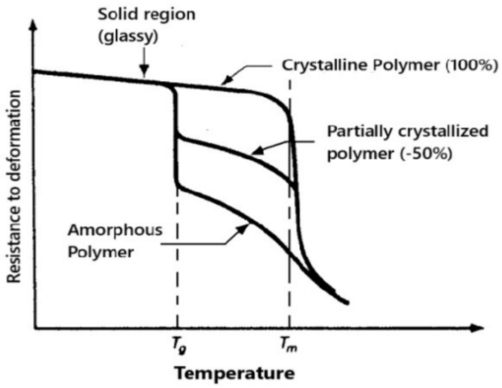

Fig. 11 Deformation resistance vs. temperature [26].

B. Presence of trapped air.

The presence of trapped air in the filament affects the quality, mechanical properties, and performance during 3D printing. One of the causes of these air inclusions is the high operating temperature. When the material stays too long in the barrel, it can overheat and even evaporate. Upon exiting, the trapped air undergoes a sudden temperature change, causing internal expansion.

On the other hand, when the temperature is lowered, although the presence of air decreases, it still exists to a lesser extent. This is due to the low compression of the material inside the barrel. In industrial processes, to avoid this problem, extruders typically use screws with variable channel depth (see Fig. 12). These screws are designed to progressively compress the material across three zones: the feed zone, where the channel depth is greater to allow material entry; the compression zone, where it is reduced to compact the material and eliminate air; and the metering zone, where the depth remains constant until reaching the nozzle. This eliminates air spaces and ensures a more uniform flow of the molten polymer. To improve performance in the process, it is necessary to design a screw with these features [27].

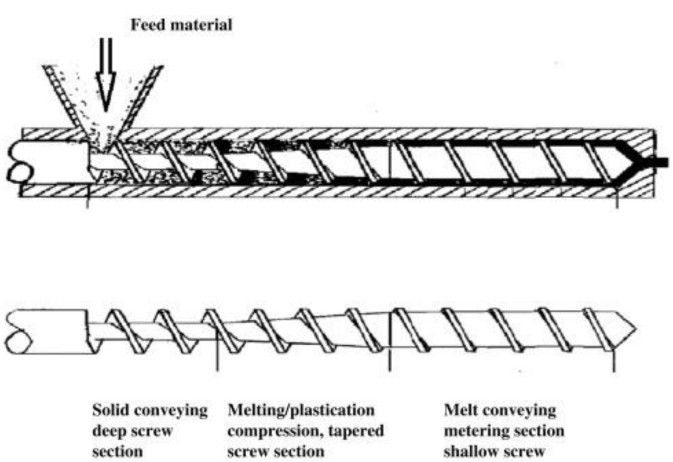

Fig. 12 Extrusion screw [28].

C. Blockages

During the PET extrusion process, blockages can occur due to the high melting temperature of the material and the lack of a preheating system. Although PET exhibits greater mobility in the barrel at elevated temperatures, the absence of homogeneous melting prevents proper material flow. To solve this issue, it is recommended to incorporate a clamp-type heater for material preheating.

VII. Conclusions

In the validation and final testing stage, extruded filament was obtained under better conditions for printing after several attempts and adjustments. The optimal configuration was found at a temperature between 240 and 260 °C for PET and a motor speed of 50%.

However, challenges arose related to the low torque of the motor, which caused frequent blockages and forced an increase in the nozzle temperature. This increase led to the appearance of trapped air in the filament, reducing its quality.

On the other hand, the guide support incorporated into the drag section was effective in preventing filament deviation, improving the alignment of the extrusion process. Preliminary tests were conducted with PLA, which proved to be more manageable due to its lower processing temperature. However, blockages persisted, limiting the ability to fully evaluate this material.

The printing of the "Benchy" test object allowed the evaluation of the produced filament's properties. Although acceptable results were obtained with the PET filament, the need to optimize the configuration and improve material flow consistency for smaller and more detailed pieces became evident.

VIII. Recommendations

To improve the product quality, the following recommendations should be considered:

A. Improve motor torque:

It is recommended to replace the current motor with one that has higher torque. This will ensure a constant flow of shredded material and reduce issues related to blockages.

B. Temperature and speed adjustments:

For PET, it is recommended to maintain an extrusion temperature of 260 °C and a heated bed at 100 °C. The printing speed should be reduced to 80 mm/s or lower, depending on the specific capabilities of the printer.

C. System design optimization:

Enhance the design of the worm screw, considering the size and configuration of the extrusion system to minimize blockages, imperfections, and to facilitate the material flow.

D. Materials and further testing:

Conduct further testing with PLA, by adjusting the shredding size and exploring lower temperature settings. This material demonstrated better consistency and could be more viable with proper adjustments.

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