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Prototype Development of a Plastic Injection Molding System for Recycled PLA

***Abstract*—At the digital fabrication laboratory (FABLAB) of a local university, the lack of equipment for recycling PLA filament waste from 3D printing has led to the accumulation of plastic and the inefficient use of resources. This project presents the development of a prototype plastic injection molding machine designed to recycle PLA material. A comprehensive literature review guided the selection of key components, including the heating system and mold configuration. Mechanical testing verified the viability of recycled PLA for reuse. The prototype was modeled in SolidWorks, with structural simulations and thermal analyses supporting its design. Experimental trials evaluated the quality of the molded parts, demonstrating high efficiency and validating the prototype's feasibility as a sustainable solution for PLA recycling in digital fabrication environments.**

***Index Terms*—Plastic injection molding, Recycled PLA, Prototype development, Sustainable manufacturing, Thermal analysis, Additive manufacturing waste**

I. INTRODUCTION

In a university-affiliated digital fabrication laboratory, an average of 103 3D prints are produced each academic quarter, consuming approximately 8.6 kilograms of PLA filament. It is estimated that 7.76% of these prints are discarded due to factors such as machine calibration errors, user mistakes, or material overuse. This percentage represents not only a substantial material loss but also raises environmental concerns, as discarded PLA contributes to plastic waste accumulation.

Although PLA is biodegradable under specific industrial composting conditions, its disposal still presents a sustainability challenge when not properly managed. The accumulation of PLA waste impacts both environmental quality and operational efficiency, as failed prints necessitate the continual purchase of new filament. Moreover, the lack of an in-house recycling system restricts opportunities to implement a circular economy within the lab—an approach in which waste materials are recovered and reused in future prints or manufacturing processes.

A. Background of the problem

The accumulation of plastic waste in university-based digital fabrication laboratories, such as academic FABLABs, exemplifies a broader global challenge in managing the byproducts of additive manufacturing. While PLA is considered a more sustainable alternative to petroleum-based plastics, improper disposal practices still contribute to environmental degradation. At present, failed prints and surplus PLA at the FABLAB are routinely discarded, resulting in both increased waste volume and the loss of potentially reusable material.

A critical limitation within the lab is the absence of equipment capable of processing and recycling PLA waste. This constraint not only leads to inefficient material usage but also obstructs the adoption of sustainable practices within the 3D printing workflow. On a global scale, initiatives to recycle PLA in small-scale settings remain limited, with minimal research and development of recycling systems tailored for educational or low-resource environments—particularly in developing countries such as Honduras.

The development of a plastic injection molding machine in this type of FABLAB offers a promising and innovative approach to address this gap. Such a system would not only enable the reuse of discarded PLA but also establish a scalable, replicable model for sustainable digital fabrication in academic and maker environments.

B. General objective

Develop a prototype plastic injection molding machine capable of recycling and reusing PLA material from failed or excess 3D printed parts through a structured design, fabrication, and testing process.

II. STATE OF THE ART

The recycling of polylactic acid (PLA), a common material in 3D printing, has gained importance due to its environmental implications and the demand for sustainable manufacturing. As plastic waste increases, reprocessing methods—particularly injection molding—have emerged as viable solutions. These systems are especially useful in small-scale and educational settings, supporting circular manufacturing practices [1].

Recent developments aim to reduce energy use, prevent PLA degradation, and improve the quality of recycled parts. Gravity-fed vertical injection machines, designed for home workshops and small enterprises, offer a simplified alternative to screw-based extruders by lowering mechanical complexity and cost. Their design enhances accessibility for small-scale recycling efforts. A typical configuration of such machines is illustrated in Fig. 1 [2], [3].

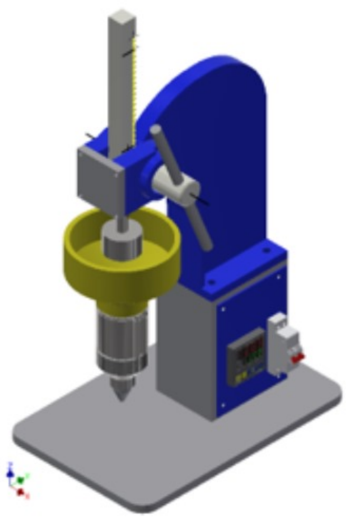

Fig. 1. Generic plastic injection machine

These machines typically use band heaters, PID temperature controllers, and thermocouples to ensure precise thermal regulation—critical for consistent, high-quality molding [2], [4]. Proper temperature control allows PLA to reach optimal melting points without degrading, ensuring smooth mold filling and part integrity [5].

Studies propose improving heating systems through high-performance elements, insulation, and closed-loop feedback control. These enhancements increase thermal stability, reduce waste, and improve part repeatability [6]– [8]. For instance, a system using band heaters and thermocouples for HDPE achieved stable melting with reduced cycle times [9].

Further innovations include incorporating magnetic nanomaterials (MHD) to enhance melt flow, reducing defects by 23.21% and improving system performance by 70.98% using Riga magnetic fields and metaheuristic optimization [10]. RHCM (Rapid Heating and Cooling Molding) also improves aesthetics and reduces surface defects using precise mold temperature control via electric heating and water cooling [11].

Automation has advanced with LabVIEW and Arduino-based systems, enabling real-time control of injection pressure, timing, and temperature. These setups have successfully processed hybrid materials like PET and PP with cocoa pod husk ash, enhancing biodegradability and performance [12].

Finally, AI has been applied to optimize molding cycles by analyzing large datasets to reduce manual intervention and improve stability [13], [14]. Deep learning models further support fault detection by fusing multimodal sensor data for more accurate anomaly detection during production [15].

III. METHODOLOGY

A. *Research variables*

The primary **dependent variable** in this study is the *quality of the final injected product*. This includes two key performance indicators:

- **Structural integrity**, which refers to the strength and durability of the molded parts, determining their suitability for functional applications.
- **Surface finish**, which evaluates the smoothness and absence of surface defects, influencing both the aesthetic and functional aspects of the product.

The **independent variables** influencing these outcomes are divided into three categories: process parameters, operational conditions, and equipment configuration:

1) **Process Parameters**
   - *Injection temperature*: Crucial for ensuring proper melting and flow of the PLA. Incorrect temperatures may result in incomplete fills, warping, or degradation.
   - *Injection pressure*: Determines the force applied to drive the molten PLA into the mold cavity. Adequate pressure ensures complete mold filling and minimizes defects such as voids.
   - *Injection speed*: Affects how rapidly the material is introduced into the mold. Controlled speeds help reduce air entrapment, bubbles, and inconsistencies in part geometry.
2) **Operational Conditions**
   - *Cycle time*: Encompasses the full injection cycle—from material feeding to part ejection. Optimizing this variable enhances productivity and system efficiency.
   - *Material conditioning*: Involves shredding failed or excess PLA into uniform particles suitable for reinjection. The quality of this preprocessing step directly impacts flow and melting behavior during molding.
3) **Equipment Configuration**
   - *Drive system*: The type of motor employed influences torque, stability, and overall control of the injection process.
   - *Nozzle and screw design*: These components govern the precision and uniformity of molten material flow, affecting the dimensional accuracy and consistency of the final parts.

Together, these variables form the foundation for evaluating and optimizing the performance of the prototype injection molding machine when processing recycled PLA.

B. *Study methodology*

To execute the project efficiently, procedures were structured into defined stages. A comprehensive literature review was first conducted to understand the operational principles of plastic injection molding machines, including how raw materials reach plasticization based on their thermomechanical properties. This analysis guided the selection of key components—heating system, injection screw, barrel, and structural design. It also covered machining principles and mold operation, leading to the adoption of a two-plate mold configuration.

A key research question was whether recycled PLA retains sufficient mechanical properties for reuse. Results confirmed its strength and hardness are comparable to industrial-grade PLA, even without additives. SolidWorks was used to model the prototype—frame and ejection mechanisms included—and to support the design process. Experimental validation then assessed operational performance: functionality tests confirmed basic operation, process parameters were fine-tuned, part quality was evaluated through surface and dimensional inspections, and energy consumption was compared against a standard 3D printer to assess efficiency.

IV. RESULTS

A. Design Parameters

A critical component in the design and fabrication of the prototype is the nozzle, whose dimensional parameters significantly influence the machine's overall performance and manufacturing feasibility. Through iterative testing and engineering calculations, the nozzle extrusion diameter was established at approximately 5 mm, with an allowable tolerance of ±3 mm. The nozzle configuration is shown in Fig. 2.

The nozzle design also incorporates a flange with a thickness of 6.32 mm, serving as the primary contact and coupling interface with the mold. When the mold is closed, the differential diameters between the nozzle and mold components provide mechanical support, effectively preventing displacement of the mold along the y-axis during the injection of molten material under pressure.

Fig. 2. Heating nozzle

The plunger is a fundamental component of the prototype, responsible for forcing the molten material into the mold cavity. A key design consideration for the plunger is its enlarged diameter at the base, which prevents the material from leaking along the barrel walls during injection and facilitates proper accumulation and flow within the chamber. To enable controlled vertical displacement along the y-axis, the nut of the threaded rod is rigidly welded to the plunger cylinder, making it the sole moving part of the system.This component is depicted in Fig. 3.

Fig. 3. Injection plunger

The heating of the PLA material is a critical parameter that requires precise control in the operation of a plastic injection molding machine. To achieve uniform and consistent temperature distribution across the entire surface of the heating barrel, while compensating for potential heat losses, two 300 watt resistive heaters were strategically installed. Their arrangement is presented in Fig. 4. This configuration ensures efficient thermal transfer, enabling the PLA to reach the optimal melting temperature necessary for effective plasticization and successful injection into the mold.

Fig. 4. Heating resistors

The vertical arrangement of the prototype was a deliberate design choice aimed at minimizing overall costs. By adopting a vertical configuration, the system leverages gravity to facilitate the downward flow of molten material into the mold, as in Fig. 5. This eliminates the need for complex and costly material transport mechanisms, thereby simplifying the prototype's design and enhancing the efficiency and control of the injection

18

process. Consequently, this approach ensures that the system remains both economically viable and functionally effective.

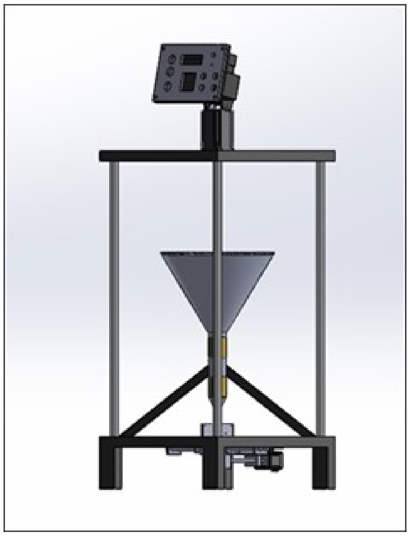

Fig. 5. Vertical configuration

B. Release Mechanism and Mold

The release mechanism employs linear guide systems designed to facilitate controlled and highly precise movements essential for the accurate operation of the injection molding machine. These guides ensure that linear forward or backward motion actuates the opening or closing of the follower arms. Even force distribution ensures synchronized arm motion, reducing mechanical wear and maintaining consistency during the injection cycle. The release mechanism is illustrated in Fig. 6.

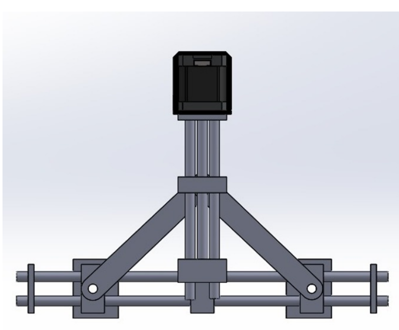

Fig. 6. Release Mechanism

The linear actuation is powered by a NEMA 17 motor, which delivers reliable and steady force to drive a follower connected to the guides. This movement enables the arms to release the finished molded part or reset to prepare for the subsequent injection cycle, ensuring smooth and efficient system operation. The integration of this mechanism enhances precision and optimizes overall machine performance by reducing downtime between cycles.

The mold designed for this prototype was machined from aluminum, selected for its superior properties in plastic injection applications. An image of the aluminum mold can be seen in Fig. 7. Aluminum's high thermal conductivity facilitates rapid heat transfer, reducing cooling cycle times and enhancing overall process efficiency. Furthermore, aluminum's machinability allows for precise fabrication of complex mold geometries, contributing to improved product quality and reproducibility.

Fig. 7. Aluminum mold

The mold design has been meticulously developed considering the nozzle's entry depth, resulting in a clamping mechanism engineered to securely and precisely align both Part A and Part B. This precise fit between mold components is essential to maintain system integrity during the injection process, as shown in Fig. 8. By ensuring minimal clearance, the design effectively reduces material leakage, promoting optimal flow of molten material into the mold and thereby enhancing manufacturing efficiency and product quality.

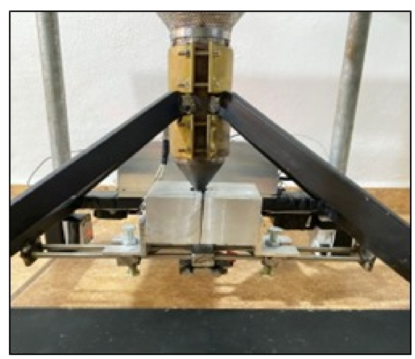

Fig. 8. Mold clamping

C. Thermal Analysis

The thermal analysis was conducted and validated using SolidWorks simulation software, revealing peak temperatures slightly exceeding 200°C, as shown in Fig. 9, within the heating barrel. The results demonstrate effective thermal performance of the prototype, with the highest temperatures localized at the heating barrel as intended. Furthermore, the iron support plates exhibit efficient heat dissipation, aided by their substantial thickness, which contributes to maintaining thermal stability and structural integrity during operation.

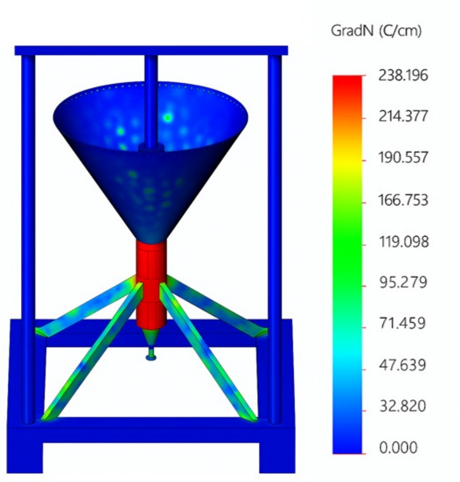

Fig. 9. Thermal study

D. Plasticization results

The injection process commences once the material reaches its plasticization temperature, maintained within a controlled range of 185 to 200°C. At these temperatures, the PLA transitions from a solid state to a viscous fluid, acquiring sufficient flowability for processing. The plunger, actuated by the prototype's screw mechanism, applies continuous pressure to the plasticized material, progressively advancing it toward the output chamber. The molten material is then forced through the prototype's conical nozzle, engineered to provide consistent and uniform flow. With a final exit diameter of 5 mm, the nozzle ensures the material exits as a filament, as shown in Fig. 10, accurately directed into the mold. Maintaining steady plunger pressure throughout this stage is critical to prevent velocity fluctuations or flow interruptions, thereby guaranteeing consistent fill and part quality.

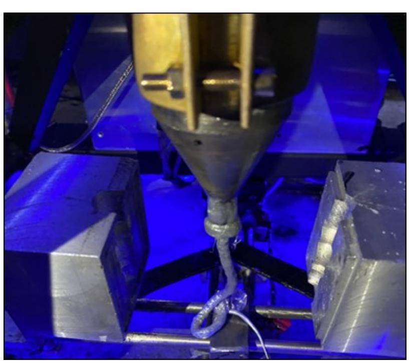

Fig. 10. Filament injection

Injection tests showed positive results, with the recycled PLA maintaining sufficient ductility for molding without additives. The molded parts accurately matched the mold design, confirming the prototype's effectiveness under the tested conditions and supporting the reuse of PLA in sustainable manufacturing. After injection, a small runner or sprue formed due to residual plastic flow in the mold's straight section, which is a typical outcome of the process. This is illustrated in Fig. 11.

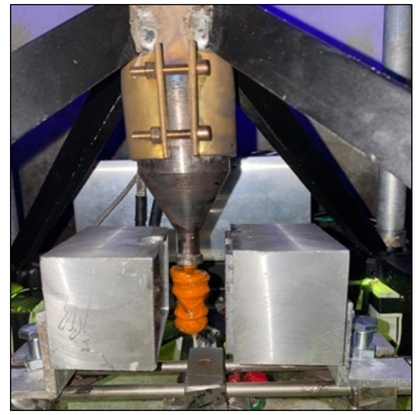

Fig. 11. Plasticization inside the mold

The parts produced by the prototype measure 43 mm in height and 24 mm at the base, precisely matching the mold dimensions. Their consistent quality is evidenced by well-defined reliefs, appropriate hardness, smooth surface finish, and strong mechanical properties. These traits confirm the success of the injection process in achieving high precision and finish. Additionally, the use of recycled PLA demonstrates that the parts retain excellent physical and aesthetic qualities, validating their suitability for reuse. This highlights the prototype's effectiveness in producing high-quality components from recycled material, supporting sustainability and efficient resource use.

E. Energy Analysis

The energy analysis compares the performance of the plastic injection molding prototype with a Voxelab Aquila 3D printer, considering operation time and energy consumption. Both machines manufacture an identical part with a volume of 12,246.27 mm³, enabling a fair comparison.

The 3D printer operates with an average print time of 35 minutes, utilizing 8 grams of filament and drawing 400 watts of power, resulting in an energy consumption of approximately 0.233 kWh. In contrast, the plastic injection molding machine completes the process in 12 minutes, including heating and injection phases, consuming 800 watts of power and a total of 0.16 kWh.

These results demonstrate that the plastic injection molding prototype is 65.7% faster and consumes 31% less energy than the 3D printer to produce the same component, as shown in Fig. 12, highlighting its efficiency advantage for manufacturing parts of this volume. Additionally, surface finish differences between both processes are clearly visible, as shown in Fig. 13.

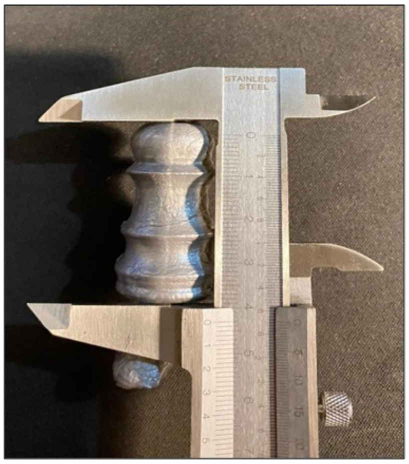

Fig. 12. Sizing of injected parts

Fig. 13. Comparison of surface finishes

V. Conclusions

A prototype injection molding machine was successfully designed and constructed to recycle PLA from failed 3D prints. This machine is specifically tailored to recycle and reuse PLA material derived from defective or discarded 3D printed parts. The project demonstrated the machine's efficiency in converting recycled PLA into reusable material while preserving its mechanical properties. Critical parameters—including melting temperature, injection pressure, screw rotation speed, and dwell time—were carefully analyzed and optimized to streamline the recycling process. These optimizations were validated through comprehensive testing, confirming the machine's functionality and efficiency in processing 3D printing waste.

The design prioritized components readily available in the local market, ensuring affordability and accessibility. Iterative improvements based on test results enhanced the machine's long-term viability, reliability, and sustainability. The prototype represents a valuable solution for small- to medium-sized enterprises and domestic users seeking eco-friendly manufacturing.

VI. Recommendations

- **Improvement in injection capacity:** A higher-capacity motor would allow manufacturing larger parts, maximizing the heating barrel's usable volume. This upgrade enables a broader product range and enhances the prototype's overall efficiency.
- **Cooling system for the mold:** Adding a cooling system to the mold would reduce cycle times and improve part quality. This can be achieved by integrating cooling channels to optimize temperature control during injection.

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