Process Parameters and Manufacturing defects for Large Scale Additive Manufacturing using Recycled Polymer Pellets

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Abstract. Large-scale additive manufacturing offers promising potential for design industries with its mold-free production, geometric freedom, and mass customization capabilities. However, using polymers in large-scale printing poses environmental challenges due to plastic waste. To address this, research on recycled polymers is crucial, but literature on the topic is limited. This paper investigates optimal process parameters and design guidelines for large-scale additive manufacturing using recycled polymer pellets. It addresses the lack of information in the literature and explores three recycled polymers which are not currently recycled by the industry: rPLA, rHDPE, and rABS. Key process parameters include temperature, layer height, feed, and extruder speed. Design recommendations include strategies to mitigate issues like warping, poor adhesion, and moisture content. By incorporating recycled polymers, the design industry can reduce its environmental impact and enhance manufacturing efficiency.

Keywords: Additive Manufacturing, Robotics, Recycled Polymers, Large-scale Additive Manufacturing

1 Introduction

Large-scale additive manufacturing offers a great potential for the design industries due to its ability to produce parts without the need for molds, its geometric freedom, and potential for mass customization. However, large scale printing with polymers presents significant environmental challenges, as it can significantly contribute to the urgent plastic waste problems. To mitigate these challenges, research on recycled polymers is crucial, yet limited literature exists on this topic. There is little information available on process parameters and design guidelines for large scale additive manufacturing with recycled polymers.

This paper investigates optimal process parameters and design guidelines for large scale additive manufacturing using recycled polymer pellets. Key process parameters for large scale additive manufacturing include temperature, layer height, and feed and extruder speed. However, the optimal parameters for recycled polymers are not readily available in the literature. Similarly, key design parameters involve geometries that are easy to print with a continuous feed and are resilient to warping, mitigate poor bed adhesion and can be compatible with polymers with higher moisture content, which are problems usually found when printing with recycled polymers.

The research presented in this paper addresses these gaps in the literature. The methodology involves prototyping with different process parameters and designs, studying the results, and elaborating recommendations. Specifically, this research investigates three polymers which are recovered by our industry partner BLIDNED, but are not being fed back to the industry: recycled PLA (rPLA), recycled HDPE (rHDPE), and recycled ABS (rABS). From these, rPLA was identified as best printing material and the optimal process parameters and design guidelines are studied.

The results of the study include recommendations for process parameters for rPLA and design recommendations to mitigate problems of warping, poor adhesion, and moisture content. The findings of this research can help the design industries reduce their environmental footprint by incorporating recycled polymers in their additive manufacturing processes. Furthermore, the design guidelines can help industries avoid common manufacturing defects such as warping and poor adhesion.

2 State of the Art

The research involves two main areas of study, which are discussed in the following subsections.

2.1 3D Printing with Recycled Polymers

3D printing with recycled polymers using Fused Deposition Modeling (FDM) is commercially available with numerous filaments made from post-consumer rPLA, rPET and rABS. The characterization of such recycled polymers has been conducted in several academic research projects, indicating good printability with a reduction in tensile and flexural strength in rPLA and smoother surface finished in rPLA and rABS (Pinho et al, 2020).

The printability with filaments of recycled polymers which are less conventional in additive manufacturing, such as PP, PS and blends of these with PLA and PET is also an active area of study. As a result, a blend of rPP and PET is presented as a promising filament feeds (Zander et al, 2019).

Academic publication from the field of design research on recycled polymer printing, describing process parameters, design guidelines through functional printed prototypes is, however, limited. Examples of such publications include the project of tiles by Bruce et al (2020), and the larger structure made of small rPET components by Nováková et al (2019). A gap in the literature is detected.

2.2 Large Scale 3D Printing with Recycled Polymers

Large scale polymer printing is an active field of study, with commercial FDM systems such as Tractus and BigRep, and robotic extruders such as Massive Dimension, Dyze Design, Cead, and Rev3rd are available on the market. Design research projects testing full-scale applications of these systems exist, including the functional bridge by Yuan et al (2018).
However, academic publications documenting large-scale printing with recycled polymers are limited to the floating farm by Banon and Raspall (2022) and the project marine environments by Dunn et al (2019), which was not tested at full scale.

3 Methodology

This research addresses the limited documentation of process parameters of large-scale additive manufacturing with recycled polymers. The research methodology includes the following steps.

- Procurement of three types of recycled plastic pellets from research partner company Comberplast.
- Initial printability tests using rPLA, rHDPE, and rABS.
- Selection of rPLA as promising candidate.
- Optimization of process parameters through fabrication experiments.
- Compilation of design and manufacturing strategies for large-scale printing with rPLA.

4 Results

The results of the different stages of the research methodology are presented in the following sections.

4.1 Procurement of Recycled Polymers

Aiming to bring large scale additive manufacturing to practical use, the research partnered with the company Comberplast, a waste management and recycling company in Santiago de Chile. The company processes plastic waste from a variety of sources. While several of the processed polymers, including rPET, already have a commercial industrial application polylactic acid (rPLA), high density polyethylene (rHDPE), and Acrylonitrile butadiene (rABS) do not have an application yet. For these three polymers, the research investigates 3D printing as an alternative their printability.

Figure 1. Pellets from recycled sources. From left to right: rABS, rHDPE, and rPET.

4.2 Description of the large-scale 3D printing laboratory

The experiments were conducted using a robotic setup (Fig. 2) that includes the following equipment:

- A robotic arm Kuka KR180, programmed using KUKAPRC in Grasshopper.
- A pellet extruder Massive Dimension MD100, with four heating zones individually controlled.
- A custom-made heated bed of 1100x500mm

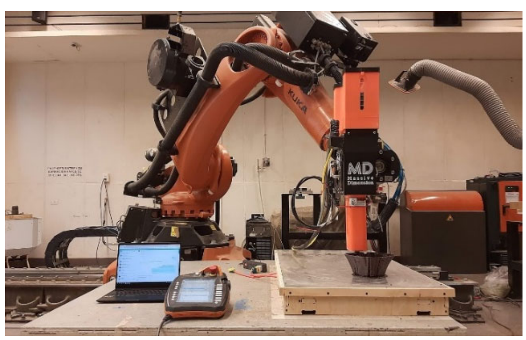

Figure 2. Setup of the large-scale 3D printing laboratory.

4.3 Initial printability experiments

In an initial stage, the three polymers, rPLA, rHDPE and rABS were tested printing a simple model cylindrical model. The results of these experimentos are summarized in Table 1 and presented in Fig. 3.

Table 1. Results of the initial tests

Polymer	Best Process Parameters	Key observations
rHDPE	Extruder Temperature: 210°C Extruder RPM: 40rpm Robot Speed: 100mm/sec Layer Height: 1.5 mm	No usable part were accomplished with this polymer. The material foams excessively and does not adhere correctly to the bed or previous layers.
rABS.	Extruder Temperature: 220°C Extruder RPM: 40rpm Robot Speed: 100mm/sec Layer Height: 1.5 mm	Printed parts present poor quality, with poor finishing and excessive warpage. The polymer foams, probably due to excessive moisture or presence of additives.
rPLA,	Extruder Temperature: 170°C Extruder RPM: 40rpm Robot Speed: 100mm/sec Layer Height: 1.5 mm	Good printability overall, with adequate resolution and structure. However, the polymer exhibits significantly larger shrinkage compared with virgin PLA, leading to warpage and peeling in larger parts.

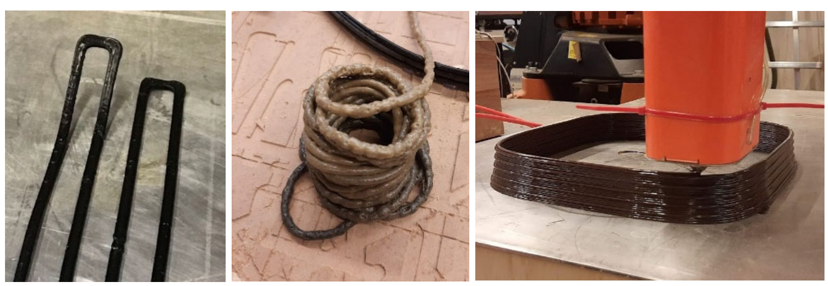

Figure 3. Printing results using rHDPE (left) rABS (center) and rPLA (right).

4.4 Process parameter optimization for rPLA

After the initial experiments, the research efforts focused on the most promising material choice: rPLA. The optimal process parameters for rPLA were established through a trial and error process using small cylindrical samples, converging at those indicated in Table 2. Figure 4 shows the setup of temperature settings in extruder zones and heated bed.

Table 1. Summary of process parameters for rPLA

Polymer	**Key observations**
Polymer	Recycled Polylactid Acid
Extruder Temperature Zone 1 (Feed)	30°C
Extruder Temperature Zone 2 (Screw)	120°C
Extruder Temperature Zone 3 (Screw)	140°C
Extruder Temperature Zone 4 (Nozzle)	160°C
Bed Temperature	80°C
Robot Speed	100mm/sec
Extruder RPM	40 rpm
Layer height	1.5 mm
Nozzle diameter	3 mm

Figure 4. Temperature settings in extruder controller and heated bed.

4.5 Design and fabrication experiments

After establishing optimal process parameters, the reliability and real life performance of the system was tested using furniture as case study. Included as a three-week assignment on a master-level design studio at Adolfo Ibáñez University, the students were invited to design furniture to be printed using the robotic system with rPLA material. A selection of four designs is included in Figure 5.

Figure 5. Selected designs for fabrication experiments using rPLA. Credits: María José Bascuñan, Pauline Brander, Camila Fuentes, Sofía Olivero, Nicolás Carter, Natalia Navarrete, Carolina Cautin, Nicolás Schnaidt, Felipe Plaza, Diego Trucco, Pedro Feijo, Florencia Rabie y Catalina Pichott.

Due to time constraints in the studio assignment, the rPLA printing of the designs were conducted at 1:2 scale, with a final size of approximately 500x500x500mm. Overall, the manufacturing was successful, achieving the four prototypes after an average of two iterations for each design. The printing time for each print was around 2 hours. Issues and takeaways detected during manufacturing include:

- Excessive shrinkage of the prints, leading to peeling from the base, even with an adequate adhesion of the first layer (Fig 6, A). Compared with previous tests conducted with virgin PLA, it is evident that the recycled polymer presents higher shrinkage.
- The creation of a 30mm brim improved the adhesion, but in large and long, straight segment prints the brim is still insufficient (Fig 6, B).
- A nozzle temperature of 160°C, which is on the lower end of the recommended in the literature, improves shrinkage and peeling.
- The high bed temperature of 80°C improves the adhesion of parts to the base and mitigates peeling.

- A rapid cooling of the print using the laboratory AC at 16°C also contributes to a better print.
- Cantilevers with angles over 45° lead to defects (Fig 6, C).

Figure 6. Manufaturing process. From left to right: A. peeling in the base. B. 30mm brim added to the build to improve adhesion. C. Defects in cantilever >45°.

Figure 7 shows the final prints at 1:2 scale, with brims removed. The overall appearance and the structure of the parts is satisfactory.

Figure 7. Final prints of using rPLA.

4.6 Design Recommendations

The results of the furniture design and fabrication experiments led to valuable insights, which enable the creation of design recommendations. These were tested in later 1:1 prints. The key challenge when printing with rPLA was the relatively higher shrinkage. The following design criteria and fabrication strategies help mitigate its consequences:

- Straight edges longer than 400mm produce peeling; therefore, designs with smaller footprint, or curved, corrugated and shorter segments are preferred. This strategy was tested in a 500x500x900mm print (Fig. 8A).
- Designs that require long and straight edges can be accomplished using brims and clamps to prevent peeling. This strategy was tested in a 1:1 (Fig. 8B).
- Lower nozzle temperature and higher bed temperatures, together with a rapid cooling of the deposited material led to best results.

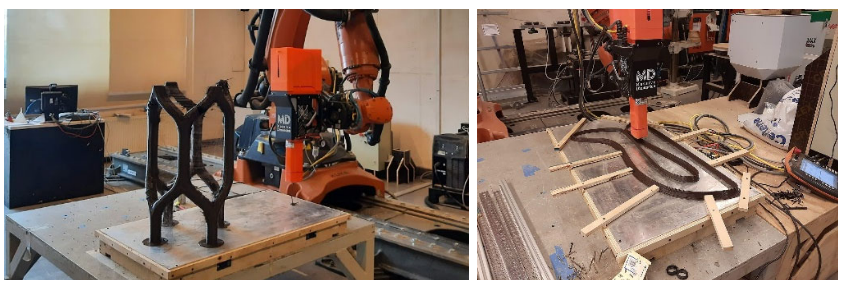

Figure 8. Strategies for large-scale printing using rPLA. (A) On the left, a design with a smaller footprint yields good results with no peeling or visible shrinkage. (B) On the right, a design with long and straighter edges is printed using clamps, which control the peeling.

5 Discussion

In the design industries, large-scale additive manufacturing presents an array of opportunities, offering unprecedented freedom in design, customization, and production efficiency. However, this potential is counterbalanced by the environmental challenges posed by its contribution to plastic waste. This paper proposes and tested the use of recycled polymers for large-scale additive manufacturing. By studying three underutilized recycled polymers —rPLA, rHDPE, and rABS— the research has identified rPLA as a standout candidate, demonstrating its feasibility for large-scale printing applications. rHDPE and rABS also demonstrated printability potential with greater manufacturing challenges, that will be addressed in future research.

The journey from initial printability tests to the establishment of optimal parameters for rPLA involved systematic experimentation. This endeavor has resulted in a set of process parameters that can serve as a foundation for industrial production using large-scale additive manufacturing with recycled polymers. The incorporation of design recommendations, born out of practical furniture fabrication experiments, further solidifies the viability of this approach, addressing the challenges of warping and adhesion.

In essence, this research further advances current efforts to consolidate a promising trajectory for the design industry, where environmentally responsible practices meet innovative manufacturing technologies. By harnessing the potential of recycled polymers in large scale additive manufacturing, the design industry can significantly reduce its environmental footprint while achieving more efficient and expressive designs.

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