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LEVALUATION OF SUSTAINABLE STRATEGIES FOR PLASTIC COMPONENT PRODUCTION IN MICROGRAVITY ENVIRONMENTS

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Abstract: The manufacturing of plastic components in microgravity presents both challenges and opportunities for long-duration space missions, as conventional processes depend on gravity-driven mechanisms and require adaptation for orbital use. This study investigates the feasibility of applying plastic injection molding in microgravity, emphasizing its potential to transform recyclable polymers into functional components using in-space resources. Different mold fabrication approaches that enable reusability were explored, including ceramic-based molds, epoxy molds with 3D-printed counter-molds, and sintering processes that enhance material strength and mold durability. Injection molding was selected for its capability to produce complex geometries with minimal post-processing and potential scalability in orbital environments. The methodology integrates a comprehensive literature review on additive manufacturing, sintering, and injection molding with experimental validation through the fabrication of ASTM D638 Type IV tensile specimens. Test samples were manufactured via fused deposition modeling (FDM) using PLA filament and by injection molding with PLA pellets, allowing comparison of mechanical performance across different mold fabrication methods. Results indicate that injection-molded PLA exhibits higher stiffness and tensile strength, whereas 3D-printed specimens demonstrate greater ductility due to anisotropy and interlayer bonding effects. Additionally, sustainable mold-making alternatives such as aluminum casting with 3D-printed patterns, direct metal additive manufacturing, and hybrid strategies are discussed. The findings highlight the importance of reusability, material circularity, and reduced payload mass to enhance mission autonomy, contributing to sustainable manufacturing and autonomous polymer production in microgravity, reducing Earth dependency and improving mission resilience.

Keywords: microgravity, plastic injection molding, sustainable manufacturing, sintering, additive manufacturing.

1. Introduction

Locally manufacturing parts and components for long-duration space missions is essential to reduce logistical costs, ensure operational autonomy, and increase resilience in harsh environments. In microgravity, traditional manufacturing processes face constraints such as the absence of gravitational forces for mold feeding and sedimentation, factors involving thermal control and pressure, as discussed in Osswald and Hernández-Ortiz (2006), which are important elements in explaining how gravity influences mold filling and why process adaptation is necessary in space. Similar challenges are also recognized in other critical fields, such as biomedical engineering, where advanced techniques are required to ensure reliability under harsh operating conditions (Bartolo et al., 2012).

Among the processes of greatest interest are additive manufacturing (3D printing) and plastic injection molding. 3D printing, especially via fused deposition modeling (FDM), is already used in orbit by the International Space Station for maintenance parts, due to its flexibility, low cost, and ability to reuse recycled polymers. However, it presents limitations regarding the anisotropy and mechanical strength of the printed bodies, as discussed in Torrado and Roberson (2016).

The Fused Deposition Modeling (FDM) 3D printing process involves heating and extruding thermoplastic filament through a nozzle, which deposits the material layer by layer according to a digital model. This technique allows for the fabrication of complex geometries with low material waste and design flexibility. The system typically uses a Cartesian structure with movement on the X, Y, and Z axes to position the dual extruder relative to the heated heating bed. It consists of components such as the spool holder, extruder, fuser (hotend), metal frame, power supply, heated bed, and electronic control module. Printers such as the Creality Ender 3, for example, combine these features in a compact design and are widely used in space missions. However, parts produced by FDM often exhibit anisotropy and lower mechanical strength due to the breakdown of interlayer adhesion (Gebisa and Lemu, 2018; Torrado and Roberson, 2016). The model of a typical FDM 3D printer is shown in figure 1, taken from BITFAB (2019).

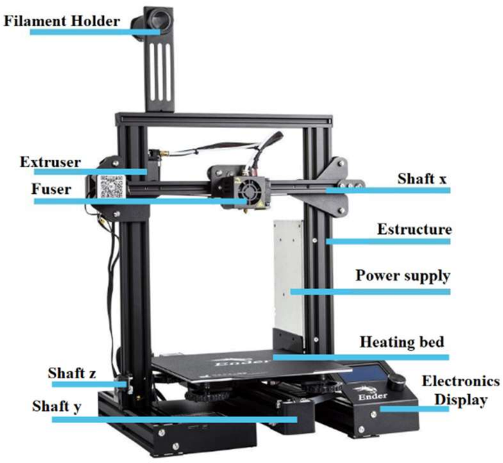

Figure 1. 3d printer model ender 3 (BITFAB, 2019).

Injection molding involves melting polymer pellets in a heated chamber and injecting them under high pressure into a metal mold, where the material solidifies into the desired shape, resulting in parts with excellent finish and dimensional accuracy. The experiments used a Macinjet 4500P benchtop injection molding machine, equipped with a digital panel for temperature control (up to 300°C), a heating chamber, a compressor-driven pneumatic piston (6 to 8 bar), a pellet feed hopper, an adjustable mold base, and a safety system. This technique is widely adopted in industry due to its high repeatability and superior mechanical performance of the final products (Rosato and Rosato, 2000; Strong, 2006). Figure 2, taken from MACINJET (2025), below, shows an illustration of the model used for injection molding.

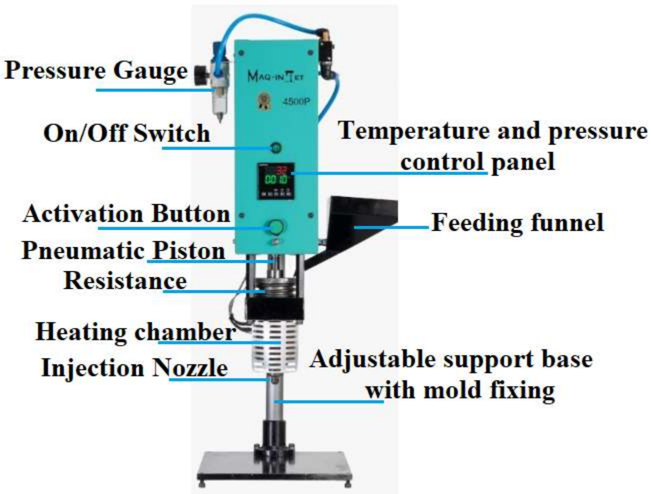

Figure 2. Injection molding machine model Mac-Injet 4500P (MACINJET, 2025).

In turn, plastic injection molding is renowned in the industry for its ability to produce parts with high surface quality and superior mechanical properties, as discussed in Rosato and Rosato (2000) and Strong (2006), with a fast and repetitive production cycle. Its application in microgravity requires solutions for producing reusable molds locally, reducing the need for transportation from Earth.

Viable alternatives include machined aluminum molds, epoxy resin molds using 3D-printed counter molds, and metal molds cast from recycled aluminum using green sand and printed plastic patterns, also presented and demonstrated in Telles (2019) and Mr. Forge (2022).

This work comparatively evaluates these methods for manufacturing ASTM D638 Type IV standard tensile test specimens, considering microgravity mission scenarios with a focus on cost, quality, sustainability, and adaptability to harsh environments. Furthermore, sintering technologies such as Selective Laser Sintering (SLS) have been widely used in the aerospace and medical industries due to their ability to produce high-precision metal and polymer parts from powders. Processes such as Cold Metal Fusion (CMF), which combine the extrusion of metal powders with polymer binders followed by sintering, have great potential for space applications because they offer safety, scalability, and compatibility with compact environments such as orbital ones, as discussed in Singh et al. (2020) and Tadmor and Gogos (2013).

2. Materials and Methods

The research was divided into two main stages: (1) manufacturing of molds for bench injection molding, Figure 3, and (2) fabrication of test specimens using two distinct processes.

For 3D printing (FDM), a Creality Ender 3 printer was used with 1.75 mm PLA filament, a 0.2 mm layer, an extrusion temperature of 200°C, a bed temperature of 60°C, a printing speed of 60 mm/s, and a ±45° raster orientation to reduce anisotropy, as discussed in Gebisa and Lemu (2018). The test specimens followed the ASTM D638 Type IV standard for tensile testing.

For plastic injection molding, a Macinjet 4500P benchtop injection molding machine was used, operating with PLA pellets and a piston system driven by an 8 bar compressor. The molds used were manufactured in three ways: industrial machining in aluminum, as shown in Figure 3 (a); molds in 8000 epoxy resin with 2300 hardener, using 3D printed PLA counter molds, as shown in Figure 3 (b); and aluminum casting using plastic patterns and green sand molding, as shown in Figure 3 (c). Mold preparation by casting was carried out according to Mr. Forge (2022).

For the tests, 10 3D printed PLA specimens and 10 injected ones were manufactured.

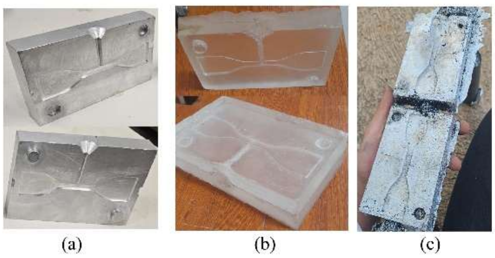

Figure 3. Manufactured Molds.

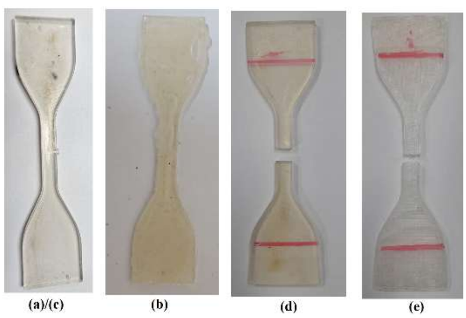

Figure 4. Sample of some test specimens.

The test specimens manufactured with aluminum molds, Figure 4 (a)/(c), presented adequate surface quality, with uniform filling and no visible bubbles, demonstrating their suitability for standardized mechanical tests. Despite this, there is the possibility of microbubbles in the structure, even if not visible, but this factor did not affect the expected results. In contrast, the specimens manufactured in resin molds, Figure 4 (b), presented air bubbles and irregular contours, making them unsuitable for reliable testing. This process will be refined in future work.

After the tensile test, the injected PLA samples, Figure 4 (d), showed clean and predictable rupture in the usable cross-section, demonstrating good fusion and homogeneity of the material. The 3D printed PLA samples, Figure 4 (e), presented fractures following intercalary planes, characterizing the typical anisotropy of the process and limiting its resistance compared to injection molding.

3. Results

This section presents the experimental results obtained from the tensile tests performed on ASTM D638 Type IV specimens manufactured through plastic injection molding and 3D printing. The analysis focuses on the mechanical properties and dimensional quality of the specimens fabricated using different mold materials and manufacturing techniques.

Initially, the practical test data are described, highlighting the differences between parts produced by FDM 3D printing using PLA filament and those injected with PLA using machined aluminum molds, cast aluminum molds, and epoxy resin molds.

The table 1 below shows the mean and standard deviation of the mechanical properties of the manufactured test specimens.

Table 1. Mechanical properties of PLA test specimens.

Properties	3D Printed PLA	Injected PLA
Modulus of Elasticity (MPa)	1571 ± 68	3047 ± 96
Tensile Strength (MPa)	70,4 ± 6.5	82,7 ± 14.5
Stretching (%)	5,35 ± 0.40	3,36 ± 0.21

Figure 5 presents a box plot graph comparing the modulus of elasticity (MPa) of the specimens obtained by 3D printing (Test A) and injection molding (Test B), highlighting the statistical distribution of the data and the difference between the average values of each process.

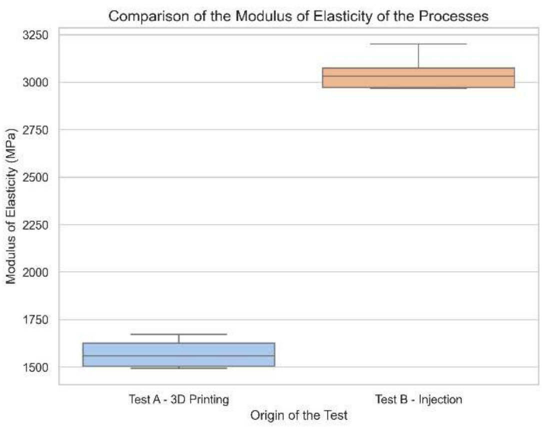

Figure 5. Comparison of the Elastic Modulus of PLA Specimens.

According to Table 1 and Figure 5, injection molding produces specimens with significantly higher stiffness and tensile strength compared to 3D-printed specimens, primarily due to better polymer chain alignment, greater

crystallinity, and the absence of weak interlayer bonds typical of FDM printing.
The box plot highlights clear and striking differences between the manufacturing processes: injection-molded samples exhibited higher elastic modulus and lower dispersion, indicating greater stiffness and uniform quality, whereas 3D-printed samples presented lower modulus and higher ductility, reflecting the intrinsic limitations of the layer-by-layer deposition process.

4. Discussion

The results obtained experimentally demonstrate the direct influence of the manufacturing method on the mechanical behavior of PLA. Injection molding results in denser and more homogeneous structures, while 3D printing introduces anisotropy due to its layered deposition nature. These findings are consistent with previous studies on FDM-produced PLA specimens, which reported similar anisotropy and reduced strength compared to molded counterparts (Ali et al., 2018). In addition to the mechanical performance analysis, it is essential to discuss the feasibility of different technologies for mold production in microgravity environments, as they determine the sustainability and autonomy of the local injection process.

According to Froes, Boyer, and Dutta (2019), Additive Manufacturing (AM) is already widely adopted in the aerospace industry to produce complex, lightweight parts with high strength-to-weight ratios. Technologies such as Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) have been successfully applied in structural and functional components for aircraft and satellites. Wang, Mosher, and Duett (2024) further highlight the potential of these technologies for on-demand manufacturing, reducing waste and lowering dependence on traditional inventories or tooling, making them particularly attractive in logistically constrained environments such as long-duration space missions. Table 2 compares the main alternatives identified in this study—aluminum block machining, metal 3D printing (SLS, CMF), aluminum casting with 3D-printed patterns, and epoxy resin molds with 3D counter-molds—with data available in Singh et al. (2020), Tadmor and Gogos (2013), Telles (2019), Mr. Forge (2022), Groover (2010), Flaherty et al. (2020), Campbell, Hopkinson, and Dickens (2011), Huang et al. (2013), Kumar and Dixit (2017), and National Research Council (1978).

Table 2. Comparison of technologies for mold fabrication in space environments.

Criterion	Aluminum Machining	Metal 3D Printing (SLS / CMF)	Aluminum Casting with 3D-Printed Patterns	Epoxy Resin Molds with 3D Counter-Mold
Dimensional accuracy	Very high	High	Medium (dependent on pattern)	Medium to low
Logistic cost	High (transporting blocks or CNC machine)	Medium (transporting powder feedstock)	Low (reused metal scrap)	Low (lightweight resin and patterns)
Energy consumption	High (CNC machining)	High (laser/sintering)	Medium (controlled melting furnace)	Low (chemical curing)
Operational complexity	High (CNC, fixturing)	High (precise control, laser, powders)	Medium (fusion and molding control)	Low (mixing and pouring)
Mold reusability	Very high (many cycles)	High (many cycles, complex geometries)	High (reusable metal molds)	Low to medium (limited service life)
Adaptability in microgravity	Feasible with large infrastructure	Promising (closed and controlled process)	Feasible (adaptable furnace, simulated gravity via centrifugal force)	Feasible (easy preparation, but limited performance)

This analysis shows there is no single solution suitable for all scenarios. Machining aluminum blocks offers very high mold precision and durability, but requires robust CNC equipment and generates high logistical costs, making it impractical for space environments (Froes, Boyer, and Dutta, 2019). By contrast, metal 3D printing technologies such as DED and SLM enable local production of complex geometries using recycled metallic powders, but demand precise thermal control, high energy consumption, and inert or vacuum atmospheres.

Aluminum casting with 3D-printed patterns represents a viable, lower-logistics-cost alternative. It can reuse metal scrap generated onboard and leverage compact furnaces adapted to microgravity, consistent with orbital casting concepts proposed by space agencies (Wang, Mosher, and Duett, 2024). Epoxy resin molds with 3D-printed counter-molds, meanwhile, allow for rapid, lightweight production useful in prototyping, but come with mechanical and thermal limitations (Najmon, Raeisi, and Tovar, 2019). The experimental results in this work with machined, resin, and cast aluminum molds demonstrate these differences: machined molds delivered excellent surface finish and dimensional stability, ensuring repeatable injection cycles. Cast molds showed technical feasibility with material reuse but require process adjustments to minimize porosity. Resin molds performed worse, with bubbles forming during curing, making them unsuitable for standardized testing and highlighting their practical limits in structurally critical applications.

On long-duration space missions, a hybrid and sustainable approach can integrate these technologies. For example, 3D printing can be used to produce patterns and counter-molds, local casting for the production of reusable metal molds, and direct metal printing (such as DED or SLM) for on-demand or geometry-critical components. These hybrid approaches align with recent advances in the integration of fused deposition modeling (FDM) and injection molding (IM) for PLA parts, demonstrating the potential for mass customization combined with improved mechanical reliability (Xu et al., 2023). This strategy reduces transported mass, increases production autonomy, and improves operational flexibility, as suggested by Wang, Mosher, and Duett (2024) and Froes, Boyer, and Dutta (2019).

5. Conclusions

A comparative analysis of ASTM D638 Type IV PLA specimens manufactured by 3D printing and injection molding demonstrated clear differences in mechanical properties. The injection molded samples exhibited a significantly higher modulus of elasticity and tensile strength, with lower elongation at break, reflecting the more rigid and brittle behavior typical of injection molded parts. The low variation in the injection molded results confirms good process control, while the printed specimens showed satisfactory interlayer cohesion but limited properties compared to injection molding. These findings are consistent with the literature for PLA, reinforcing the performance gap between the two manufacturing processes. Based on both experimental data and insights from the literature, it can be inferred that combining 3D printing with adaptable injection molding enables sustainable and flexible part production in microgravity. While 3D printing is more suitable for prototyping, injection molding allows efficient mass production, provided that mold fabrication can be achieved locally. In this context, alternatives such as green sand casting with 3D-printed patterns, direct metal additive manufacturing, and resin molds demonstrate distinct advantages and limitations, and their feasibility depends on the mission profile. Therefore, the conclusions drawn in this work highlight not only the experimental outcomes but also broader inferences supported by literature, suggesting that incorporating hybrid mold-making strategies increases production autonomy in orbit, reduces logistical costs, and supports a more sustainable and resilient model of space exploration.

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