Naveed, Nida and Anwar, Muhammad Naveed (2024) Sustainable Manufacturing through Digital Multi-Material 3D Printing. In: 2024 29th International Conference on Automation and Computing (ICAC). IEEE, pp. 1-5. ISBN 979-8-3503-6088-2

Downloaded from: http://sure.sunderland.ac.uk/id/eprint/18530/

Usage guidelines

Please refer to the usage guidelines at http://sure.sunderland.ac.uk/policies.html or alternatively contact sure@sunderland.ac.uk.

Sustainable Manufacturing through Digital Multi-Material 3D Printing

[1]Nida Naveed, [2]Muhammad Naveed Anwar

[1]Faculty of Technology, School of Engineering, University of Sunderland, UK
[2]Department of Computer and Information Sciences
Faculty of Engineering and Environment, Northumbria University, UK
nida.naveed@sunderland.ac.uk

***Abstract*—The utilisation of three-dimensional (3D) printing has become a well-established method for fabricating structural components across various materials such as polymers, metals and ceramics. Within this domain, multi-material 3D printing emerges as a pivotal advancement, offering prospects for rapid manufacturing, customised design, and structural innovation. Particularly, the incorporation of recycled materials into multi-material printing holds promise for promoting sustainability and recyclability in manufacturing processes. By leveraging multi-material printing techniques and incorporating recycled materials, this study aims to advance the sustainability agenda within manufacturing practices while concurrently exploring avenues to enhance material performance for practical engineering applications. This study focuses on the multi-material printing of pure polylactic acid (PLA) alongside recycled polylactic acid (rPLA), employing fused deposition modelling (FDM) as a cost-effective 3D printing technique. The research aims to identify the optimal composition for achieving desired material properties by exploring different percentages and layer placements of recycled material in combination with pure PLA. Detailed analysis of the mechanical properties of these 3D printed components was conducted, with the experimental results further validated through analysis of variance. The results of this study emphasis the mechanical advantages associated with the utilisation of multi-material 3D printing techniques. Moreover, the incorporation of both PLA and rPLA materials highlights the potential sustainability benefits inherent in these approaches.**

***Keywords*—** Three-dimensional (3D) printing, multi-material 3D printing, Polylactic acid (PLA), Recycled PLA (rPLA), mechanical properties.

List of abbreviations
3D: Three-dimensional
PLA: Polylactic acid
rPLA: Recycled polylactic acid
FDM: Fused Deposition Modeling
AM: Additive Manufacturing
SLA: Stereolithography
MJ: Material Jetting
BJ: Binder Jetting
DIW: Direct Ink Writing
DLP: Digital Light Processing
MMAM: Multi-material Additive Manufacturing
CAD: Computer-Aided Design
ASTM: American Society for Testing and Materials

I. INTRODUCTION

Additive manufacturing (AM), also known as 3D printing, is a manufacturing process that creates three-dimensional objects by sequentially combining constituent materials, typically layer by layer [1]. The popularity of 3D printing has increased because of its simplified manufacturing process, capability to create intricate geometrical designs, accelerated production times, and the ability to produce items on-demand [2]. Multi-material additive manufacturing (MMAM), as implied by its name, involves employing multiple materials simultaneously to fabricate an object. This technique enables the creation of 3D-printed objects with diverse colours and material characteristics. Various techniques employed in multi-material additive manufacturing encompass fused deposition modelling (FDM), stereolithography (SLA), material jetting (MJ), binder jetting (BJ), direct ink writing (DIW), material jetting (MJ), digital light processing (DLP), and hybrid additive manufacturing [3], [4].

In 2020, advancements in MMAM led to significant enhancements in system capabilities and design refinements. These improvements encompass a broader range of techniques. For instance, DIW now integrates multiple nozzles for increased versatility, while multi-material FDM utilizes a bi-extruder head for enhanced functionality. Additionally, MJ-enabled MMAM boasts improved printing resolution facilitated by a machine vision setup, while a vat-less multi-material SLA employs an aerosol jetting system for greater efficiency. DLP-driven MMAM has adopted dynamic fluidic control, enabling a cleaning process-free operation. Furthermore, a hybrid MMAM system has emerged, combining DIW, FDM, MJ, along with two supplementary approaches: robotic arms and a photonic curing system [5].

Multi-material additive manufacturing (MMAM) faces challenges similar to those encountered in 3D printing. These challenges include limited material selection, high energy consumption, and elevated costs [6]. Additionally, MMAM grapples with issues related to material bonding and residual stress at the interface. The diverse properties of various materials, including miscibility and wetting constraints, further complicate the process control [7]. When materials are mismatched, defects such as cracks, pores, residual stresses, and compromised dimensional stability may arise during real-world applications [8]. Improper mixing of multiple materials can occur due to their distinct properties, and there is also a risk of material contamination during material changes. In addition to this, limited information exists on multi-material extrusion-based 3D printing, including equipment constraints, component design, and printing materials [9]. MMAM also encounters challenges with computer-aided design (CAD) limitations, material modelling software, and designers' unfamiliarity with the technology. Limited materials hinder its integration into modern manufacturing processes [7]. MMAM indeed shares similar challenges with traditional 3D printing in post-processing and quality control. Ensuring consistent quality can be complex due to material mixing and intricate geometries, making thorough examination challenging [10].

PLA's benefits include eco-friendliness, ease of printing, safety for food and medical use, colour variety, and solvent weldability [11]. Recycling PLA diminishes its molecular weight and mechanical characteristics, limiting continuous recycling [12]. This research aims to investigate Polylactic Acid (PLA) samples printed with systematically varied placement and recycled PLA percentage. Comparisons was made with individual pure PLA and recycled PLA samples, focusing on mechanical properties. The results provide insights for optimising material blends to improve performance and sustainability in additive manufacturing.

II. MATERIAL AND METHOD

This research aims to investigate the mechanical properties of multilayer 3D printed parts. For this study the Polylactic Acid (PLA) samples printed with recycled Polylactic Acid (rPLA) with systematically varied placement and percentage of both the materials. The 3D printer used for this experiment is the Ultimaker S5 that has a potential for multi-material printing. Figure 1 shows the schematic diagram how multi-material 3D printer words. Ultimaker S5 printer typically come with advanced slicing software (Ultimaker Cura) that supports multimaterial printing. The software allows users to assign different materials to different parts of the model, adjust printing parameters, and manage the printing process effectively. For this study, the two different materials were printed by controlling the layering sequence and thickness of each material using Ultimaker Cura software.

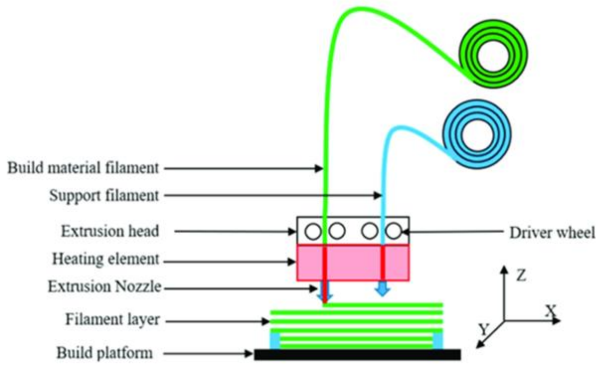


Figure 1: Schematic diagram to explain how multi-material 3D printer works with Fused Deposition Modelling (FDM) [13]

The chosen technique for this study is Fused Deposition Modelling (FDM), with specific process parameters are an infill density set at 100%, raster angles configured to [45 -45], infill speed maintained at 35 mm/s, bed temperature set to 60 ºC, and an extrusion multiplier of 1. These parameters were selected based on the positive outcomes observed in previous studies [11], [13]. As mentioned above, the samples were prepared using PLA and rPLA with systematic variations in their placements and material percentages and their details are provided in Figure 2. The samples were created according to American Society for Testing and Materials (ASTM) D638 standards using SolidWorks, featuring dimensions of 136.6 mm length, 19 mm width, and 6 mm thickness, with a narrow section measuring 86.6 mm in length. Three identical samples were fabricated for each configuration to assess the repeatability and reliability of the outcomes. All results were compared with those of pure PLA and rPLA samples prepared using the same process parameters as a baseline reference. Figure 3 and Figure 4 show both sets of the samples.

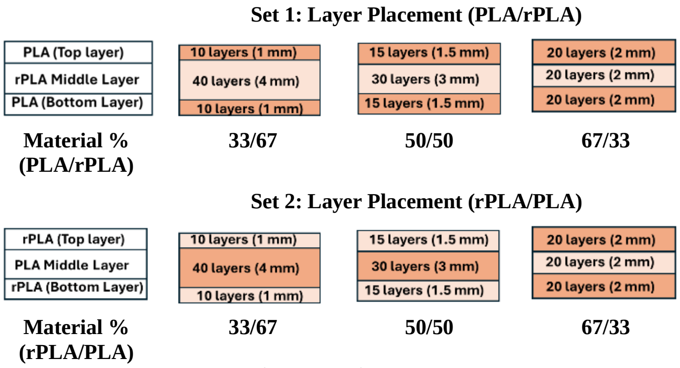


Figure 2: shows the details of two sets of sample preparation with systematic variations.

Figure 3: Multi-layer 3D printed Set 1 samples

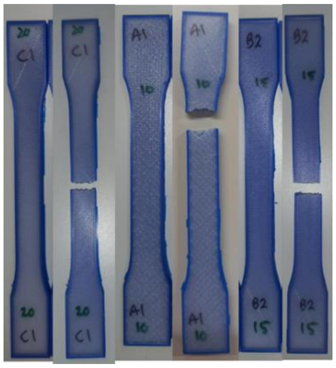
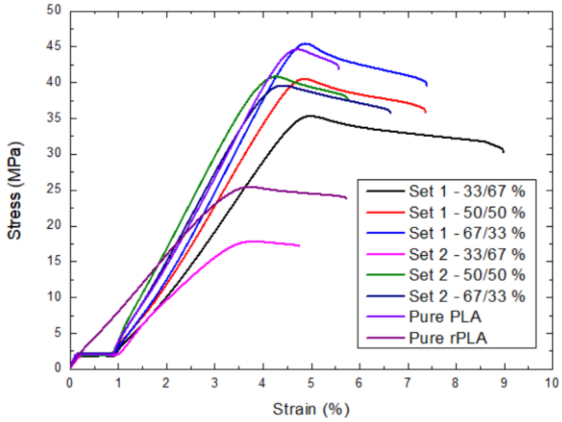


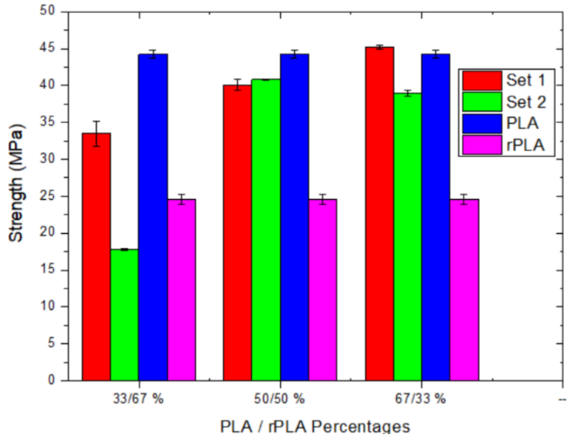
Figure 4: Multi-layer 3D printed Set 2 samples

III. RESULTS AND DISCUSSION

Figure 5 (a) depicts stress-strain line graphs for all samples. The findings reveal that samples from Set 1, featuring PLA material on the top and bottom layers with the middle layer filled with rPLA, exhibit superior mechanical properties compared to Set 2 samples, where the rPLA material is placed on the top and bottom layers with the middle layer covered by PLA material. Furthermore, samples prepared with a material percentage of 67% PLA and 33% rPLA demonstrate the highest performance and exhibit superior strength compared to samples with other material percentages, as illustrated in Figure 5 (b). Hence, the positioning of PLA in the top and bottom layers of Set 1 samples contribute to better structural stability and resistance to deformation under stress, leading to improved mechanical properties. The observed superior performance of samples with a material percentage of 67/33% PLA/rPLA suggests that this particular composition offers an optimal balance of mechanical strength. Further investigation was conducted through analysis of variance on tensile properties.



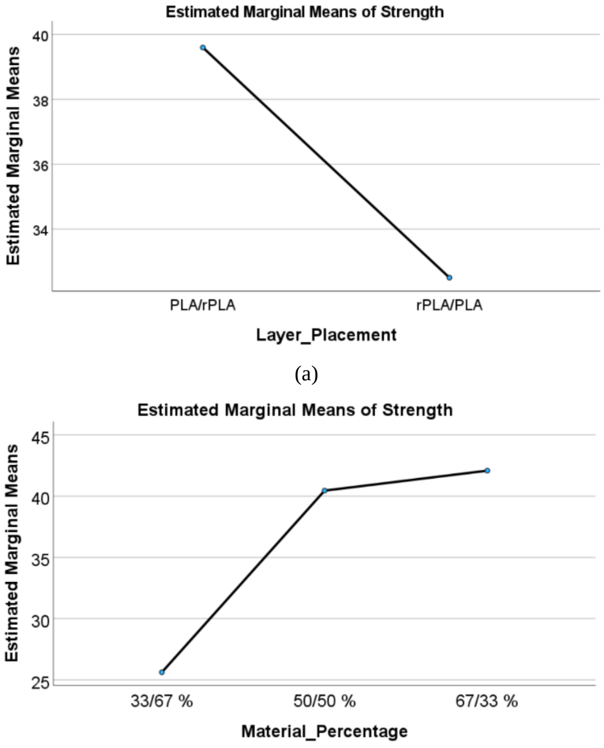
(a) Stress-strain curves for all the samples



(b) Tensile strength

Figure 5: shows material properties of multi-material 3D printed samples.

The analysis of variance was utilised to observe the influence of both the independent parameters layer placements and material percentages on tensile strength using IBM SPSS Statistics 29.0. This analysis reveals both the primary and the combined influences of these parameters on tensile strength. The primary effect refers to the direct influence of individual parameters, whereas the interaction effect represents the combined influence of two independent parameters on tensile strength.

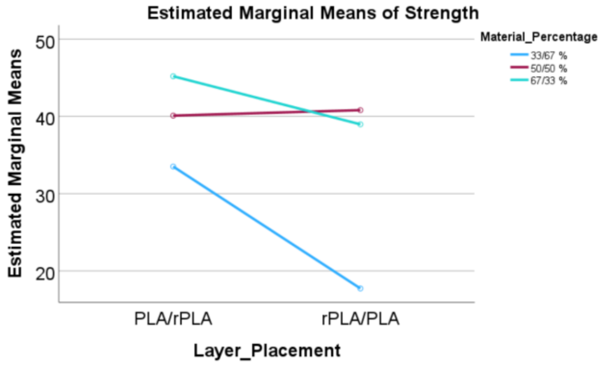


(a)

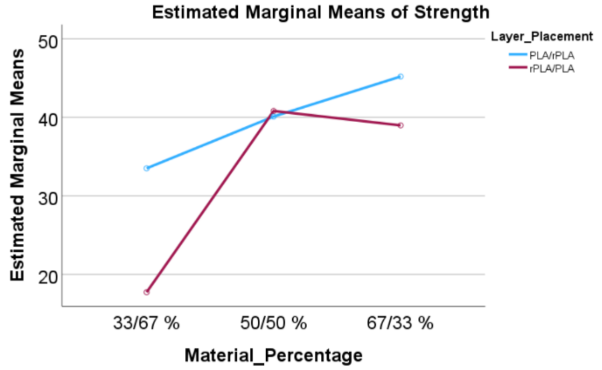
(b)

Figure 6: Main effect on tensile strength (a) Layer placements (b) Material percentages.

The main effects of layer placements and material percentages, as well as their interaction effects on tensile strength, were analysed, and the results are depicted in Figure 6 and Figure 7. The average tensile strength values across different levels of layer placements and material percentages were utilised to generate the main effect graphs. It is evident from Figure 6 (a) that the highest tensile strength corresponds to the Set1 layer placement, featuring PLA material on the top and bottom layers with the middle layer filled with rPLA. The analysis of the mean further indicates that a material ratio of 67% PLA and 33% rPLA has a positive effect on tensile strength (see Figure 6 (b)). Figure 7. illustrates the interaction effects of the parameters, averaging out the means across all dual-factor combinations. If two lines intersect on the plot, this suggests potential interplay between the two associated factors [14]. The interaction between these parameters can be clearly seen in Figure 7 (a) and Figure 7 (b). These results indicate that layer placement and material percentage play a significant role in influencing tensile strength. These observations align with the experimental findings discussed previously. The layered structure composed of different materials can enhance the tensile strength of the pure material sample, indicating that reinforcing the pure material with additional materials is effective for specific applications [15], [16]. Compared to single-material 3D printing, multi-material 3D printing provides greater flexibility for creating functional prototypes with significantly enhanced and diverse properties [17].



(a) Layer Placement*Material Percentage



(b) Material Percentage* Layer Placement

Figure 7: Interaction effects on tensile strength

The study demonstrates that the optimal layer placement, with PLA material on the top and bottom layers and rPLA in the middle, yields the highest tensile strength. Specifically, a material ratio of 67% PLA to 33% rPLA enhances tensile strength, as evidenced by the analysis of the mean values. This approach offers several advantages: it increases material efficiency by reducing dependence on virgin PLA, lowers material costs through the use of rPLA, and enhances mechanical properties by improving tensile strength. Additionally, the strategic placement of materials provides design flexibility, allowing for customised properties in different sections of the prototype.

From a sustainability perspective, the incorporation of rPLA promotes the reuse of plastic waste, contributing to a circular economy and reducing the environmental footprint by lowering virgin material consumption, carbon emissions, and energy usage [18]. The study encourages sustainable innovation, fostering research and development in environmentally friendly manufacturing processes. Moreover, the demonstrated effectiveness of material reinforcement with rPLA can inspire broader adoption of sustainable practices across various industries, potentially leading to significant environmental benefits on a larger scale. In conclusion, this study not only advances the technical understanding of multi-material 3D printing but also provides a viable pathway towards more sustainable and cost-effective manufacturing practices. The ongoing nature of this study will involve further experiments exploring additional process parameters, as well as variations in material placement and percentages, in pursuit of identifying the optimal parameters.

IV. CONCLUSION

The results of this study underscore the mechanical benefits of employing multi-material 3D printing techniques. Furthermore, the combination of PLA and rPLA materials demonstrates the potential sustainability advantages inherent in these methods. Through careful optimisation of layer arrangement and material composition, enhanced mechanical performance can be achieved, while also reducing dependence on conventional, non-renewable resources.

V. ACKNOWLEDGEMENT

The authors would like to thank Mr. David Winter for his valuable assistance in fabricating the 3D printed samples. Additionally, thanks are extended to David Harrison, Shern Yen Jong, and Samodya Bimsara Karunathilake for their contributions to the tensile testing.

REFERENCES

[1] S. S. Babu, L. Love, R. Dehoff, W. Peter, T. R. Watkins, and S. Pannala, ‘Additive manufacturing of materials: Opportunities and challenges’, MRS Bulletin, vol. 40, no. 12, pp. 1154–1161, Dec. 2015, doi: 10.1557/mrs.2015.234.

[2] M. H. Warsi, M. Yusuf, M. Al Robaian, M. Khan, A. Muheem, and S. Khan, ‘3D Printing Methods for Pharmaceutical Manufacturing: Opportunity and Challenges’, Current Pharmaceutical Design, vol. 24, no. 42, pp. 4949–4956, Nov. 2018, doi: 10.2174/1381612825666181206121701.

[3] D. Han and H. Lee, ‘Recent advances in multi-material additive manufacturing: methods and applications’, Current Opinion in Chemical Engineering, vol. 28, pp. 158–166, Jun. 2020, doi: 10.1016/j.coche.2020.03.004.

[4] J. Xu, K. Wang, H. Sheng, M. Gao, S. Zhang, and J. Tan, ‘Energy efficiency optimization for ecological 3D printing based on adaptive multi-layer customization’, Journal of Cleaner Production, vol. 245, p. 118826, Feb. 2020, doi: 10.1016/j.jclepro.2019.118826.

[5] S. Hasanov et al., ‘Review on Additive Manufacturing of Multi-Material Parts: Progress and Challenges’, Journal of Manufacturing and Materials Processing, vol. 6, no. 1, Art. no. 1, Feb. 2022, doi: 10.3390/jmmp6010004.

[6] A. Verma, A. Kapil, D. Klobčar, and A. Sharma, ‘A review on multiplicity in multi-material additive manufacturing: process, capability, scale, and structure’, Materials, vol. 16, no. 15, p. 5246, 2023.

[7] V. Vaghasia, H. Parmar, R. Chaudhari, J. K. Vora, K. Abhishek, and S. Kumari, ‘Recent advancements in the fabrication of multi-material structures by additive manufacturing’, AIP Conference Proceedings, vol. 2960, no. 1, p. 030017, Jan. 2024, doi: 10.1063/5.0183002.

[8] X. Zheng, C. Williams, C. M. Spadaccini, and K. Shea, ‘Perspectives on multi-material additive manufacturing’, Journal of Materials Research, vol. 36, no. 18, pp. 3549–3557, Sep. 2021, doi: 10.1557/s43578-021-00388-y.

[9] A. Nazir et al., ‘Multi-material additive manufacturing: A systematic review of design, properties, applications, challenges, and 3D printing of materials and cellular metamaterials’, Materials & Design, vol. 226, p. 111661, Feb. 2023, doi: 10.1016/j.matdes.2023.111661.

[10] K. Kanishka and B. Acherjee, ‘Revolutionizing manufacturing: A comprehensive overview of additive manufacturing processes, materials, developments, and challenges’, Journal of Manufacturing Processes, vol. 107, pp. 574–619, Dec. 2023, doi: 10.1016/j.jmapro.2023.10.024.

[11] N. Naveed, ‘Investigate the effects of process parameters on material properties and microstructural changes of 3D-printed specimens using fused deposition modelling (FDM)’, Materials Technology, vol. 0, no. 0, pp. 1–14, May 2020, doi: 10.1080/10667857.2020.1758475.

[12] F. R. Beltrán et al., ‘Evaluation of the Technical Viability of Distributed Mechanical Recycling of PLA 3D Printing Wastes’, Polymers, vol. 13, no. 8, Art. no. 8, Jan. 2021, doi: 10.3390/polym13081247.

[13] M. J. Park, J. Bae, and Y. K. Ju, ‘Structural Behavior of a Composite Curtain Wall Fabricated by the Fused Deposition Modeling 3D Printing Method’, Polymers, vol. 14, no. 7, Art. no. 7, Jan. 2022, doi: 10.3390/polym14071431.

[14] S. R. Rajpurohit and H. K. Dave, ‘Analysis of tensile strength of a fused filament fabricated PLA part using an open-source 3D printer’, Int J Adv Manuf Technol, vol. 101, no. 5, pp. 1525–1536, Apr. 2019, doi: 10.1007/s00170-018-3047-x.

[15] S. Kumar, R. Singh, and M. Singh, ‘Multi-material 3D printed PLA/PA6-TiO2 composite matrix: rheological, thermal, tensile, morphological and 4D capabilities’, Advances in Materials and Processing Technologies, vol. 8, no. 2, pp. 2329–2348, Apr. 2022, doi: 10.1080/2374068X.2021.1912527.

[16] D. M. Baca Lopez and R. Ahmad, ‘Tensile Mechanical Behaviour of Multi-Polymer Sandwich Structures via Fused Deposition Modelling’, Polymers, vol. 12, no. 3, Art. no. 3, Mar. 2020, doi: 10.3390/polym12030651.

[17] R. Singh, R. Kumar, I. Farina, F. Colangelo, L. Feo, and F. Fraternali, ‘Multi-Material Additive Manufacturing of Sustainable Innovative Materials and Structures’, Polymers, vol. 11, no. 1, Art. no. 1, Jan. 2019, doi: 10.3390/polym11010062.

[18] F. R. Beltrán et al., ‘Evaluation of the Technical Viability of Distributed Mechanical Recycling of PLA 3D Printing Wastes’, Polymers, vol. 13, no. 8, Art. no. 8, Jan. 2021, doi: 10.3390/polym13081247.