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Robust Interlayer Bonding in PLA-TPU Composites via Optimized Overlap 3D Printing

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Abstract—Material extrusion 3D printing has made significant strides, yet challenges remain in seamlessly integrating multiple polymer materials in a single print. This abstract introduces a novel technique that precisely overlaps two polymer materials during the printing process, expanding the capabilities of additive manufacturing. Leveraging advanced control systems to synchronize the deposition of two distinct polymers, this method ensures a seamless transition and strong adhesion between layers. Optimizing material flow rates, temperature profiles, and layer bonding mechanisms is crucial for achieving high-quality prints with enhanced structural integrity and material properties. This approach unlocks possibilities across various industries. For instance, in the automotive sector, it enables the fabrication of lightweight components with tailored mechanical properties, such as reinforced sections overlapped with flexible elastomers for vibration damping. In the medical field, the technique facilitates the creation of complex implants with biocompatible coatings for improved integration and reduced rejection rates. Beyond traditional applications, this technique paves the way for developing functional prototypes, customized products, and advanced composite structures with superior performance characteristics. Through collaborative efforts and continued innovation, this method promises to redefine the boundaries of additive manufacturing and drive the next wave of technological advancement. By enabling the precise deposition of overlapping polymer materials, it significantly enhances the potential of 3D printing technology, offering new solutions to complex manufacturing challenges and contributing to the advancement of various fields.

***Index Terms*—3D printing, Material Extrusion, Overlapping Layers, Polymer.**

1. Introduction

Additive manufacturing (AM), particularly material extrusion 3D printing, has facilitated substantial progress in multi-material fabrication. Yet, integrating different polymers remains challenging, especially when the materials exhibit contrasting thermal and mechanical properties [1]. Ensuring strong bonding between these polymers is essential to prevent delamination and achieve high-performance components [2].

Polylactic Acid (PLA), known for its biodegradability, ease of processing, and relatively low melting temperature, is widely used in various applications. However, its brittleness limits its use in situations requiring flexibility. [3] Thermoplastic Polyurethane (TPU), by contrast, is characterized by its flexibility, durability, and elasticity, making it ideal for applications that require impact resistance and deformation under stress [4]. Combining PLA's rigidity with TPU's flexibility presents opportunities for multi-functional parts, but achieving effective bonding between these materials during 3D printing poses a significant challenge.

Integrating rigid and flexible polymers like PLA and TPU in a single print adds complexity due to their distinct melting points, flow behaviors, and adhesion properties [5,9]. Conventional dual-material printing often leads to weak bonding at the interface, particularly when there is chemical incompatibility between the materials. This weakness in bonding compromises the mechanical integrity of printed parts, making it difficult to produce components that seamlessly incorporate both rigid and flexible sections.

In response to these challenges, various strategies, such as mechanical interlocking designs and adjustments to extrusion parameters, have been explored to enhance bonding. While these techniques can improve bonding strength, they often introduce defects or inconsistencies in the printed layers [6]. A more effective solution is needed to allow for seamless transitions between rigid and flexible materials without sacrificing the quality or mechanical properties of the final part [7].

This paper presents a novel technique that enables precise overlapping of PLA and TPU during a single print. By synchronizing the extrusion of both materials and optimizing critical parameters such as flow rate, nozzle temperature, and overlap ratio, the method ensures strong bonding and smooth transitions between materials. This approach addresses common issues like delamination and weak adhesion, particularly in applications that require both rigidity and flexibility.

The technique utilizes advanced control systems to dynamically adjust printing parameters, ensuring that the overlapping of materials occurs without misalignment or defects. This innovation opens new possibilities for industries such as automotive, where rigid sections reinforced with flexible TPU can be employed in parts requiring impact resistance or vibration damping. Additionally, in the medical

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field, this method offers potential for creating implants or wearable devices that combine rigid support structures with flexible interfaces for enhanced comfort and functionality.

This study delves into the development and validation of this overlapping technique, exploring its mechanical performance through tensile and shear testing, and highlighting its potential applications in various industries. The paper is structured to first review existing literature on multi-material AM, followed by the methodology, experimental setup, and optimization parameters. Results from mechanical testing are then presented, leading to a discussion of the broader implications and future directions of this research.

2. Methodology

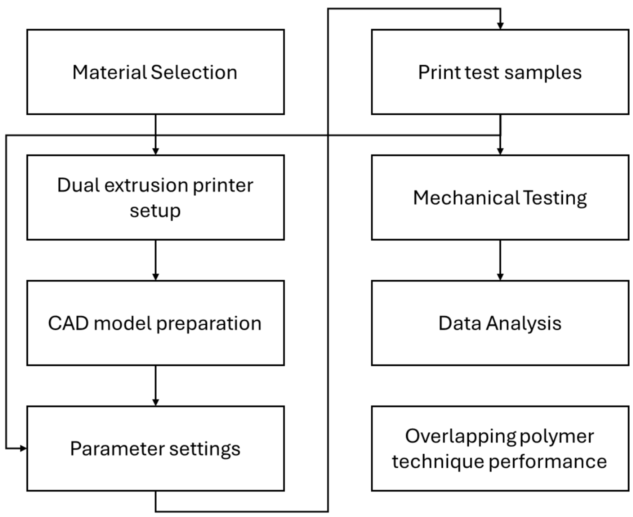

Fig. 1. Research methodology

The research methodology, illustrated in Figure 1, employs a systematic and iterative framework designed to overcome the thermal and mechanical incompatibilities between rigid PLA and flexible TPU. The process initiates with material selection and CAD model preparation, where specific interlocking features are designed to enhance adhesion beyond simple surface contact. A critical feedback loop connects parameter settings with the dual-extrusion setup, enabling the dynamic synchronization of flow rates and temperatures along with the calibration of a 50% overlap ratio to ensure intermolecular diffusion without defect formationas shown in Fig. 2. Following the successful fabrication of test samples, the methodology concludes with a rigorous validation phase comprising mechanical tensile and shear testing alongside Scanning Electron Microscopy analysis, ensuring that the final overlapping polymer technique performance is quantitatively verified against the inherent material limits.

This study introduces a novel technique that enables the seamless overlapping of two polymer materials using material extrusion 3D printing. The chosen materials are PLA, a rigid biodegradable polymer, and TPU, a flexible and durable elastomer. By synchronizing the extrusion of PLA and TPU, the technique ensures interlayer bond while addressing the challenges associated with their differing thermal and mechanical properties.

The process involves careful optimization of nozzle temperatures, material flow rates, and overlap ratios to maintain structural integrity and achieve smooth transitions between the two materials. A dual-extrusion 3D printer is used, and the key process parameters are adjusted based on the behavior of the two materials during printing.

A. Materials and Printer Settings

The materials selected for this study includes PLA which is a rigid, low-melting-point polymer (melting temperature: 210°C) widely used in 3D printing for its ease of use and environmental friendliness. However, its brittleness limits its application in parts requiring flexibility and TPU which is a flexible, elastic material known for its durability and resistance to impact, making it ideal for applications requiring flexibility. TPU has a higher melting temperature of 240°C, which poses challenges for achieving good adhesion with PLA. These materials were provided in filament form and used to fabricate test samples via material extrusion 3D printing. The dual extrusion printer details and settings are tabulated in Table 1. [8]

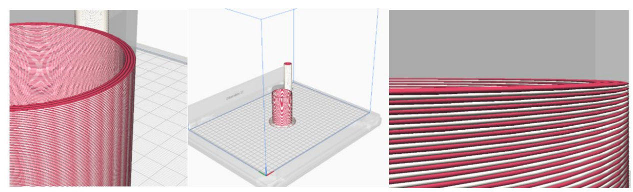

Fig. 2. CAD model preparation and slicing using Cura 5.0

Table 1
Experimental setup and settings for the dual extrusion 3D printer

Parameter	Details
3D Printer Model	Ultimaker S5
Nozzle Diameter	0.4 mm for both materials
Layer Thickness	0.2 mm for both materials
Build plate temperature	60 °C
Extruder Temperature PLA	210 °C
Extruder Temperature TPU	240 °C

B. Process Parameters and Optimization

To achieve a bond between PLA and TPU, several key process parameters were optimized starting with the flow rate for both materials was calibrated to ensure smooth extrusion and bonding at the overlap zones. A flow rate of 0.1 mm^3/s was set as the baseline, with fine adjustments to maintain consistent deposition. The overlap between PLA and TPU was controlled by setting the nozzle paths to intersect at specified points. A 50% overlap ratio was used to ensure sufficient bonding without excessive material buildup. The differing melting points of PLA and TPU required careful control of the nozzle temperature for each material. The higher temperature for TPU (240°C) ensured smooth extrusion, while PLA was printed at 210°C to prevent degradation. The cooling time between layers was also adjusted to accommodate the differences in thermal behavior.

The print speed was adjusted between 40 mm/s and 60 mm/s to ensure proper bonding, with slower speeds at the overlap regions to allow time for bonding between layers. A mechanical interlocking design was incorporated into the overlap zones of the CAD model to enhance adhesion between the rigid PLA and flexible TPU. This interlocking feature was designed to maximize shear strength and prevent delamination.

Test samples were printed using the dual-material 3D printer, with each sample containing regions where PLA and TPU overlapped. Multiple prints were conducted with varying process parameters to determine the optimal settings. After printing, the test samples were subjected to tensile and shear tests to evaluate the strength of the bonding between PLA and TPU. A universal testing machine (Instron 3366) was used to apply tensile force at a rate of 5 mm/min, and shear testing was performed to measure the bond's resistance to lateral forces.

C. Experimental Procedure

The experimental procedure started with the CAD model preparation. A cylindrical test sample was designed with specific overlap regions for PLA and TPU. The CAD model included interlocking features to improve bonding between the rigid and flexible sections.

D. Measurement and Evaluation

The mechanical evaluation focused on characterizing the novel properties of the hybrid polymer structure, specifically the functional integration of the two distinct materials. The primary objective was to validate the ability to combine PLA's structural rigidity with TPU's useful elasticity, allowing the flexible sections to serve as effective shock absorbers or vibration dampers. Consequently, the Ultimate Tensile Strength (UTS) of the overlapping region was measured to verify that the interface possesses sufficient integrity to transfer mechanical loads to the TPU without separation. Shear tests were performed to ensure the composite can withstand lateral stresses during deformation, which is critical for dynamic applications where the TPU is expected to absorb impact. Finally, the samples were visually inspected to confirm structural continuity at the transition zones, ensuring the part functions as a cohesive unit despite the inherent adhesion challenges between the differing polymers.

3. Results and Discussion

A. Structural Integrity and Microstructural Analysis

The novel overlapping technique was successfully applied to print cylindrical test samples using PLA and TPU, demonstrating the ability to create a functional composite that leverages the distinct mechanical advantages of each polymer.

Visual inspection of the printed samples revealed seamless transitions between the rigid PLA and flexible TPU sections, with no visible signs of delamination or separation (Figure 3).

The experimental setup, utilizing optimized flow rates and overlap ratios, was instrumental in overcoming the processing challenges associated with the differing melting temperatures of the two materials.

Scanning Electron Microscopy (SEM) analysis was conducted to evaluate the bond quality at the microstructural level (Figure 4). The images confirmed distinct layer visibility with good material integration at the bonding zone. Notably, no major voids or defects were observed in the overlap region, and the material flow appeared consistent. This microstructural continuity suggests that the interlocking design incorporated into the overlap regions effectively anchored the flexible TPU phase to the rigid PLA matrix. By establishing a stable interface, the technique ensures the component performs as a cohesive unit, capable of integrating PLA's structural rigidity with TPU's elasticity within a single contiguous part.

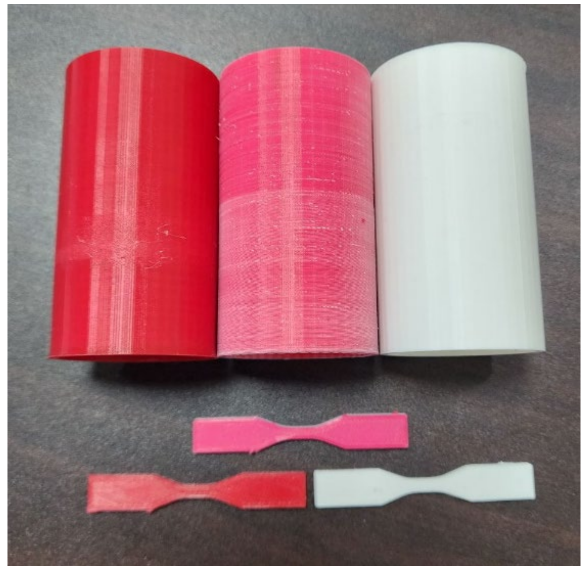

Fig. 3. Successful print of overlapping two polymers. (red) TPU, (red-white layers) TPU-PLA overlapped print, (white) PLA

B. Mechanical Performance and Failure Modes

Mechanical testing was performed to validate the structural integrity of the combined PLA-TPU composite, specifically ensuring the interface could support the distinct functional roles of the materials [10]. The overlap region yielded an Ultimate Tensile Strength (UTS) of 28.6 MPa. This result confirms that the connection between the differing polymers is sufficiently robust to maintain continuity under load.

Crucially, analysis of the failure modes revealed that fractures predominantly occurred within the bulk materials rather than at the overlap interface. This indicates that the joint strength exceeds the inherent limits of the bulk polymers, preventing premature separation. This structural continuity is vital for utilizing TPU as a shock absorber or flexible hinge, as it ensures the component can endure mechanical stress and deformation without delaminating from the rigid PLA foundation [11]. These findings validate that the optimized process parameters successfully established a bond capable of transferring mechanical loads, rather than merely achieving surface adhesion.

C. Thermal Mismatch and Layer Misalignment

Despite the successful bonding and mechanical performance, some layer misalignment was observed during deposition (Figure 4). This misalignment, particularly pronounced at the transition zones, is attributable to the significant difference in nozzle temperatures required for the materials—210°C for PLA versus 240°C for TPU. These temperature-induced discrepancies led to variations in material flow and cooling behavior, causing minor shifts in layer alignment that affected the surface finish.

While this misalignment did not compromise the overall structural integrity in this study, it could potentially weaken the bond in highly critical applications. Addressing this issue requires further refinement of the printing process, specifically regarding temperature synchronization. Potential solutions include optimizing cooling times to synchronize solidification rates, fine-tuning nozzle temperatures to equalize extrusion consistency, or modifying toolpaths to account for the differential flow properties of PLA and TPU.

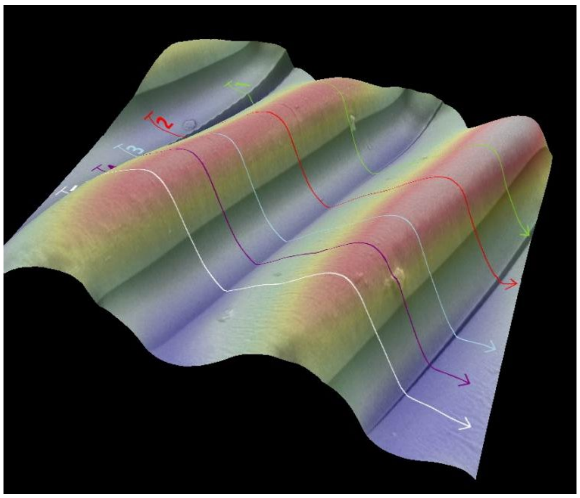

Fig. 4. Layer misalignment of the overlapping polymers

D. Industrial Applications and Implications

The successful bonding of PLA and TPU in a single print eliminates the need for post-processing or manual assembly, thereby reducing production costs and time. This capability opens new possibilities for applications requiring parts with distinct mechanical properties. In the automotive industry, the seamless combination of rigidity and flexibility allows for the creation of custom shock absorbers or vibration damping components that endure mechanical stress without delamination. Similarly, in the medical field, the technique enables the fabrication of biocompatible devices, such as prosthetics or implants, that feature rigid support structures integrated with flexible interfaces for enhanced patient comfort and functionality [12], [13].

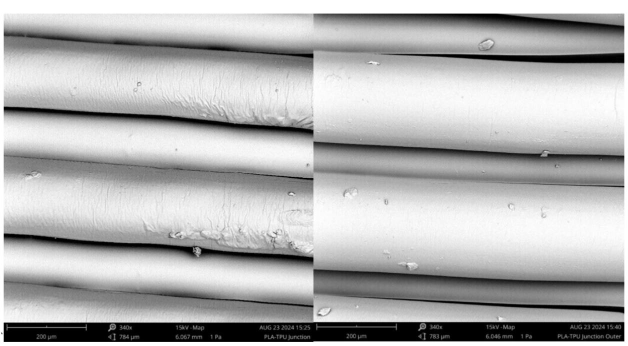

Fig. 5. SEM Image of the printed overlapping TPU and PLA. (left) inner side of the cylinder, (right) outer side of the cylinder

4. Conclusion

The novel technique for overlapping PLA and TPU in material extrusion 3D printing has demonstrated strong potential for producing high-performance, multi-material parts with seamless transitions between rigid and flexible sections. The successful optimization of process parameters has resulted in robust bonding, high tensile strength, and excellent shear resistance. While minor issues such as layer misalignment remain, ongoing refinements will further enhance the technique's applicability and performance. This method holds great promise for advancing multi-material additive manufacturing across a range of industries.

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