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Reviewed Paper

CHARACTERIZATION OF 3D PRINTED AND WIRE EMBEDDED THERMOPLASTIC COMPOSITE STRUCTURES

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Abstract

This research evaluates and characterizes the thermal and physical characteristics of thermoplastic specimens embedded with resistive wire using a Fused Filament Fabrication 3D printer. The specimens were manufactured through a novel approach "Pause and Go" in additive manufacturing for embedding resistive wires into a 3D printed thermoplastic substrate using a custom-built wire embedding tool integrated into a commercially available desktop scale Independent Dual Extruder (IDEX) printer. Wire-embedded test specimens were produced via 3D printing using Polylactic Acid. The 26-gauge nichrome wire was embedded in the top substrate and continued the printing to fully embed the wires. Thermal testing was carried out and observed steady-state temperatures after 30 minutes. The wire pulls tests characterized the bonding strength of the wire and substrate.

1. Introduction

The integration of conductive materials into 3D printed structures has emerged as a significant area of interest, driven by the potential to create multifunctional composites that combine mechanical strength with electrical conductivity. Traditional manufacturing methods for embedding conductive wires into thermoplastic substrates are often limited by complexity, cost, and precision issues (Ahn et al., 2002). Recent advancements in additive manufacturing (AM), specifically Fused Filament Fabrication (FFF), offer new possibilities for embedding conductive elements directly into 3D printed parts, thus simplifying the process and enhancing the performance of the resulting composites (Gao et al., 2015, Yao et al., 2017). The state-of-the-art of wire embedding using both conductive and resistive materials in thermoplastic substrate has accomplished and demonstrated by utilizing several different techniques. Early methods involved embedding wires or conductive materials on a 3D printed substrate through a secondary process such as adhesive bonding, which often resulted in poor interfacial bonding and reduced overall part strength (Park et al., 2009). Other approaches, such as ultrasonic embedding, improved the precision of wire placement but introduced complexity in the process, increased the manufacturing costs, and required specialized equipment (Kim et al., 2014; Zhang et al., 2016). These methods also presented challenges in maintaining uniform thermal and mechanical properties across the wire embedded composite structure, often leading to localized failures or degradation over time. The need for an efficient, scalable process that embeds conductive and resistive materials without compromising the mechanical properties of the thermoplastic substrate remains a critical challenge in the field. Addressing these limitations is essential for advancing the practical applications of such composites in areas like flexible electronics, sensors, and structural health monitoring.

Legacy methods of embedding conductive wires typically involve post-processing steps that can weaken the mechanical integrity of the composite or complicate the manufacturing workflow (Sun et al., 2018). To address these challenges, this study introduces a novel "Pause and Go" technique for embedding conductive wires during the 3D printing process. This method leverages the capabilities of a custom-built wire embedding tool integrated with a commercially available desktop Independent Dual Extruder (IDEX) printer, allowing for precise placement of wires within the thermoplastic matrix without compromising the structural integrity of the printed part. The research focuses on Polylactic Acid (PLA) due to its widespread use in FFF 3D printing and its distinct mechanical properties. PLA is known for its ease of printing and biodegradability, making it suitable for a variety of applications, while ABS offers greater toughness and thermal resistance, which is more critical for more demanding engineering applications (Zhao et al., 2016, Hutmacher et al., 2001; Torrado et al., 2015). To embed the conductive material, 26-gauge nichrome wire was selected for its high electrical resistance and ability to withstand elevated temperatures. The embedding process involves pausing the 3D print at specific layers, integrating the wire using the custom tool, and then resuming the print to encapsulate the wire within the thermoplastic substrate. This technique ensures that the wire is fully embedded and securely bonded to the surrounding material, which is crucial for maintaining the composite's mechanical and electrical properties. The characterization of the wire-embedded thermoplastic specimens includes thermal testing to observe steady-state temperatures. The thermal performance of the composites is assessed by monitoring the temperature distribution and stability over time, providing insights into their suitability for applications involving thermal management. Additionally, wire pull tests are conducted to determine the bonding strength between the wire and the thermoplastic substrate, highlighting the effectiveness of the embedding process (Gibson et al., 2015; Ning et al., 2015).

By developing and validating this novel embedding technique, the research aims to contribute to the broader field of additive manufacturing and composite materials, offering practical solutions for creating advanced functional composites with embedded conductive elements. The outcomes of this study have the potential to significantly enhance the performance and application range of 3D printed thermoplastic composites in various industries, including electronics, automotive, and aerospace.

2. Methodology

2.1 Materials and Equipment

Dichloromethane (DCM) was used as a surface treatment to facilitate the embedding of the wire into the wire pull specimen. DCM is commonly used to eliminate striations often found on the surface of 3D-printed objects resulting from traditional nozzle extrusion. DCM is a colorless and volatile liquid mainly used in the pharmaceutical industry and as a degreasing agent, breaking the bonds of polycarbonate molecules and releasing them for deposition. The fiber component of the composite test specimens consisted of 26-gauge nichrome wire and embedded into the specimens during 3D printing.

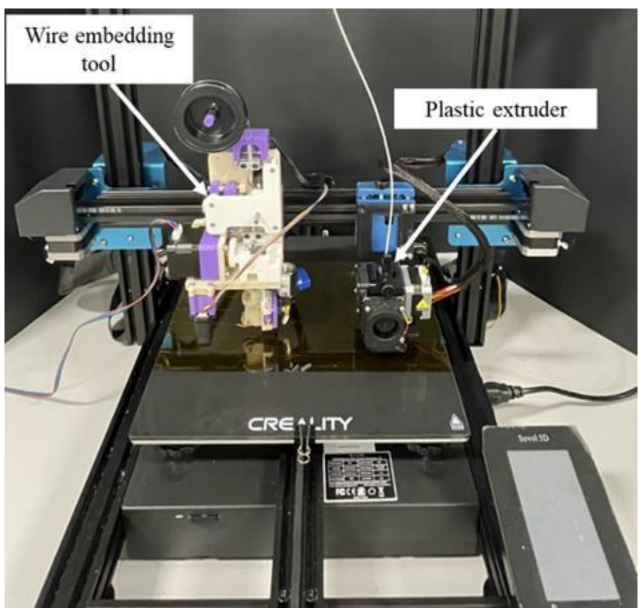


Figure 1: Figure 1. Sovol SV04 IDEX 3D printer with integrated wire embedding tool

The Wire Embedding Tool (WET) is a custom-built and adaptable tool designed for integration with a commercially available IDEX desktop 3D printer, replacing one of the two available thermoplastic filament extruders. The tool is designed to transport wire through a feed and wire-cutting system while concurrently applying DCM surface treatment to embed conductive wire into thermoplastic substrates. The integrated tool, shown in Figure 1, was installed on a Sovol SV04 3D printer using a customized mounting plate with the wire feed system utilizing the same power supply previously connected to the left thermoplastic filament extruder. The remaining plastic extruder is connected to a custom extension plate designed to compensate for the elevation difference between the embedding tool and the previous extruder configuration. Modified

Geometric Code (G-code) was developed to allow the embedding tool to operate alongside the remaining plastic extruder as part of a continuous integrated print and embedding program.

2.2 Wire Pull Test Specimens

The wire-embedded specimens were designed to be 25 mm x 50 mm, as depicted in Figure 2. The intent behind the specimens was to conduct pull out testing to evaluate the bonding strength of embedded conductive wires in a polymer matrix. The tests were conducted on an Instron 5969 machine, which did not have a test specific mounting system to accommodate wire pull specimens. Specimen geometry was selected for simplicity based on the requirement for a custom-made mount and enclosure compatible with the testing machine.

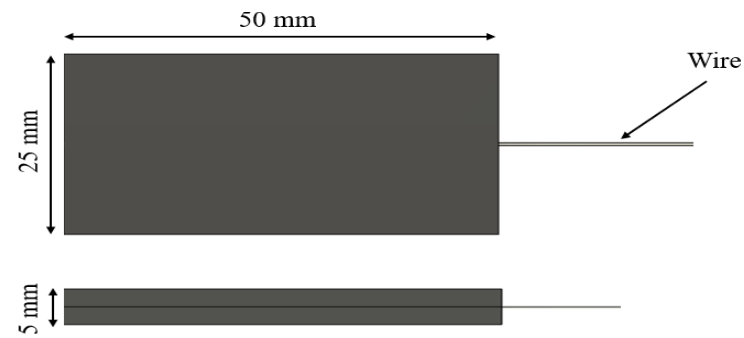


Figure 2: Wire pull testing specimen's dimensions.

The wire-embedded specimens were manufactured using PLA printed on a Sovol SV04 IDEX 3D printer with a custom-made wire embedding tool. For the experiment, five specimens were printed with a 0-degree raster angle, and an addition five specimens printed at a 90 degree raster angle. Testing included different raster angles to observe any changes print direction might have on the embedding strength of the wires. Table 1 includes the print and bed temperature used for both 0 degree and 90 degree raster angles.

Table 1. Wire pull test specimen 3D print specifications.

Number of Specimens	Material	Raster angle (°)	Print Temperature (°C)	Bed Temperature (°C)
5	PLA	0	202	60
5	PLA	90	202	60

A custom G-code for thermoplastic and conductive wire extrusion was loaded into the modified Sovol SV04 3D printer to begin manufacturing the specimens. The printer build plate was prepared using thermal tape to ensure the prevention of DCM on the machine as shown in Figure 3. During the printing process of the brim, the right nozzle's z-axis was adjusted accordingly for each specimen. After the printing of the brim was successful, the initial layers of the specimen were printed. Once the first thermoplastic layers were complete, the plastic extruder returned to its home position and the wire embedding tool began its programmed run. The tool was programmed to pause before the embedding movement to allow time to secure the free end of the wire to the build plate with thermal tape. At the end of the first programmed pause, the applicator ball valve was opened, allowing DCM to saturate the applicator brush. The embedding tool then began its run across the specimen. Once the wire reached the other side of the bed, it was secured with thermal tape and the nozzle returned to its position. After wire embedding each specimen was inspected to ensure proper wire embedding to allow subsequent encapsulation in thermoplastic. After wire embedding, the machine was set to print the upper layers of the specimen, once again adjusting the z-axis offset to ensure that the specimen would not warp or to have gaps within the specimen. At the end of the print, the specimens were inspected to verify the wire was fixed within the substrate and ready for wire pull testing. As shown in Figure 4, the specimens were produced in both 0-degree and 90-degree raster angles. The ends of the wires were clipped to avoid having excess wire being pulled through the specimen during testing.

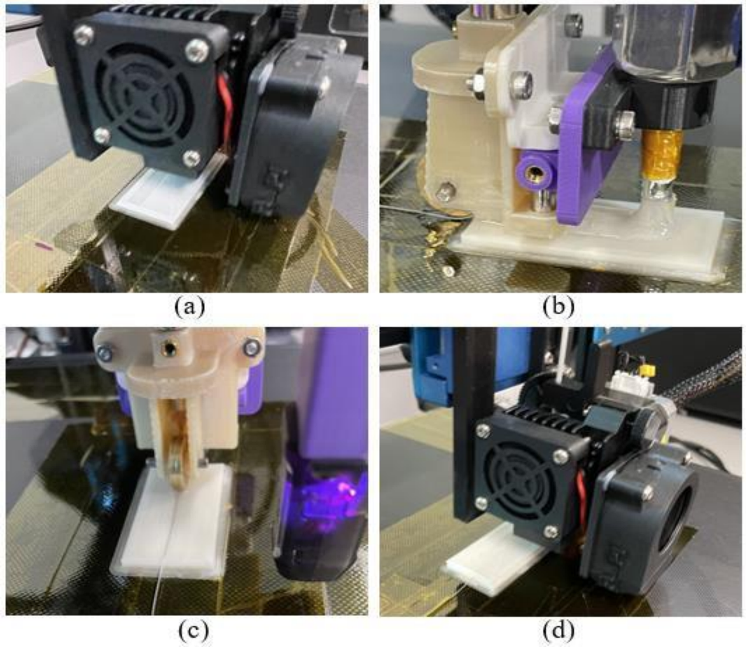


Figure 3: 3D printing and wire embedding process for the wire pull specimens: (a) Printing base layer (b) Application of DCM (c) Wire embedding (d) Printing top layer to complete specimen

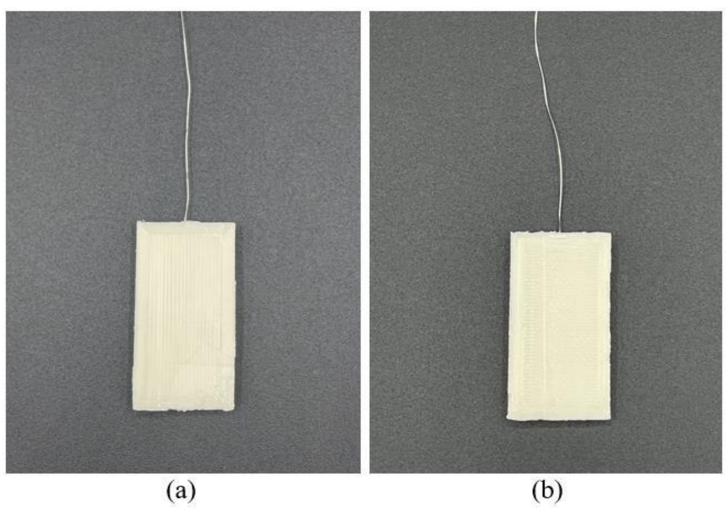


Figure 4. Wire pull test specimens: (a) 0-degree raster angle; (b) 90-degree raster angle.

2.3 Wire Pull Specimen Enclosure

A specimen enclosure was designed to accommodate the wire pull specimen and mount on the Instron testing machine T-slot mount. The enclosure was intended to limit shear stress on the specimen while permitting full load on the wire parallel to the orientation of the embedded wire. Figure 5 demonstrates how the specimen was inserted into the enclosure and both halves of the enclosure were then combined to securely fix the specimen for testing. A channel was included in the enclosures design to allow the specimen wire to move independently of the enclosure for placement in the Instron testing machine grips.

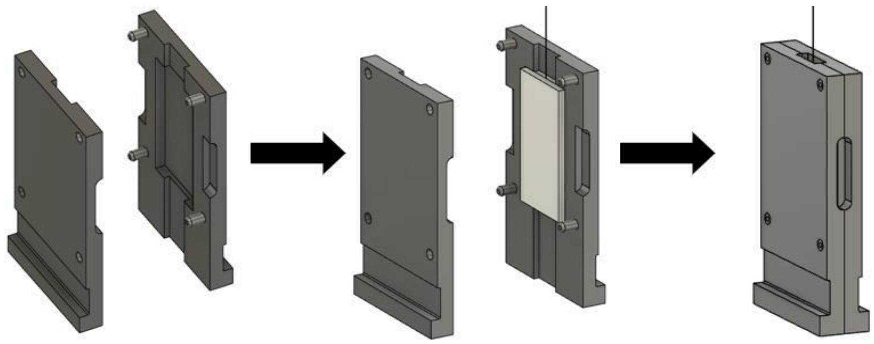


Figure 5. Wire pull test specimen integrated with enclosure.

The testing enclosure included a slot dimensioned to accommodate the wire pull specimen and four set pins to ensure both halves of the enclosure would remain fixed during testing. The T-beam formed by assembling the two halves of the specimen enclosure was sized to fit in the T-slot mount of the Instron 5569 testing machine. The wire pull specimen enclosure was 3D printed from Acylonite Styrene Acrylate (ASA) on a Raise3D E2 printer.

3. Experimental Setup

3.1 Thermal Testing

Thermal testing was performed on select specimens to determine their thermal characterization and behavior. The fabricated specimens had the wires on each end cut to 1 inch in length for conformity between tests. The specimens were individually placed on an insulated surface and a Naweisz NP3005 power supply was connected to both ends of the wire. A k-type thermocouple connected to a DAQ device was attached to the bottom of the specimen to verify that the specimen reached the target temperature, and two 1-kilogram weights were placed to ensure nothing moved over the course of each test. Lastly, a FLIR A70 series IR camera was set up to collect a top-down view of the test. The thermal testing was performed at 5 volts and an initial current of 2.05A for 5 minutes to reduce the chances of thermal shock. Once heated for 5 minutes the current was raised to 2.13 amperes as the final current for the remainder of the experiment. The thermocouple was used to calculate the current temperature of the specimen as the IR camera's emissivity was adjusted to match. Once both the camera recording and the thermocouple are turned on simultaneously, the specimen would then be left to heat for an hour.

3.2 Wire Pull Tests

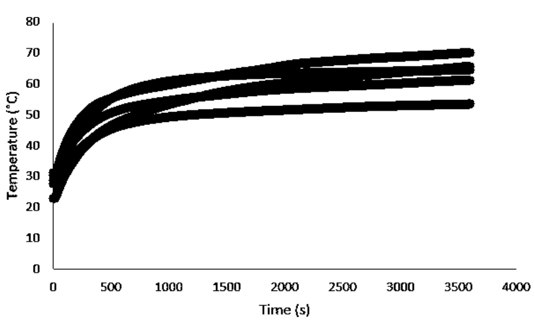
The wire pull-out test for nichrome wire and thermoplastic substrate was based on guidance from ASTM D7332 and ASTM C900-06. The wire pull specimen and enclosure were designed to ensure the direction of force was coincident with the longitudinal axis of the wire, as shown in Figure 6. The specimen was inserted and assembled with the specimen enclosure. The enclosure was then slotted into the Instron T-slot mount and the wire secured in the grips to hand tight. The crosshead speed of the test was set at 1 mm/min and collected displacement (mm) and force (N) data.

Figure 6. Wire pull out test fixture procedure.

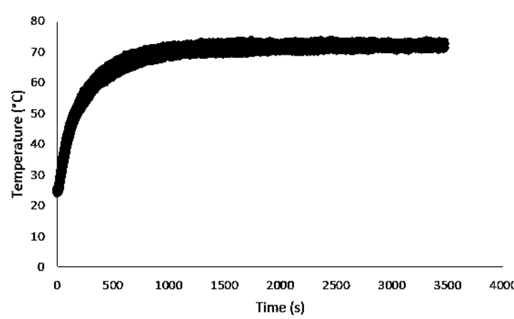
4. Results and Discussion

4.1 Thermal Characterization Results

The thermal testing of the 90-degree raster specimens, as seen in Figure 7, reached a steady state temperature of 70°C after around 10 minutes. Figure 7 (a), shows the temperature profile that was based on thermocouple measurement. In the thermocouple-based testing, both top and bottom thermocouples showed a similar temperature profile and reached at steady state after 10 minutes. However, the two thermocouples those were placed below the mold showed a relatively low temperature (the difference of 10°C and 12°C compared to the top surfaces). These differences were attributed to the thickness of the mold and distance of the surface from the wires. In Figure 7 (b), the IR camera- based temperature is shown. These are collected from the IR camera and the region of interest was various locations across the wire-embedded specimens.



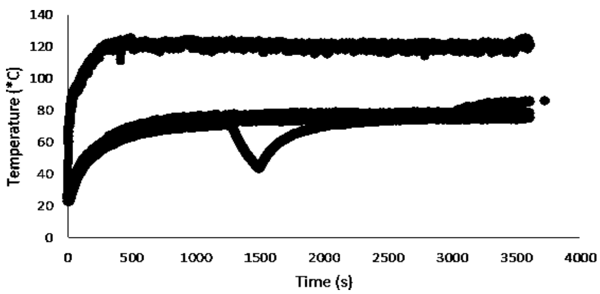
(a)



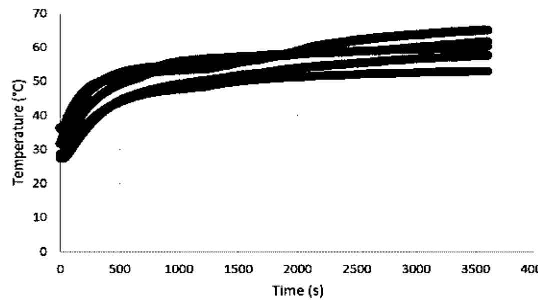
(b)

Figure 7. Thermal testing of 90° specimens: (a) Thermocouple measurements; (b) IR camera temperature measurements.

Similar temperature distribution and profiles were noticed in the 0-degree specimens as shown in Figure 8. There are two outliers to acknowledge with the IR camera data of the 0-degree specimens as shown in Figure 8(a). One specimen had emissivity of the camera set incorrectly so the temperature appears much higher than it should and one had a power hitch at approximately 1500 seconds into the test. Thermocouple readings provided more consistent data for each of the samples.



(a)



(b)

Figure 8. Thermal testing of 0º specimens: (a) Thermocouple measurements; (b) IR camera temperature measurements.

4.2 Wire Pull-Out Testing Results

The wire pull test was designed to investigate the wire pull-through resistance of a conductive wire embedded in 0º and 90º polymer matrices. Test results indicated consistent load versus slip behavior, with one 90º specimen as an outlier, requiring approximately 50% less force to produce wire slip within the matrix. The remaining samples demonstrated a similar maximum load force of 26N before the initial slip, as shown in Figure 9. Following the initial slip an increased load was measured as the trailing wire within the matrix began to assume the tensile stress. A divergence in test results near the maximum load with half of each raster group reaching a maximum load of approximately 68N and the other half a maximum load of approximately 49N.

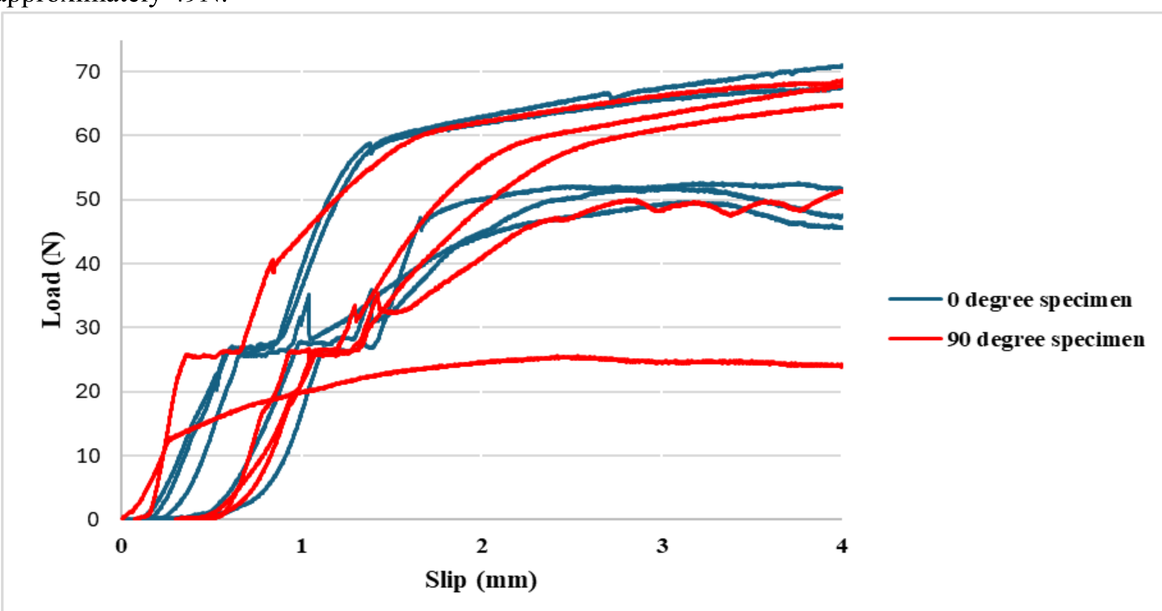


Figure 9. Load versus slip results recorded during wire pull tests.

5. Conclusion

In this study, we successfully demonstrated the fabrication of wire-embedded specimens using a custom- built 3D printer. On the printed specimens, we performed thermal testing and wire pull-out testing. The thermal test result exhibited that all PLA samples reached a steady state at around 70°C after a duration of around 10 minutes. A steady state temperature with a relatively short period without melting the substrate was a major milestone for this research. This result will support self-heating parts manufacturing for various applications including embedded circuitry and sensors. The wire pull-out test also confirmed the robust bonding between wires and the PLA substrate. Further characterization such as X-CT or nondestructive testing will confirm the shape and deformation of the wire and plastic that might happen during the embedding process.

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