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DEVELOPMENT OF WIRE DELIVERY TOOL WITH DESKTOP 3-D PRINTER FOR MULTIFUNCTIONAL ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufacturing (AM), also known as 3D printing, has significantly advanced in recent years, especially with the introduction of multifunctional 3D-printed parts. AM fabricated monolith has multiple material capabilities, thus various functionalities are well-perceived by the manufacturing communities. As an example, a traditional fused filament fabrication (FFF) 3D printer fabricates multi-material thermoplastic parts using a dual extrusion system to increase the functionality of the part including variable stiffening and gradient structures. In addition to the multiple thermoplastic feedstocks in a dual extrusion system, multifunctional AM can be achieved by embedding electronics or reinforcing fibers within the fabricated thermoplastic parts, which significantly impacts the rapid prototyping of hybrid components in manufacturing industries. State-of-the-art techniques such as coextrusion systems, ultrasonic welding tools, and thermal embedding tools have been implemented to automate the process of embedding conductive material within the 3D-printed thermoplastic substrate. The goal of this tool development effort is to embed wires within 3D 3D-printed plastic substrate.

This research consisted of developing a wire embedding tool that can be integrated into an FFF desktop 3D printer to deposit conductive as well as resistive wires within the 3D-printed thermoplastic substrate. By realizing the challenges for discrete materials interaction at the interface such as nichrome wires and Acrylonitrile Butadiene Styrene (ABS) plastics and polylactic acid (PLA), the goal of this tool was to immerse wire within ABS and PLA substrate using transient swelling mechanisms under non-polar solvent.

A proof-of-concept test stands with a wire feed system and the embedding wheel was first designed and manufactured using 3D printing to examine if a traditional roller-guided system, primarily used for plastic extrusion, would be sufficient for wire extrusion. The development of the integrated wire embedding tool was initiated based on the success of the proof-of-concept wire extrusion system. The design of the integrated wire embedding tool consisted of three sub-assemblies: wire delivery assembly, wire shearing assembly, and swivel assembly. The wire delivery assembly is responsible for feeding the wire towards the thermoplastic using the filament delivery system seen within FFF printers. For the wire shearing mechanism, a cutting Tungsten carbide blade in conjunction with a Nema-17 external stepper motor was used to shear the wire. For the wire embedding assembly, a custom swivel mount was fabricated with a bearing housing for a ball bearing that allowed for a 360-degree motion around the horizontal plane. A wire guide nozzle was placed through the mount to allow for the wire to be fed down into a brass embedding wheel in a tangential manner. Additionally, the solvent reservoir was mounted such that an even layer of solution was dispensed onto the thermoplastic substrate. Through this tool development effort, the aim was to develop technologies that will enable 3D printing of wire-embedded monolith for various applications including a self-heating mold of thermoset-based composite manufacturing as well as smart composites with embedded sensors.

Keywords: Additive Manufacturing, Wire Embedding, ABS, PLA, 3D printing, Extrusion.

1. INTRODUCTION

Additive manufacturing (AM) is the process of creating objects by joining materials in a layer-by-layer fashion from a 3D computer-aided design (CAD) part as opposed to subtractive or formative manufacturing methods [1]. The general AM procedure commences with a CAD file, which is then transformed into a stereolithography (STL) file. This STL file essentially segments the design into individual layers that will be sequentially printed [2]. Finally, through a range of techniques, the selected material is deposited or bonded layer by layer until the product is fully realized [3]. Various AM process technologies have garnered substantial interest in both academic and industrial circles, primarily due to their capacity to craft intricate geometries while tailoring material properties to specific requirements [4]. Significant advancements brought by the AM-based production process include the reduction of lead time and cost with reduced human intervention and streamlining of the product development cycle [5].

In recent years, material extrusion-based AM has transformed to include the manufacturing of structures with multi-materials. One notable advancement is the development of the integration of polymers with multi-materials, including metals and wires within a printed monolith. This integrated approach introduces new possibilities for manufacturing by combining the mechanical properties of metals with the design flexibility of polymers and the conductive capabilities of wires. This innovative method has been explored in various studies, such as those by Khondoker et al. [6], Fernandez et al. [7], and Bailey et al. [8], which demonstrate the potential of AM to create functional, multi-material products, which were previously challenging to achieve. This technology has the attention of many industries including automobile, aerospace, marine, and medical, proving its potential to change the manufacturing industry.

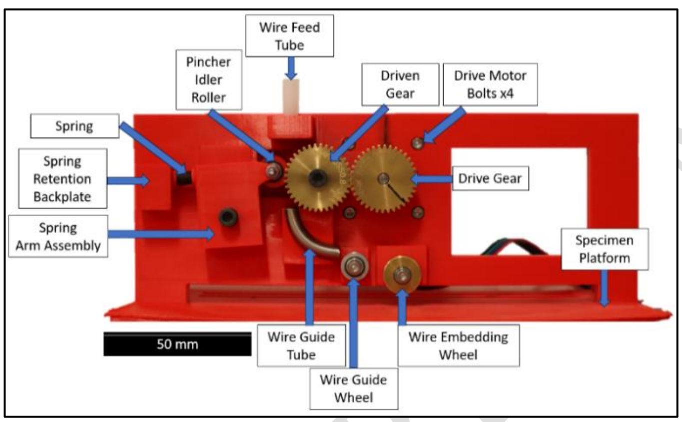
Research endeavors into multi-material AM have been undertaken, each driven by distinct objectives and employing their unique, well-established techniques. For example, an approach by utilizing liquid metal co-extrusion within styrene-ethylene-butylene-styrene (SEBS) filaments, enabling the direct 3D printing of stretchable circuits was demonstrated by the authors in [6]. In this method, liquid metal is carefully injected through a precision needle, smoothly enclosed within thermoplastic elastomers, all achieved through a custom tri-extruding device system engineered to align with Fused Deposition Modeling (FDM) printers. This intricate process sets up the simultaneous extrusion of both metal and thermoplastics through a singular point, forming a continuous strand of conductive thermoplastic medium. In another work of multi-material-based 3D printing, a significant breakthrough of tool development and integration with desktop scale 3D printers was developed to deposit shape memory alloy (SMA) wire and copper wire to thermoplastic substrates [7-8]. These breakthroughs necessitated the utilization of custom printing techniques and the precise application of Joule heating for wire embedding. Joule heating, a technique that leverages the conduction of wires to establish a strong bond with a thermoplastic substrate via current-induced heating, played a pivotal role in this achievement [9]. Given the multi-faceted nature of the process, involving multiple stages encompassing both the printing and embedding procedures, it fittingly earns the title of multi-process AM.

While effective methods for multi-material additive manufacturing have been explored in several research investigations, each method has its own set of limitations. For instance, while the work in [6] has achieved success in directly printing stretchable and flexible electronics, some notable limitations have emerged. One key challenge is the rapid drop in the polymer melt's temperature, which often falls below its glass transition temperature. This makes it difficult to maintain precise control over the extrusion process, resulting in liquid metal droplets taking an oblong shape rather than a fully spherical and continuous form. Achieving a continuous jet of liquid metal encapsulated in SEBS relies on a delicate balance between surface tension and viscous drag forces, which can be sensitive to various parameters. Consequently, it becomes challenging to produce continuous wires consistently. Additionally, the experiment employed a needle with an inner diameter of 400 micrometers, limiting the range of core diameters that could be produced. This study found it impossible to create wires with a core diameter of less than 400 micrometers [6].

Similarly, the work in [7, 8] has developed methods of embedding SMA and copper wires into thermoplastics using a custom-made tool integrated with desktop 3D printers. The embedding of SMA in thermoplastics polymer actuators presents a promising yet complex approach. The primary limitation is the manual embedding process. This method is labor intensive, and each wire embedment lacks precision, leading to variations in actuator performance [7]. Complex geometries might not be suited for this method, limiting its applications. There are also constraints related to the length of SMA wire that can be embedded, potentially limiting actuators requiring extended wire lengths. Moreover, this approach is limited to specific material restricting its broader use. Their other research presents an integrated software solution for multi-process 3D printing to embed electronic components and circuits into 3D printed parts. While this method holds promise, it is important to note several specific limitations. One significant limitation is the reliance on a specific 3D printer, LulzBot TAZ 5, which may raise concerns about its adaptability to other printer models, as custom tools have been tailored to this 3D printer [8]. Additionally, the need for manual component placement and soldering introduces human error and time-consuming processes. The research focuses on simple electronic circuits, leaving the question regarding the feasibility of embedding complex circuits. Material compatibility, interoperability with other CAD and Electronic Computer-Aided Design (ECAD) software, and the ability to handle non-planar geometries remain areas in need of further research. Also, issues related to scalability, safety, and long-term reliability have not been addressed.

Recognizing the limitations evident in these research studies, this research addresses the critical challenges in the integration of metals, conductive wires, and electronic components into thermoplastic materials, as well as develops the broader multi-process AM approach.

In this research paper, a newly developed wire delivery tool is presented. The custom-made tool was integrated into a desktop 3D printer. This tool was designed to deposit conductive and resistive wires within a 3D-printed thermoplastic substrate. Recognizing the challenges associated with materials interaction, particularly between nichrome wires and thermoplastics such as Acrylonitrile Butadiene Styrene (ABS), a non-polar solvent such as Dichloromethane (DCM) was used which induced the transient swelling of the thermoplastic surface. This mechanism permitted the conductive material to become securely immersed in thermoplastic and causes minimal surface deformation. In addition, the custom-made wire delivery tool uses a swivel mechanism that allowed the embedding of various American Wire Gauge (AWG) wires, in one-dimensional and two-dimensional planes. This research represents a step forward for multi-material AM offering new prospects for embedding wires within thermoplastic substrates. In the following sections, the tool developmental efforts are presented. At first, a testbed of the wire delivery was designed and manufactured. After successful demonstration of wire delivery system, a custom-made wire embedding tool was designed for semi-automated wire embedding into 3D printed parts.



2. DESIGN AND ANALYSIS

2.1 Experimental Test Stand Design

The proof-of-concept test stands for wire transportation and embedding was manufactured via 3D printing and assembled using commercially available hardware. The chassis was fabricated out of Polylactic Acid (PLA) as a single component using a Raise3D E2 desktop 3D printer with the manufacturing parameters as listed in **Table 1**.

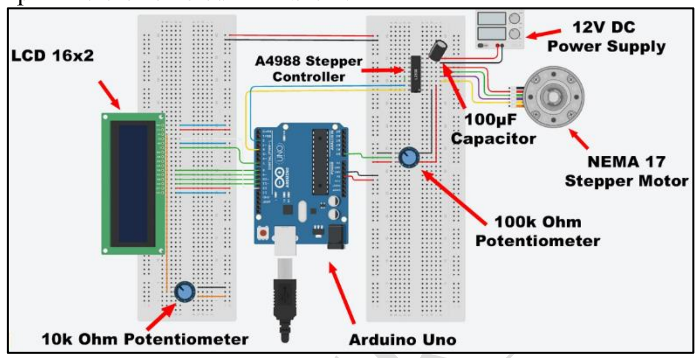


Table 1. Test stand 3D print manufacturing parameters.

Figure 1: Test stand motor wire diagram.

Filament material	Nozzle diameter (mm)	Print temp. (°C)	Bed temp (°C)	Infill density (%)	Infill pattern
PLA	0.4	210	75	100	Gyroid

Commercially available components including bolts, nuts, washers, springs, bearing idler rollers, and gears were integrated into the chassis to achieve the extrusion of the nichrome wire as shown in Figure 1. The spring retention assembly and idler pincher roller were also 3D printed using PLA. A slot was included at the base of the wire embedding wheel to allow thermoplastic test samples to slide between the wire embedding wheel and the bottom of the wire embedding platform.

As shown in Figure 2, a Nema 17 stepper motor was controlled by an A4988 driver connected to an Arduino Uno which included a Liquid Crystal Display (LCD) that monitored pulse frequency in microseconds from the A4988. A maximum of 12 watts of DC power was supplied to the A4988 driver by a laboratory power supply. A potentiometer was included in the motor controller design to allow real-time adjustment of pulse frequency allowing variability in motor speed.

Figure 2: 3D printed Test stand prototype for feasibility study of a wire deposition tool.

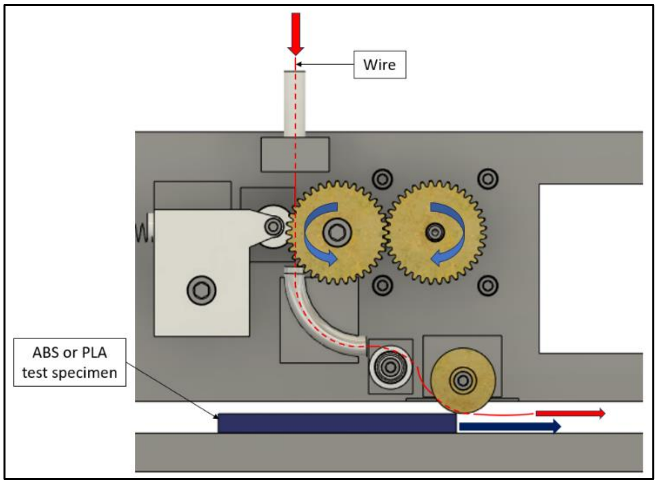


Figure 3. Wire embedding test process.

2.2 Validation of wire delivery system using test stand

Nichrome wire of 26 AWG (0.4038 mm) was used during initial thermoplastic substrate embedding tests. For each test, the wire was inserted through the top wire feed tube and pincher rollers before being aligned under the embedding wheel. DCM solution was applied to ABS test samples before each trial using a solvent applicator marker and then positioned on the test stand platform in contact with the wire and embedding wheel as shown in **Figure 3**. Before activating the test stand motor, a lab technician grasped the Nichrome wire with steel pliers to prevent the wire from lateral movement as the specimen was guided under the application wheel. Upon activation of the motor, the ABS samples were pushed under the embedding wheel in such a way as to match the wire feed rate to prevent wire buckling.

2.3 Automated Wire Delivery Tool Design

From a test stand design of the wire delivery system, the tool development effort was graduated to the next step which is the automated wire delivery and embedding tool. The designed and developed wire embedding tool was mounted on a Sovol SV04 desktop Independent Dual Extruder (IDEX) 3D printer in place of the left thermoplastic extrusion assembly, as shown in **Figure 4.** The main frame was designed to mount directly on the existing gantry mounting plate using the existing bolt configuration. The stepper motor previously used to feed thermoplastic filament was integrated into the wire feed assembly drive gear. The z-offset probe was also adapted to the tool by mounting it on an extension from the lower tool frame, allowing for auto home functions before wire embedding trials.

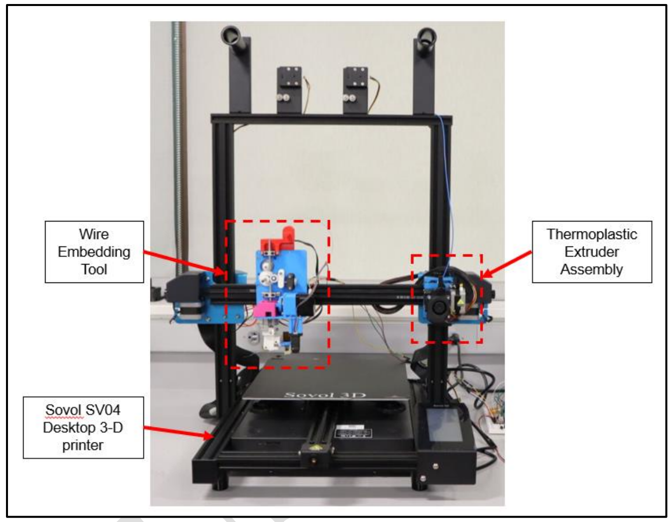


Figure 4. Wire embedding tool mounted on Sovol SV04 3D printer.

The design of the 3D printer-mounted embedding tool began after the conclusion of test-stand wire embedding validation trials. The mounted automated wire embedding tool went through multiple iterations, with the system shown in **Figure 5** resulting from a combination of lessons learned from previous configurations. This initial integrated prototype design was composed of three sub-assemblies modularly mounted on a custom chassis which has been 3D printed out of PLA filament. The sub-assemblies previously mentioned included the wire delivery assembly, the shear assembly, and the wire embedding assembly.

The wire delivery assembly consisted of a Nema 17 stepper motor, a speed reduction gear configuration which contained a set of two spur gears, a 13 mm concaved pulley driver wheel and a 5 mm convex idler roller, a spring arm assembly, and the wire spool holder. To ensure sufficient grip between the concave pulley wheel and the idler roller, a compression spring with a 6 mm diameter was used. To adjust the force applied by the spring, a screw was integrated. The wire was initially fed through a shaft with a 1 mm inner diameter which served as a wire guide and prevented excess buckling. Off-the-shelf mounts were used to connect the shafts to the chassis. The step angle for the Nema 17 stepper motor was 1.8 degrees per step, however, precision of the motor was improved through the use of micro stepping configuration. The motor was coupled to a spur gear with 15 teeth which further transmitted the rotational motion to a 30 teeth spur gear, resulting in a 2:1 gear ratio for an overall reduction of the feed rate to achieve higher precision. The motor along with the gears were intended to drive a roller that was assisted by the tensioner arm having an idler attached to translate the rotational motion onto linear motion of the wire. The wire feed subassembly ensured that the wire was fed towards the polymer substrate.

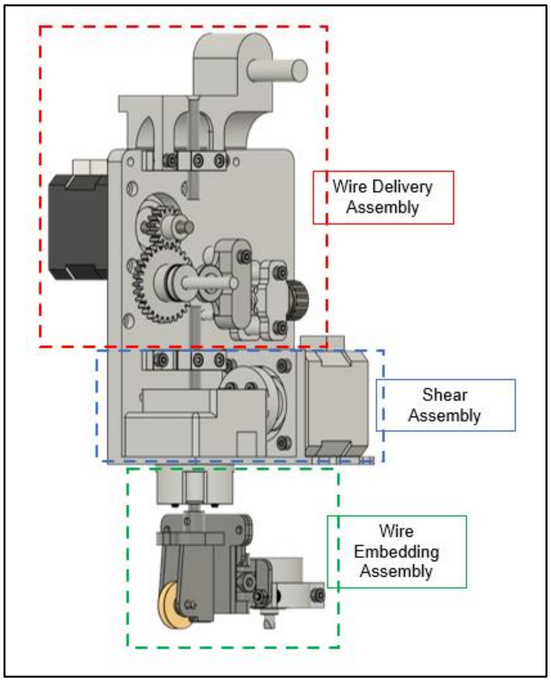


Figure 5. CAD model of wire embedding tool

The shear assembly was designed around two tungsten carbide blades, a linear external stepper motor, and a custom coupling mechanism. One of the blades was stationary while the other was attached to the Nema-17 external stepper motor. This was achieved through the use of a custom 3D printed platform and a coupling mechanism. These components combined allowed for a force of approximately 120 N to be applied to shear the wire. The cutting mechanism was bolted to the chassis using an adaptor plate which was also 3D printed to spec. This mechanism was responsible for shearing the wire once the embedding of the wire had been completed.

The wire embedding assembly consisted of a frame designed to mount the wire embedding wheel, and DCM applicator mount with adjustable offset height. The embedding assembly was attached to the tool chassis using a shaft through a dual bearing pillow block, allowing for 360-degree motion. The hollow shaft served as a wire guide, allowing the wire to be fed toward the brass embedding wheel in a tangential manner. Additionally, a custom bracket with a single threaded hole allowed for the DCM reservoir and applicator to be mounted. The total weight of the wire embedding tool prototype once all of the subassemblies had been mounted was found to be approximately 710 g, while the original Sovol SV04 thermoplastic extruder was 480 grams.

2.4 Integrated wire embedding tool trials

Preliminary integrated embedding tool trials consisted of three objectives. The first objective was to evaluate how the Sovol SV04 printer firmware responded to the integration of the embedding tool. The second was to execute the auto home command to confirm the z-offset probe would function in its mounted position on the embedding tool. The final objective was to run wire embedding tests to assess the wire delivery assembly, z-offset relative to thermoplastic test samples, DCM applicator, and wire embedding wheel. The open-source Marlin based firmware used by the Sovol SV04, made it possible to develop custom g-code commands to support the integrated wire embedding trials.

Preliminary wire embedding trials used ABS specimens (127mm x 25 mm x 2 mm) printed using the settings in **Table 2**. 100% infill was selected as a baseline, with other infill levels to be tested in subsequent trials.

Table 2. Integrated tool thermoplastic test sample parameters.

Filament material	Nozzle diameter (mm)	Print temp. (°C)	Bed temp (°C)	Infill density (%)	Raster orientation (°C)	Infill pattern
ABS	0.5	255	100	100	0	Line

Each integrated embedding trial consisted of running a custom g-code program to have the tool move over the specimen with the embedding wheel and DCM applicator in contact with the ABS sample surface. As the gantry of the 3D printer moved the tool longitudinally over the sample, DCM was applied to the surface followed by the brass wheel with the wire feeding under to be pressed into the sample surface.

2.5 Analysis

A preliminary analysis was conducted to select the appropriate stepper motor for the wire shearing assembly. Starting with the wire shearing mechanism, the selection of the stepper motor was based on the maximum shear force, V_{max}, required to successfully cut the 26-gauge nichrome wire. The analytical calculation utilized the Maximum Shear Stress (MSS) theory equation [11] (seen in **Equation 1**), to first determine the τ_{max} value of the nichrome wire (which is the maximum shear stress value) used to compute the maximum required shear force.

$$\tau_{max} = \frac{S_{ut}}{2n} \tag{1}$$

Where S_{ut} is the tensile strength (approximated to be 781 MPa [12]), and n is the factor of safety, taken to be 1 due to the desired outcome of fracture.

The shear force could then be computed using the standard shear equation:

$$\tau_{max} = \frac{V_{max}Q}{It} \tag{2}$$

Combining **Equation 1** and **Equation 2**, the expression to compute the shear force can be seen in **Equation 3**:

$$V_{max} = \frac{3\tau_{max}A_c}{4} \tag{3}$$

where A_c is the cross-sectional area of the 26-gauge wire. The maximum shear force required to shear the wire was computed to be 37 N.

To meet the theoretical force requirement, a secondary Nema 17 stepper motor was utilized, however the difference was that this motor was a captive stepper motor which rotated a 34 mm long Tr8x8 power screw instead of a smooth shaft. The power screw was responsible for the translation motion of the tungsten-carbide blade to cut the wire. Based on the manufacturer specifications of the Nema-17 external stepper motor (supplier: "oyostepper"), the maximum torque delivered by the stepper motor was computed to be 0.366 J. Based on the previous calculations regarding the shear force required for 26-gauge nichrome wire, the selected Nema-17 external stepper motor needed to apply at least 60 N of linear force. Since the selected external stepper motor utilized a 34 mm long power screw to convert angular motion into linear motion, the torque output by the power screw was computed using the power screw specifications provided by the manufacturer, seen in **Table 3**.

Table 3. Power screw specifications according to the manufacturer (oyostepper)

Body Length (mm)	Lead/Revolution (mm)	Lead/Step (mm)	Number of Leads	Screw Type
34	8	0.04	4	ACME

The expression seen in **Equation 4** [11] was used to compute the torque required to actuate the blade,

$$T_R = \frac{F d_m}{2}\left(\frac{l + \pi f d_m}{\pi d_m - f l}\right) \tag{4}$$

where F is the theoretical shear force previously calculated to be 60 N, d_m mm which is the power screw mean diameter, l=8 mm which is the lead/revolution, and f is the friction coefficient between the male and female interface. The friction coefficient was selected to meet the self-locking condition, where $f > \frac{l}{\pi d_m}$ [11]. Therefore, any value greater than 0.364 for the friction coefficient was deemed acceptable. Once all the variables were substituted into **Equation 4**, the torque needed to successfully shear the wire was 0.176 J. Since the torque needed to shear the wire was less than the maximum amount of torque that the captive Nema 17 motor was able to deliver (0.366 J), the use of this particular stepper motor was justified. Although, the calculation yielded theoretical values, additional iterative calculations were performed using **Equation 4** to determine the maximum force that the power screw can transfer to the shear blade. The value of maximum force was approximately 120 N.

3. RESULTS AND DISCUSSION

3.1. Test stand wire feeding and embedding

Wire embedding trials were first conducted using the proof-of-concept test stand to observe and improve the movement of the wire through the feed assembly. While also studying the feasibility of using a wire embedding wheel to press the wire into a thermoplastic substrate. **Figure 6** demonstrates a DCM-treated ABS test sample being pushed under the wire embedding wheel as the nichrome wire was fed through and pressed into the sample.

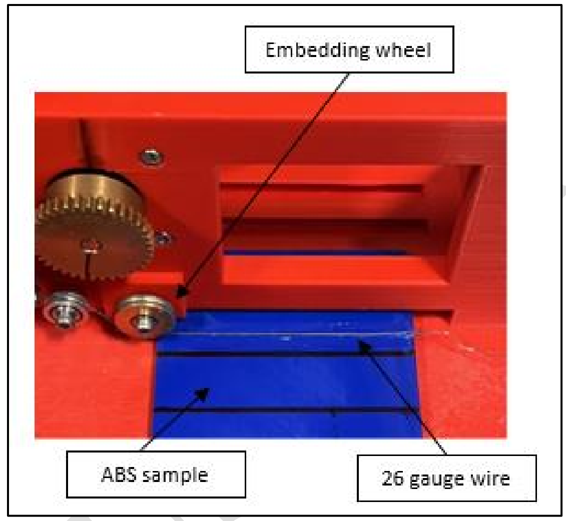


Figure 6. Test stand ABS wire embedding trial.

A subsequent trial using a 26-gauge wire with ABS specimen was allowed to sit undisturbed until the DCM evaporated resulting in embedding of the wire into the thermoplastic substrate as shown in **Figure 7.**

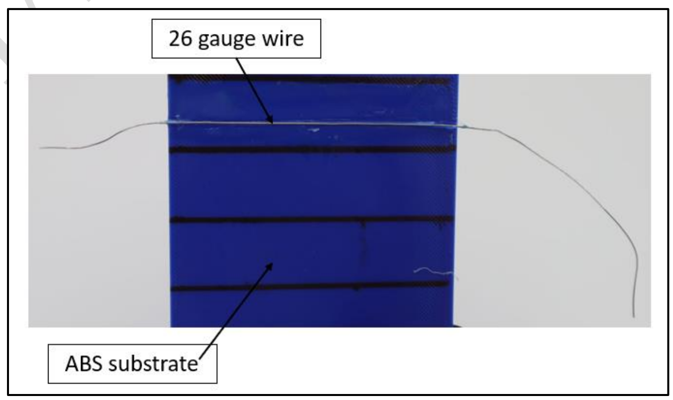


Figure 7. 26-gauge Nichrome wire embedded into ABS specimen.

3.2 Mounted wire embedding tool initial trials

Once the tool was mounted on the Sovol SV04 3D printer, a custom g-code toolpath was generated to test the wire embedding process. Since the right extruder responsible for the thermoplastic extrusion was not functional due to the difference in z-offset between the two heads, a previously fabricated plastic sample was taped onto the bed. The g-code commands consisted of the tool laying a single line of wire longitudinal to the polymer substrate. **Figure 8** showcases the tool while in operation with proper labeling.

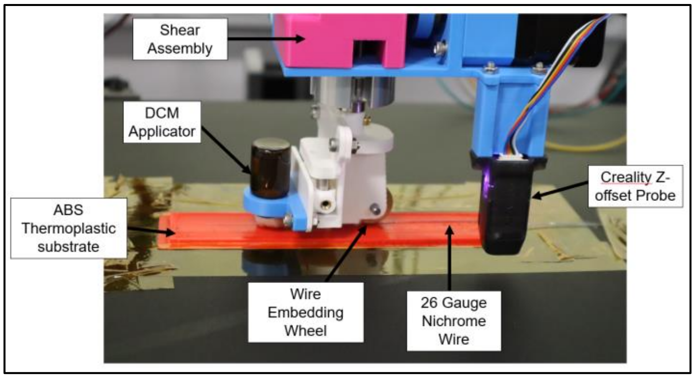


Figure 8. Wire embedding tool testing.

From the test trial initially performed the embedding process was attained. The resulting sample after completing the first test trial can be observed in **Figure 9**.

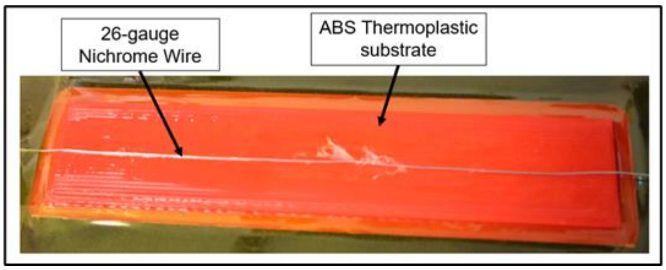


Figure 9. Initial test trial outcome.

4. CONCLUSION

In this paper, a tool development effort is presented. The in-lab developed tool is capable of embedding Nichrome wire into the 3D printed plastic substrate under non-polar solvent. As part of the tool development effort, the outcome such as wire embedding capability was demonstrated by submersing the wire within the printed substrate. Additionally, the tool was designed to be co-mounted to an independent dual extrusion, IDEX, 3D printer (Solvo SV04) commercially available allowing for thermoplastic extrusion and wire embedding. This technology will ultimately introduce a new and innovative wire embedding technique, which can potentially provide a similar bonding between the wire and the polymer compared to alternative methods that are currently available.

Future investigation will ensure the proper z-offset between the tool and the nozzle so the polymer extrusion and the wire embedding can be performed as a single operation. Additionally, experiments will be conducted to determine the ideal dispensing volume of solvent required to prepare the surface of various thermoplastics such as ABS, ASA, and PLA for wire embedding.

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