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MATERIAL EXTRUSION ADDITIVE MANUFACTURING MOLDS FOR THERMOSET COMPOSITES

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Abstract

In the composite manufacturing industry, production tooling commonly requires preheating for molding. The most commonly used method for preheating is indirect heating, in which heat is transferred from heat sources to the materials by convection and radiation. However, in the case of direct heating, in which heat is generated directly within a material by passing an electric current through it, the tools are preheated through joule heating. In this project, we manufactured a self-heating mold for direct heating. The manufacturing process involves 3D printing self-heating tooling, in which resistive wires are embedded into the tool at every so number of layers using a programmed 3D printer. Thermal characterizations were performed on the self-heating tool and a thermoset composite layup process was performed to study the suitability of the mold.

1. Introduction

In the composite manufacturing industry, the preheating of production tooling is a critical step to ensure proper curing and enhanced mechanical properties of the final composite product. Traditionally, this preheating is achieved through indirect heating methods, such as convection and radiation, where heat is transferred from external sources to the mold material [1]. While effective, these methods often suffer from inefficiencies and uneven temperature distributions, leading to potential inconsistencies in the composite structure [2, 3].

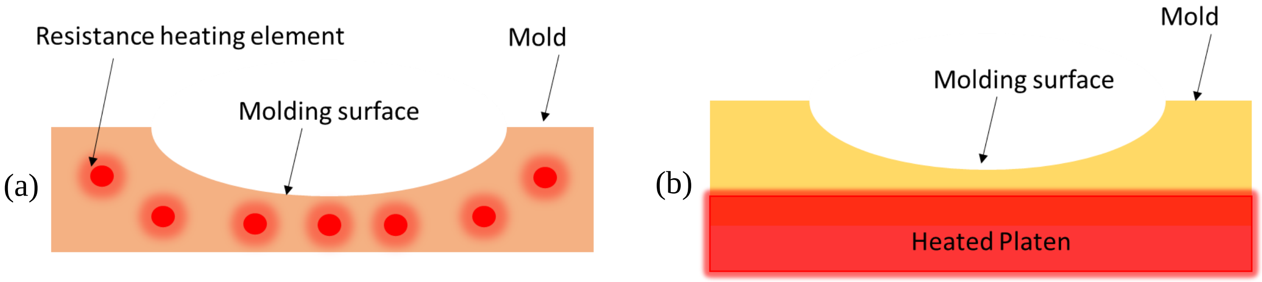

Figure 1: Method of direct and indirect heating of composite molds (a) direct heating of mold with embedded resistance heating elements and (b) indirect heating of mold using heated platen.

Direct heating, specifically through joule heating, presents a promising alternative. In direct heating, heat is generated within the material itself by passing an electric current through it, resulting in more uniform and efficient temperature control. This method can significantly reduce energy consumption and improve the heating precision of the molds used in composite manufacturing. As an example, self-heating mold was developed at Oak Ridge National Laboratory to study the effectiveness in out-of-oven autoclave molding process [4]. The results showed the potential to replace the traditionally manufactured composite molds for the thermoset based fiber reinforced composite structures manufacturing.

The advent of material extrusion additive manufacturing (AM), commonly known as 3D printing, has revolutionized the production of complex and customized tooling. 3D printing allows for the precise fabrication of molds with embedded functionalities, such as heating elements, directly integrated into the structure. This study leverages the capabilities of 3D printing to develop a self-heating mold for thermoset composites. By embedding resistive wires into the mold during the printing process, we aim to achieve efficient and uniform preheating through direct joule heating.

The manufacturing process involves using a programmed 3D printer equipped with a custom-built tool for embedding resistive wires at specified layers. This "pause and embed" technique ensures that the wires are accurately positioned and securely integrated within the mold structure. Similar research of conductive wire embedded within 3D printed substrate has been reported in many applications including sensors, electrical circuits, and induction coils [5-7]. The chosen resistive wire material, nichrome, is known for its high electrical resistance and thermal stability, making it an ideal candidate for this application.

Thermal characterizations were performed on the fabricated self-heating mold to assess its heating efficiency and temperature uniformity. Additionally, a thermoset composite layup process was conducted using the self-heating mold to evaluate its suitability for composite manufacturing. This involved curing the thermoset composite within the mold and analyzing the resulting composite's quality and mechanical properties. This research aims to demonstrate the feasibility and benefits of using 3D printed self-heating molds in the composite manufacturing industry. By integrating direct heating capabilities into the mold design, this approach has the potential to enhance the efficiency, consistency, and overall quality of composite production processes. The findings from this study could pave the way for broader adoption of advanced manufacturing techniques in various industrial applications.

2. Methodology

2.1 Materials and Equipment

To fabricate the self-heating mold, we used a Desktop Scale Sovol 3D printer. A custom-made wire delivery tool was developed. Table 1 below gives an inventory of all items used in this research. This table lists each material and piece of equipment used along with its specifications and purpose.

Table 1: Materials and Equipment Table

Equipment's	Specifications	Purpose
PLA (Polylactic Acid)	Prusa Polymers	Manufacturing of plastic composite tooling

Resistive Wire	Master Wire Supply 26g 100’ Nichrome 80 Wire	Allows for the flow of electrical current and the generation of heat
DCM (Methylene Chloride)	Uniclean America	Promotes adhesion of resistive wire to thermoplastic
Thermal Tape	Polyimide Hi-Temp Masking Temp	Protects from high- and low-temperatures
Mini Ball Valve	¼" 316 PN63	Regulates the flow of DCM into the brush applicator
Brush Applicator	Brush Tip 21 Guage Round Nylon 5mm	Applies DCM to thermoplastic

Figure 2 illustrates the components of the custom-made wire embedding tool, providing a detailed description of its structure and functionality. This diagram provides a reference for understanding the tool’s overall design. The detail design and working principle of the tool can be found in [8].

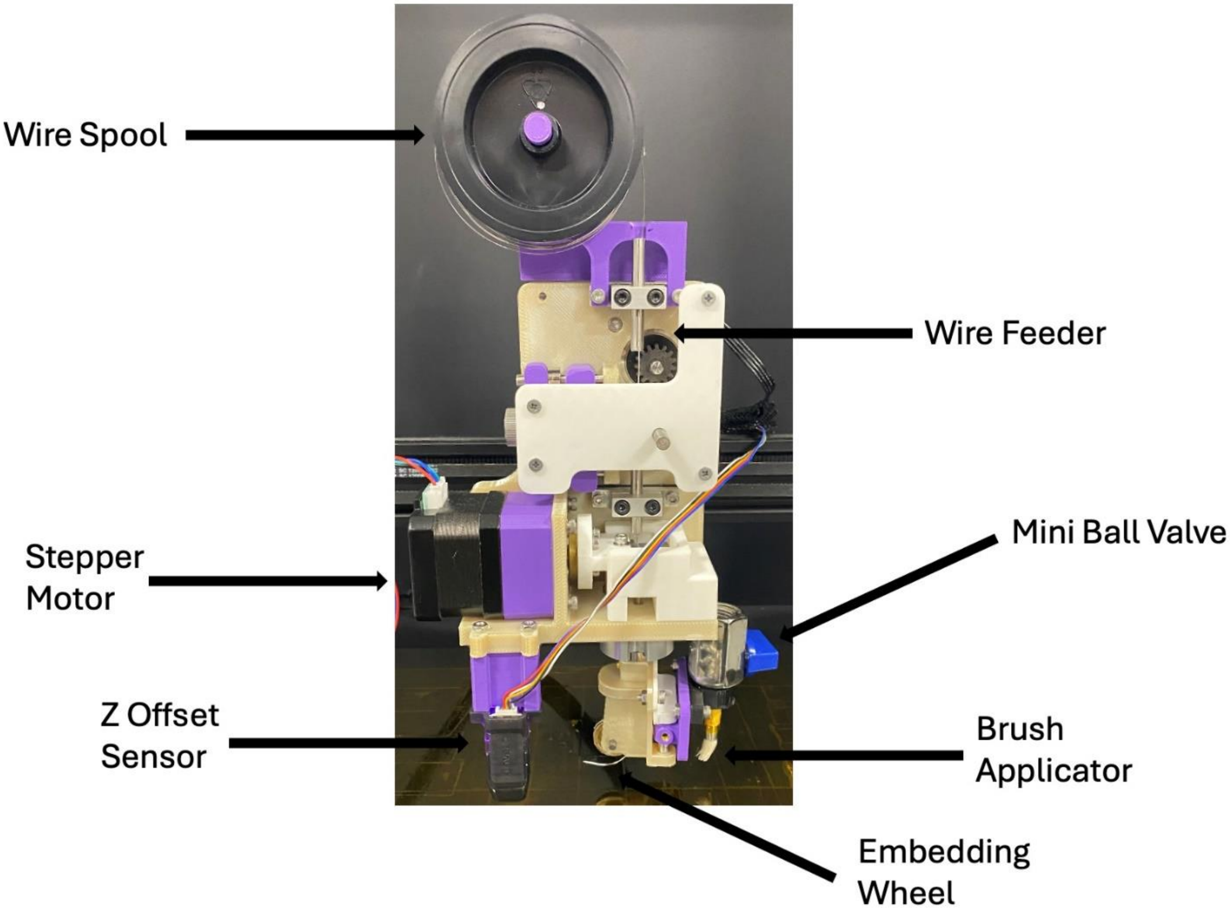

Figure 2: Components of the wire embedding tool developed in-house and mounted to a desktop 3D printer Solvol [8].

2.2 3D Printing Process of self-heating mold

To begin the 3D printing process of the thermoplastic specimens, the Sovol 3D printer was calibrated using the auto-home function. After calibration, a brim was printed to ensure bed adhesion. During this phase, minor adjustments were made to the z-axis to fine-tune the nozzle height. Once the brim was completed, the thermoplastic specimen printing began as shown in figure 3(a) . Continuous monitoring was carried out to ensure consistent layer formation across the specimens. After 35 layers (7.25 mm), the process was paused, and the g-code was modified to integrate the wire embedding process. A 26-gauge Nichrome wire was secured onto the surface of the specimen using Kapton tape to prevent movement.

Dichloromethane (DCM) was primed into the left extruder and applied to soften the surface, facilitating wire integration as shown in figure 3 (a) and (b). The wire was then embedded using the left nozzle of the 3D printer, which compressed the wire into the softened thermoplastic until fully embedded. The process was visually inspected, and additional manual compression was applied where needed to ensure the wire was flush with the specimen's surface. Once embedded, the excess wire was trimmed, and the ends were secured with thermal tape. The right nozzle resumed printing the remaining layers, covering the embedded wire. Throughout the process, the z-axis adjustments were monitored to ensure proper coverage and printing quality. After the final layer was printed, the specimen underwent visual inspection and was carefully removed from the build plate.

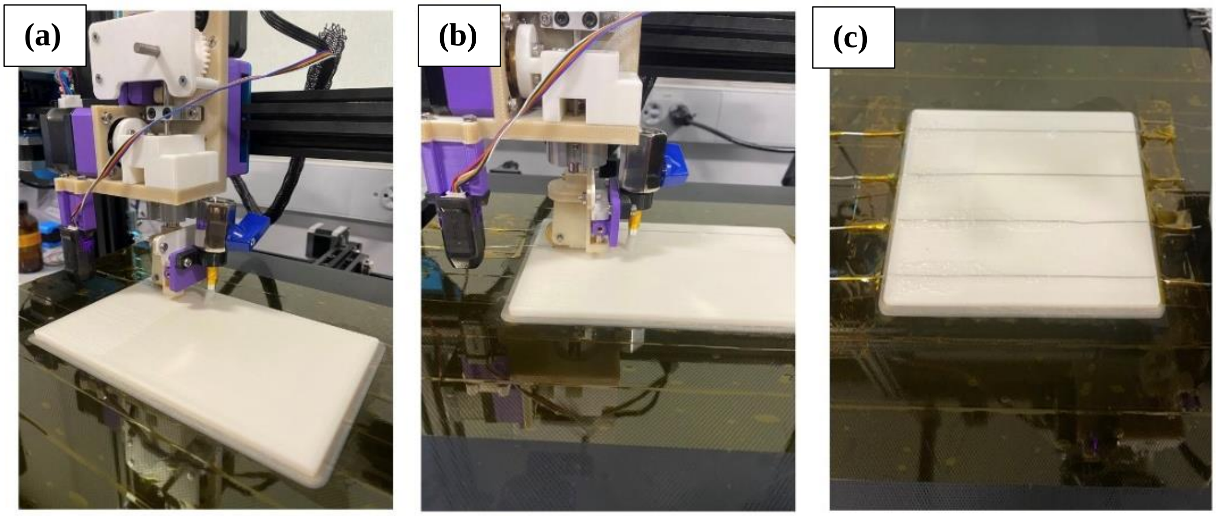

Figure 3: Step-by-step 3D printing and wire embedding process for the self-heating mold: (a)after printing the substrate part, the deposition of DCM onto 3D printed PLA was performed using solvent dispenser (b) simultaneous wire embedding was performed on the swelled substrate, (c) completed the self-heating mold manufacturing with wire embedding process.

3. Thermal Characterization

A thermal characterization of the self-heating mold was performed to measure its thermal performance such as temperature distribution and temperature profile over the molding surface. During the test, a Naweisz NP3005 power supply was connected to the nichrome wires to form a complete circuit with the mold. Two k-type thermocouples were placed on the bottom of the mold with one directly below a wire and one in between two wires. The mold was heated to test the thermal properties of the mold. The four (4) wires were all tied together to form a parallel connection, each wire had the same resistance since the length was constant. In each wire an equal amount of 1.25 V was supplied from the power supply. A FLIR A70 series IR camera was set up to collect a top-down view of the test. The test was performed at room temperature, around 25 °C, and lasted over the course of one hour. The power supply stayed at a constant 5 V for the test and had an initial current of 2 A for the first 10 minutes, so as not to thermal-shock the mold and a final current was 4 A.s

4. Results and Discussion

4.1 Thermal Performance of the Mold

Heat distribution was measured and compared by logging the data from the thermocouple and IR camera. Thermocouple T1 was placed in between wires 3 and 4, and thermocouple T2 was placed directly under the wire 4 was located. Both T1 and T2 thermocouples were place at the bottom of the mold or opposite surface to the mold surface.

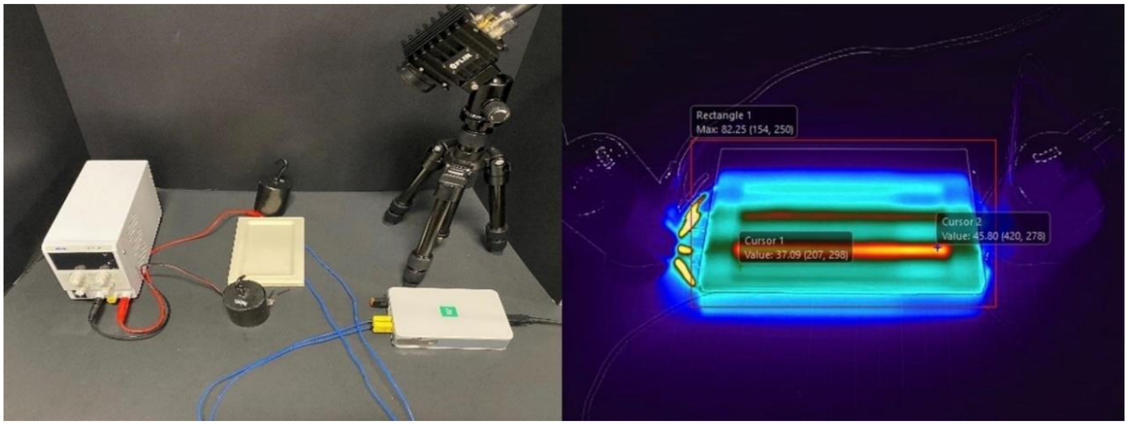

Figure 4. Experimental setup of self-heating mold for thermal characterization

As shown in Figure 5, T1 had a relatively slower ramp of heating and stayed at room temperature until around 8 minutes during the test. After that time period, a gradual climb to a final resting temperature of 32°C was reached. T2 on the other hand had a more notable rise of temperature to 30°C during the initial ramp up phase of 2 amps. After the initial ramp, the final steady temperature state of 37°C was reached at the final current of 4 A.

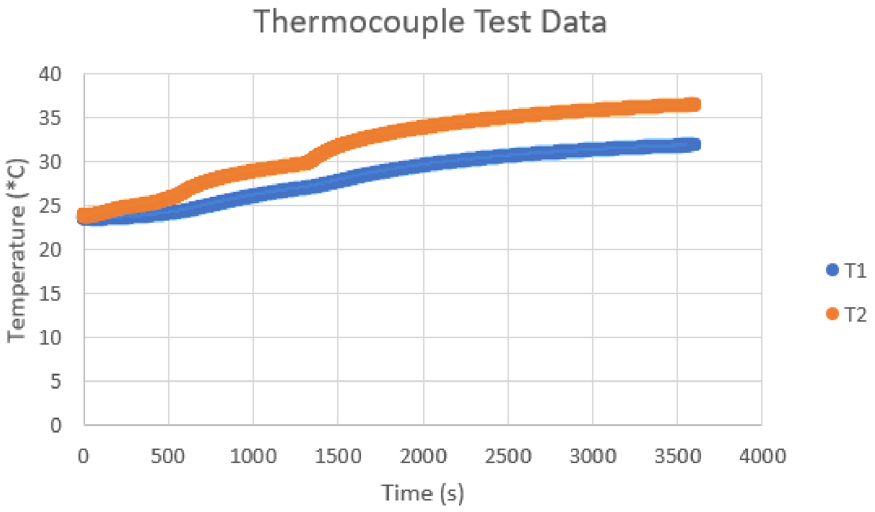

Figure 5: Thermal characterization and calibration of the thermocouple data for the mold testing

For the heat distribution on the top of the mold, the thermal IR camera recorded the temperature distribution in each of the four wires heated throughout the test. As shown in figure 6, wire 1 and wire 4 which were closer to the outside and a thicker layer of PLA material to heat caused both of those wires to only heat to a steady state temperature of 37°C. The inside or embedded wires 2 and 3 had relatively less PLA above them. Thus, both wires were able to heat the surrounding material relatively faster and more effectively which lead to reach the steady temperature of 46°C.

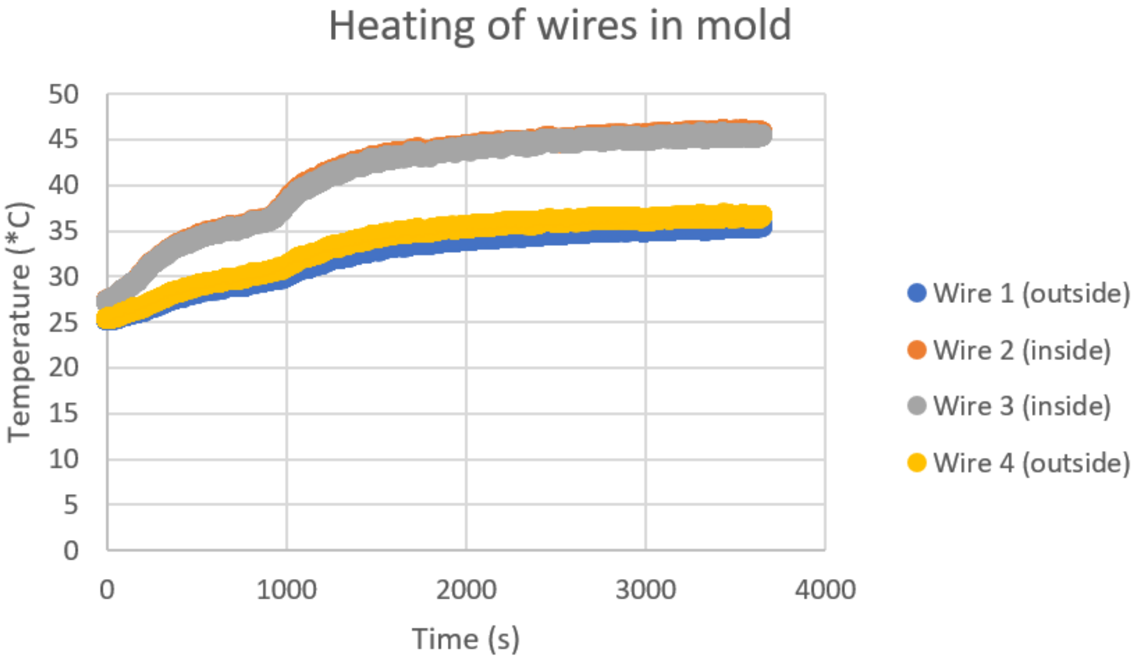

Figure 6: Temperature distribution over the wires and PLA substrate

4.2 **Composite mold comparison with CAD model.**

The composite mold was scanned using an Einscan Pro 2X 3D scanner, with the scan data exported as an STL file and analyzed in Autodesk Recap Photo. The comparison tool was used to align the 3D scan with the original CAD model, setting a tolerance of ±0.217 mm and a comparison range of ±2.166 mm, as recommended by the software. The comparison showed that the interior face of the mold generally conformed to the CAD design, but deviations were observed at the outer edges. Swelling of up to +0.650 mm was detected on the interior mold face, while the outer edges displayed a reduction of approximately -0.650 mm. These variations in surface geometry were likely the result of warping during the 3D printing process, caused by temperature-induced filament contraction. As a result, composite layups using the mold may exhibit similar topographical variations, reflecting the deviation from the original design.

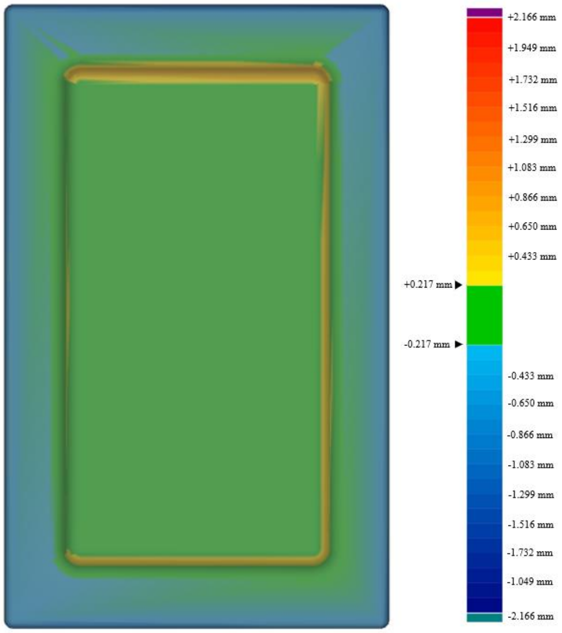

Figure 8: Difference analysis between the composite mold CAD model and 3D scan of the manufactured composite mold using Autodesk ReCap Photo.

5. Conclusion

In this research, we successfully demonstrated the fabrication of the self-heating mold using a custom-made tool integrated with a desktop scale 3D printer. The thermal test of the self-heating mold depicted that uniform temperature distribution across the mold surface. However, a marginal temperature differences were noticed between the heating wires that are embedded at the middle of the mold. Higher the thickness of the mold i.e. the higher thickness of the PLA substrate around wire dissipated more heat compared to the area of the mold that has lower thickness. The advantage of direct heating of mold in composite manufacturing is the control of spatial temperature distribution and overall heating process. Three-dimensional scanning characterization revealed the deformation zone on the fabricated mold by comparing an ideal part such as CAD. It was found that there was a nominal variation of ± 0. 650 mm throughout the inner and outer surfaces of the mold. Overall, this research paper demonstrated the potential of the manufacturing process.

However, for it to be adopted in large-scale composite production, further characterization at higher temperatures and with various thermoplastic materials needs to be explored.

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