HYBRID ADDITIVE AND SUBTRACTIVE MANUFACTURING OF DIRECT-HEATED TOOLING

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Abstract

Pre-heating is a common requirement for production tooling in applications such as compression and injection molding. While the carbon fiber reinforcements commonly used in large-area additive manufacturing improve the thermal conductivity of polymers, they are still far below that of metal tooling. This study presents a method for direct, local Joule heating of tooling without the need for additional heating elements. A current is induced in the composite tooling, resulting in resistance heating of the substrate. High conductivity material is locally embedded to achieve local control over the heating characteristics. Embedding of the conductive material is accomplished by selectively switching material compositions during the printing process. Demonstration tooling is produced using hybrid additive and subtractive manufacturing using an AMBIT XTRUDE in a HAAS machining center and evaluated with thermal imaging. Direct heating of tooling expands the potential applications of additive manufacturing by overcoming the challenges of low thermal conductivity materials.

Introduction

Production tooling is a proven successful application of additive manufacturing (AM) for the reduction of manufacturing lead time [1]. Material Extrusion (MEX) on a large scale has shown the potential to produce substantial polymer tooling and has been applied for molding composites and compression molding [2]. Still, polymer tooling has faced limited adoption due to a few detrimental characteristics, one of which is low thermal conductivity compared to metal tooling. The thermal conductivity of the common AM materials, even with high carbon fiber loading, is still insufficient compared to traditional metal tooling [3]. The relatively low thermal conductivity makes the traditional approach of indirect heating tooling using embedded heating elements or cartridges a poor match for this material (Figure 1a). Therefore, there is an opportunity for alternative heating methods for polymer tooling.

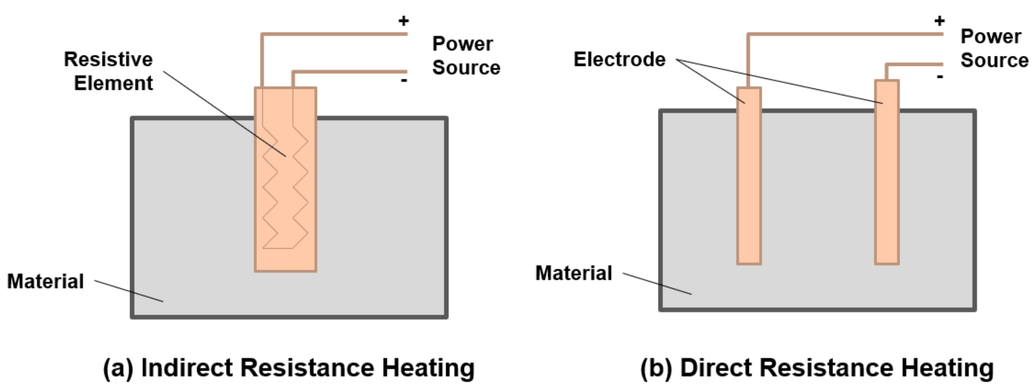


Figure 1. Primary methods of electrical resistance heating include a) indirect resistance heating and b) direct resistance heating.

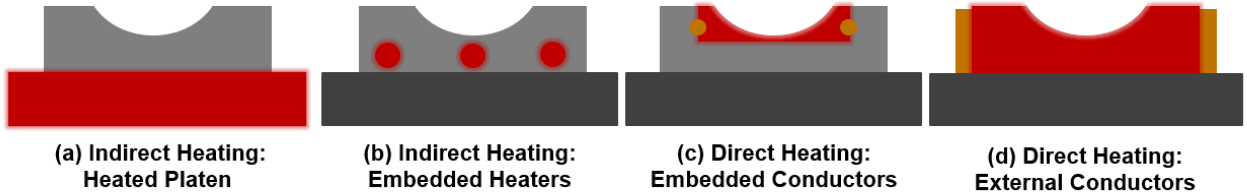


Figure 2. Compression mold heating approaches: a) indirect heating of a platen, b) indirect heating of tooling, c) proposed direct heating of tooling using embedded conductors, and d) proposed direct heating of tooling using external conductors.

Indirect heating of compression mold tooling is the leading approach, where cartridge heaters are used to heat a platen on which the compression mold is mounted (Figure 2a). However, this approach falls short when low thermal conductivity materials are used. To overcome this, researchers have attempted to move the indirect heating elements closer to the tooling surface (Figure 2b), where precise temperature control is most critical [4]. However, this can lead to hot spots and temperature gradients throughout the tooling. An alternative resistance heating approach is the direct heating of the tooling material (Figure 1b). While indirect resistance heating primarily relies on a resistive element to generate heat, it depends on the tooling material's thermal conductivity to spread that heat throughout the mold. On the other hand, direct heating relies on current flow through the material resulting in Joule heating [5]. Joule heating is more dependent on the resistivity of the material and less dependent on thermal conductivity. The carbon fiber content of polymer material can be used to tune the electrical conductivity [6], [7]. The ability to tune the electrical material properties of the tooling makes direct heating a possible approach to overcome the challenges of low thermal conductivity (Figure 2c). If local control over the tooling heating is not required, external conductors can be used for direct heating (Figure 2d).

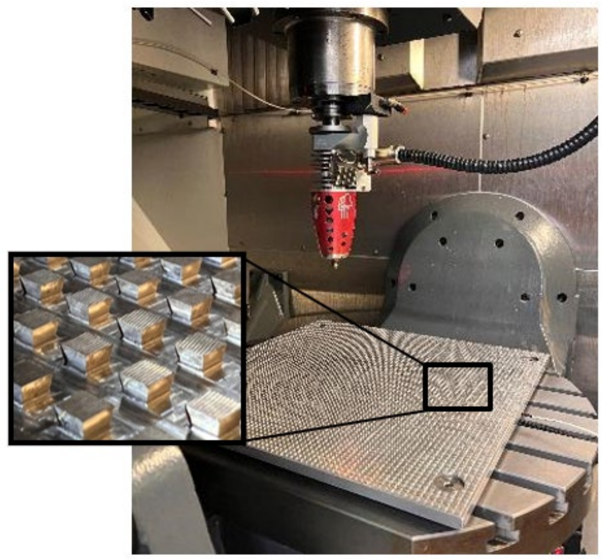


Figure 3. A Hybrid Manufacturing Technologies AMBIT XTRUDE installed in a HAAS 5-axis mill with custom print bed.

This study aims to determine if direct heating of polymer/CF tooling is a potential alternative to indirect heating. This objective will be achieved by: a) testing the ability to tune the electrical resistance of objects produced using MEX by adjusting the carbon fiber content and b) evaluating the heating characteristics of the objects when using a direct heating approach. A machining center with hybrid additive and subtractive manufacturing capabilities is used to produce test coupons consisting of different carbon fiber contents (Figure 3). Electrically conducting elements are embedded into these samples via 3D printing, to which a voltage is applied, resulting in direct heating. The successful demonstration of direct heating of carbon fiber composite tooling shows there is potential for alternative heating approaches for tooling produced using AM.

Methodology

To evaluate how carbon fiber content affects electrical properties, five samples (76 x 452 x 13 mm) were printed using different carbon fiber contents (0%, 5%, 10%, 15%, 20%) by blending the neat ABS and ABS/20% CF pellets (Figure 4). Pellets were weighed and manually blended before being fed into the single screw extrusion AMBIT XTRUDE (Hybrid Manufacturing Technologies, McKinney, TX, USA). The ORNL slicer (Oak Ridge National Lab, Oak Ridge, TN, USA) was used to conduct process planning for the additive process, and Mastercam was used for subtractive processes.

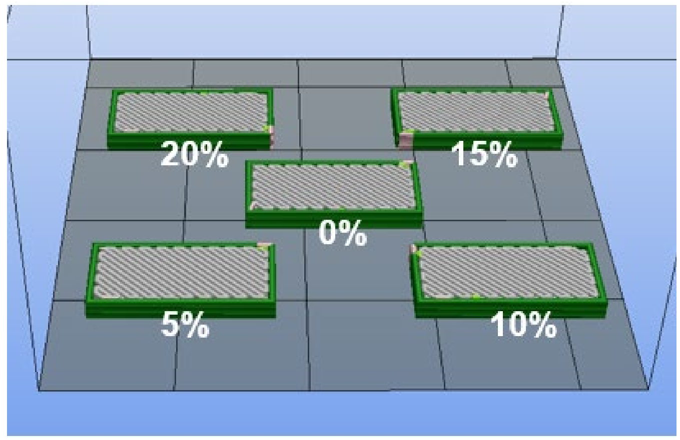


Figure 4. Process plan for printing test samples and the associated carbon fiber content.

The samples with ABS/20%CF conductors were produced in six steps. Then the sample was printed using the AMBIT XTRUDE, purging the material during material changes (Figure 5a). Once the sample cooled, it was machined on exposed faces, and two 3.2 mm deep grooves spaced 50mm apart were milled with a 20° dovetail tool to help lock the next layer of material in place (Figure 5b) [8]. The grooves were filled with ABS/20% CF (Figure 5c). Once cooled, the top surface was machined flat again, and two holes were drilled in the conductors (Figure 5d). Brass threaded inserts were installed in the holes using a soldering iron (Figure 5e). Ring terminals attached wires to the sample, connecting it to the power supply and multimeter (Figure 5f).

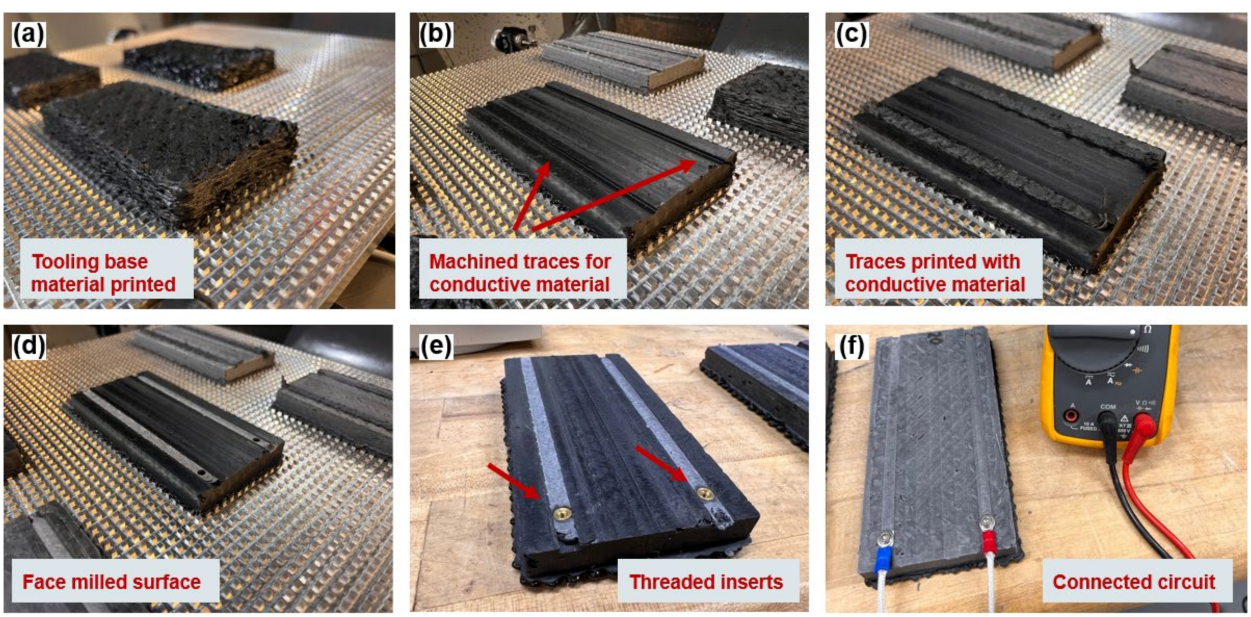


Figure 5. Sample production consisted of a) printing base material, b) machining slots for conductive traces, c) filling conductors via printing, d) surface machining of conductors, e) installing threaded inserts, and f) wiring into an electrical circuit.

After testing was completed on the samples with embedded ABS/20%CF conductors, the samples were flipped over, and the second set of grooves was cut using the 20° dovetail cutting tool. A 14-gauge solid copper wire was stripped and embedded into the groove, being retained temporarily in place through thermal staking (Figure 6). The grooves were filled with the ABS/20%CF polymer using the AMBIT XTRUDE, embedding the wires within the conductors. The ABS/20%CF polymer was used to fill the grooves on all samples produced, no matter the carbon fiber content of the base material. Instead of connecting these samples to the electrical circuit using a threaded insert, the exposed wires were connected using a lever nut splicing connector (WAGO GmbH, Minden, Germany). A complete summary of the test samples produced can be found in Table 1.

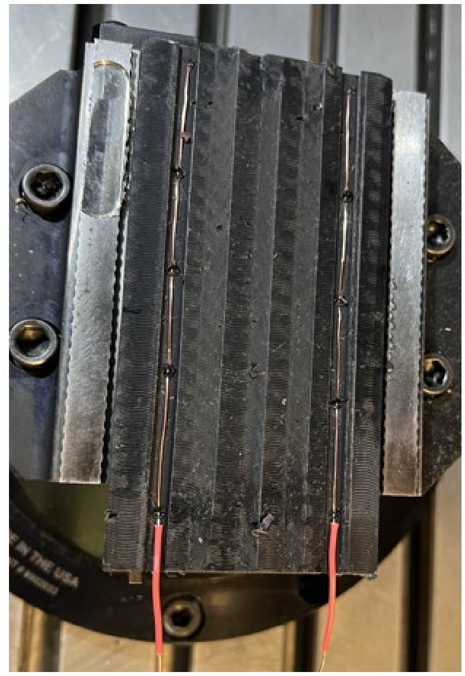


Figure 6. Embedding copper wires in the sample.

Before connecting the power supply, the resistance of the circuit was measured using a Fluke 115 digital multimeter (Fluke, Everett, WA, USA). The two-wire resistance method was used. This approach is acceptable for this preliminary study, but further work should be done to better characterize the materials' resistivity to better guide tooling systems, including integrated heating.

The circuit was connected to a Harrison 6284A DC power supply (Hewlett-Packard Company, Berkeley Heights, NJ, USA) set to output a measured 25V DC. The current output from the power supply was documented. The power supply had a current limiter set to 2.1A and would automatically adjust the voltage to maintain a constant current at the limit if the system exceeded that threshold. Ohm's law was used to calculate the heater's power output using the values measured. It should be noted that power output was calculated based on resistance and current at the start of the experiment and would be expected to shift with a temperature change.

Table 1. Summary of the test samples and experiments conducted.

Sample ID	Bulk Material	Conductor Material	25V DC	118V AC
A1	ABS / 0% CF	ABS / 20% CF	✓	-
A2	ABS / 5% CF	ABS / 20% CF	✓	✓
A3	ABS / 10% CF	ABS / 20% CF	✓	-
A4	ABS / 15% CF	ABS / 20% CF	✓	-
A5	ABS / 20% CF	ABS / 20% CF	✓	-
B1	ABS / 0% CF	Copper & ABS / 20% CF	✓	-
B2	ABS / 5% CF	Copper & ABS / 20% CF	✓	✓
B3	ABS / 10% CF	Copper & ABS / 20% CF	✓	-
B4	ABS / 15% CF	Copper & ABS / 20% CF	✓	-
B5	ABS / 20% CF	Copper & ABS / 20% CF	✓	-

Thermal imaging was used to measure the heating rate of the samples. The temperature at the center location and the peak temperature across the sample were monitored for a ten-minute duration using a FLIR T420bx thermal camera (FLIR Systems AB, Sweden). A video was captured throughout the duration of the experiment, with a still image captured at the ten-minute mark.

To evaluate the impact of a higher voltage heating system, the samples with a 5% carbon fiber content, samples A2 and B2, were also connected 118V AC power source (Table 1). Ohm's law was used to calculate the power output. The samples were monitored for ten minutes using the FLIR thermal camera.

Results and Discussion

Measurement of the sample resistance showed that as the carbon fiber content increased, the resistance in the sample dropped (Table 1). The samples produced from neat ABS, A1 and B1, both had resistance values greater than the multimeter could measure. The addition of a copper wire in the conductor groove, represented by sample group B, reduced resistance in all cases. The rapid drop in resistance moving from a 5% to 10% carbon fiber content suggests that the percolation threshold was reached, which aligns with expectations [6]. There has been considerable work completed in the modeling and experimental evaluation of the electrical and thermal conductivity of polymer materials with conductive fillers, which can help guide future efforts to tune in the appropriate resistance for tooling [7], [9].

Recorded current values from the power supply are documented in Table 1. Three samples reached the current limit, A5, B4, and B5. The system automatically drops the voltage to maintain this current limit. The measured resistance and current were used to calculate the power output for these samples (Table 1). These results suggest that if appropriately tuned, a heater could be designed to utilize the total power output of the power supply. The ability to heat the tooling more quickly would be driven by the available capacity of the power supply and not a limitation of the tooling material properties. This heating rate can outperform tooling using indirect heating, which has the rate of heating limited by the material thermal conductivity.

Table 2. Sample resistance and current measurements with associated power calculation.

Sample ID	Bulk Material	Conductor Material	Resistance (Ω)	Current (A) @ 25V DC	Power (W) @ 25V DC
A1	ABS / 0% CF	ABS / 20% CF	Over Limit	0.00	-
A2	ABS / 5% CF	ABS / 20% CF	2,836	0.02	1.1
A3	ABS / 10% CF	ABS / 20% CF	50	0.32	5.1
A4	ABS / 15% CF	ABS / 20% CF	23	0.60	8.3
A5	ABS / 20% CF	ABS / 20% CF	9	2.10*	39.7
B1	ABS / 0% CF	Copper & ABS / 20% CF	Over Limit	0.00	-
B2	ABS / 5% CF	Copper & ABS / 20% CF	2,364	0.02	0.9
B3	ABS / 10% CF	Copper & ABS / 20% CF	25	0.60	9.0
B4	ABS / 15% CF	Copper & ABS / 20% CF	9	2.10*	39.7
B5	ABS / 20% CF	Copper & ABS / 20% CF	5	2.10*	22.1

* Current Limit Reached

During thermal testing of samples A1-A5, a high heating concentration around the threaded inserts was observed (Figure 7). The localized heating near the terminals only occurred in the samples with the ABS/20%CF conductors. Applying Kirchhoff's Law would show that this is likely due to a voltage drop along our conductor due to the relatively high resistivity of the composite-filled polymer conductor. These samples experienced local heating to an extent where melting occurred in these locations. The melting prevented the ten-minute thermal imaging experiments from being completed on these samples.

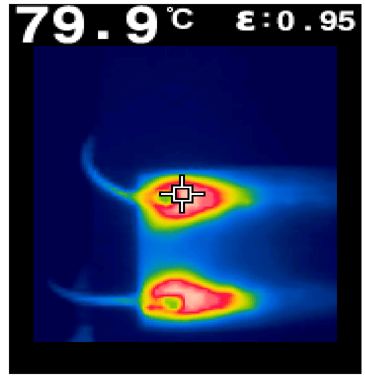


Figure 7. Thermal image of sample A5.

Samples B1-B5 presented less concentrated heating than the samples that did not contain the embedded copper conductor. Thermal images after ten minutes of heating show that samples B2, B3, and B4 did experience heating along the length where copper wire and ABS/20%CF are embedded in the part (Figure 8c-e). The upper left portion of the image shows the temperature at the center of the sample, while the value in the upper right reads the maximum temperature in the sample. As our calculated power output predicted, sample A1 did not exhibit any heating (Figure 8a). Sample B2 shows some signs of heating, which is generally well spread throughout the part but represents only a 2.5° C increase from the ambient lab environment of 25° C. The resistance in sample B2 is likely too high to result in substantial heating at 25V, which led to further testing of that sample at a higher voltage to determine if the distributed heating would remain with more heat generation resulting from the higher current flow.

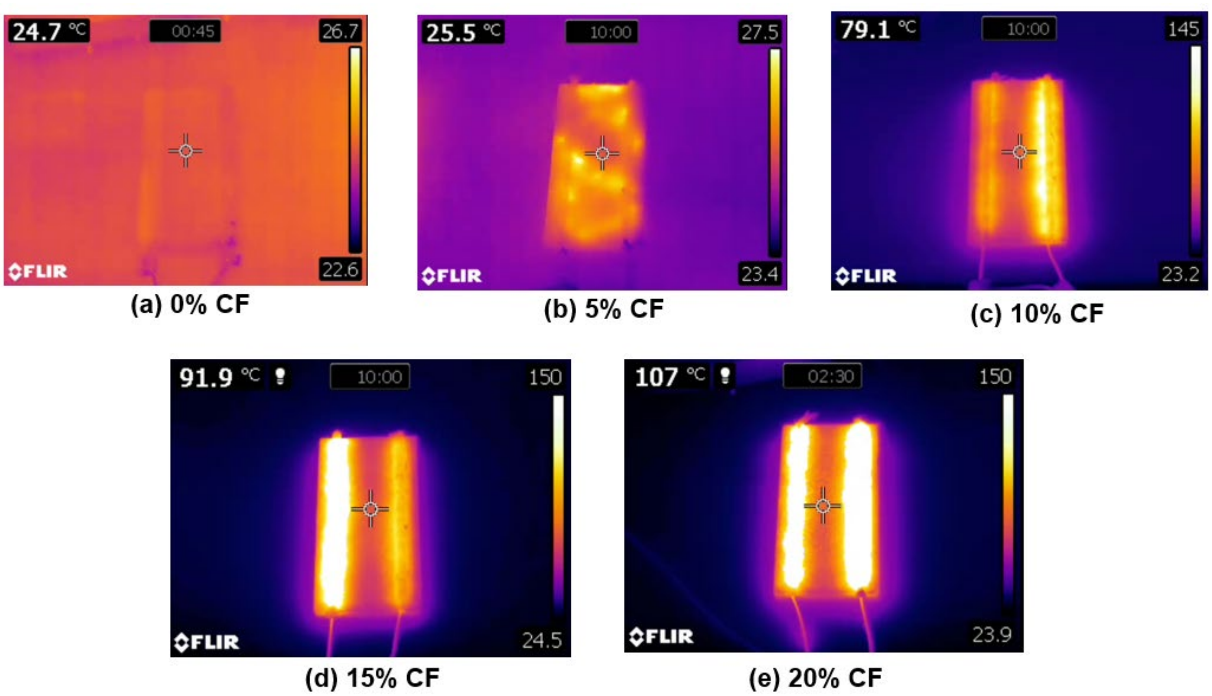
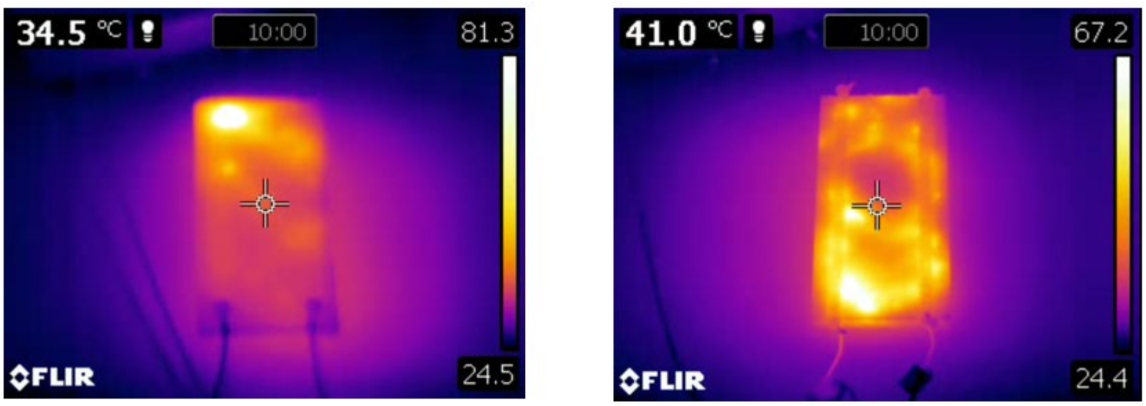


Figure 8. Thermal images of test samples after ten minutes of heating: a) sample B1 shows no heating, b) sample B2 shows signs of even heating, c) sample B3 shows concentrated heating, d) sample B4 shows concentrated heating, e) sample B5 shows concentrated heating.

A high voltage of 118V AC was connected to samples A2 and B2. Sample A2 shows concentrated heating, but this time it is at the opposite end of the sample from the conductors (Figure 9a). This suggests that while the conductor of sufficiently low resistivity, the bulk ABS/5%CF material may have experienced inconsistent blending. This is likely, due to the short single screw extrusion system used, and the simple blending of neat ABS and ABS/20%CF pellets. Sample B2 shows similar distributed heating as observed at 25V DC, but the temperature increase after the ten-minute heating period was much greater (Figure 9b). Sample B2 experienced a peak temperature increase of 42.2° C from the 25° ambient lab temperature at 118V Ac compared to only 2.5° C temperature increase at 25V DC. Importantly, the heating of samples A2 and B2 was achieved after only a ten minute period, compared to five hours to achieve similar temperatures when indirect heating was used to heat additively manufactured composite compression mold tooling [3]. While both samples A2 and B2 show some inconsistency in heating across the samples, they suggest that direct heating has potential if the carbon fibers can be distributed more evenly through the polymer matrix, and the fiber content can be tuned to the application.



(a) 5% CF Fill
Embedded ABS/20%CF

(b) 5% CF Fill
Embedded Copper Wire

Figure 9. Thermal image after ten minutes of heating for samples containing 5% carbon fiber by weight with a) ABS/20%CF conductor (A2), and b) copper wire and ABS/20%CF conductor (B2).

Conclusions

Direct heating of carbon fiber reinforced polymer tooling produced using a large-scale MEX was demonstrated as having potential as an alternative approach to the indirect heating method employed today. Small sections of composite tooling were printed with various carbon fiber contents and either an ABS/20%CF embedded conductor or an ABS/20%CF and copper wire conductor. Testing at lower voltages resulted in hot spots around the conducting regions, while higher voltages resulted in more even heating. While further work is required to implement direct heating on production tooling, the results demonstrate the potential for direct heating of AM tooling. A tremendous advantage of the proposed method is that we can avoid interrupting a printing process to have technician manually embed heating elements or conductive wires. There is even potential to eliminate the machining process for the conductive traces and simply leave a bead-width void wherever a conductive trace is needed and then switch materials in process. The only manual step would be to connect the circuit leads upon completion.

Additional work establishing the electrical materials properties of the polymers is needed. It is likely that insufficient blending occurred between the neat ABS and the ABS with 20% CF content within the short screw single screw extruder used in this study. Better could improve the consistency of heating within the samples. Direct measurement of the electrical material properties independent of the demonstration assembly would also help guide the design of different heating configurations. Different carbon fiber loading in the polymer will likely result in changes to the coefficient of thermal expansion, which could lead to delamination between the dissimilar material regions after thermal cycling. However, the application of functionally graded materials may provide a potential route to managing these stresses. In addition, a strategy for placing regions of the conductor, resistor, and insulator in the tooling will be needed to achieve the required heating safely. Current could potentially be applied across the entire tool if local heating control is not required, eliminating thermal gradients in the tool. Despite these challenges, direct heating can expand the applications of large-scale MEX into tooling applications where rapid heating and precise temperature control are required.

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