Effective thermal conductivity of 3D-printed continuous fiber polymer composites

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ABSTRACT

3D printing, especially fused filament fabrication, presents a potentially attractive manufacturing technique for thermal applications such as polymer heat exchangers due to the ability to create complex internal geometries which can be used to enhance convective heat transfer. Recently, commercial and modified open-source printers have utilized continuous fibers such as carbon fiber to create continuous fiber reinforced polymer composites (FRPCs) which enhance the mechanical properties of the printed products. This continuous filler network can also serve to improve thermal conductivity. In this study, the effective thermal conductivity of 3D-printed FRPCs is characterized using a steady-state, modified, guarded hot plate apparatus. The effect of the fiber direction and volume fraction on the effective thermal conductivity of the 3D-printed composites was characterized experimentally and modeled analytically using series and parallel models. Thermal conductivities of up to 2.97 W/mK were measured for samples in which the fibers were aligned with the direction of heat flow. Measured values were in good agreement with analytical model predictions. The importance of fiber conductivity on overall performance of the FRPCs was further demonstrated using a handlaid-up, pitch-based carbon fiber sample which exhibited an effective thermal conductivity of 23.6 W/mK.

GRAPHICAL ABSTRACT

KEYWORDS

Additive manufacturing; 3D-printed continuous fiber reinforced polymer composites; fused filament fabrication; thermal conductivity enhancement; heat exchangers

1. Introduction

Polymer heat exchangers have many advantages over metal heat exchangers, including lower weight, fouling resistance, corrosion resistance and ease of manufacturing [1]. As such, they are of significant interest for a range of applications, including HVAC and industrial waste heat recovery. However, when convective heat transfer coefficients are high, the
thermal resistance of conduction within the solid phase can become the limiting performance factor for these heat exchangers. Scheffler et al. [1] studied the effect of wall thickness of various types of polymers on the overall heat transfer coefficient and compared it with corrosion resistant metals for distillation applications. They showed that the overall heat transfer coefficient depends on the thermal conductivity as well as the thickness across which heat is transferred. The inherent thermal and mechanical properties of polymers often contradict the requirements for effective heat exchangers.

The thermal conductivity of the polymers used in these applications can be improved through the addition of high-conductivity filler materials to create composites and there exists a significant body of work about these emerging technologies [2]. For example, Raman et al. [3] used boron nitride (300 W/mK) as a ceramic thermal filler to improve the thermal conductivity of PPS, which resulted in thermal conductivities of up to 5 W/mK being achieved from a 0.26 W/mK resin matrix for a 60 percent filler volume fraction. For metal fillers, Boudenne et al. [4] used copper particles as a conductive filler in a polypropylene matrix to increase the effective thermal conductivity to almost 2.2 W/mK for 50 percent volume fraction. The literature shows that the most promising high thermal conductivity polymer matrix composites (PMCs) are those which incorporate carbon-based fillers, including carbon fibers, graphite, and graphene, due to their extremely high intrinsic thermal conductivities. Yu et al. [5] used graphite nanoplates with 25% volume fraction and were able to obtain a thermal conductivity of 6.44 W/mK.

The additive manufacturing (AM) of polymers and PMC components has many distinct advantages stemming from the ability to create complex geometries as a single part [6]. AM offers the creation of complex surface morphologies and internal geometries and structures with unprecedented surface area-to-volume ratios, potentially allowing for a new generation of novel heat exchanger technologies. Among AM techniques, fused filament fabrication (FFF) is one of the more popular polymer AM techniques due to widespread adoption of low-cost, open-source hardware and software. Very recently, significant research has focused on developing PMCs and nanocomposites specifically for FFF feedstock [7,8] with several commercial filaments recently available from suppliers such as SainSmart, ROBO 3D, and Proto-pasta [9]. So far, studies have focused primarily on the mechanical properties of AM [10–13]. Despite using highly conductive fillers (including copper, aluminum, silver, graphite, and chopped carbon fiber) and significant fill ratio, the best commercially available FFF composite feedstocks still offer limited effective thermal conductivity [9, 14, 15].

One method of addressing the shortcomings of typical discontinuous FFFPMC feedstocks is by printing continuous fibers of higher conductivity material within the polymer matrix. Continuous fiber printing is a promising technique of producing composites because it makes use of both printing and continuous network advantages. Tian et al. [16, 17] investigated the mechanical properties of continuous carbon fiber composite components printed at different temperatures, layer heights, and feed rates utilizing a modification made on their printer which also supported recycling of printed samples for subsequent reuse in the printer. Li et al. [18] fed a continuous carbon fiber tow with a 1.75 mm polyactic acid (PLA) filament and used a chemical treatment process to ensure good adhesion between the fiber and the matrix. Again, this was to study the mechanical behavior of the printed parts which is similar to the results presented in [19]. Vaneker fabricated their own continuous fiber filament using a pultrusion mechanism and used it to print mechanically testable samples [19]. Melenka et al. developed a model to predict the elastic constants of continuous Kevlar fiber-nylon composite, printed using the commercially available Markforged MarkOne printer [20]. Dickson used the same printer to investigate the behavior of carbon, glass, and Kevlar fibers [21]. Continuous carbon nanotube yarn was also employed as a filler inside a polymer filament and characterized mechanically and electrically by Gardner et al. [22]. Ibrahim et al. printed continuous wire polymer composites using a modified printer and characterized a range of mechanical properties in [23, 24]. Thus, while there has been significant study of the mechanical properties of the 3D-printed continuous fiber polymer composites (FRPCs), thermal transport properties of the printed composites have, until now, remained unexplored [25].

With AM of FRPCs, the effective thermal conductivity limitations resulting from the discontinuous point-to-point contacts of particle-laden PCs is removed. Furthermore, the inherent alignment of the conductive fibers in the printing direction can facilitate control over the directionality of heat flow through the printed composites. Therefore, the objective of this study is to experimentally characterize the thermal performance of 3D-printed continuous carbon fiber composites. Their effective thermal conductivity is quantified as a function of fiber volume fraction and build orientation (which dictates fiber orientation). The results are also
compared to established models for effective thermal conductivity to gauge the applicability of these models to AM FRPCs and gain insight into the effect of design factors including fiber conductivity and volume fraction on the effective thermal conductivity of the 3D-printed composites.

2. Methodology

2.1. Fabrication and design of FRPC samples

The commercially available Markforged MarkOne FFF 3D printer was used to print the samples employed here to investigate the effective thermal conductivity of continuous fiber reinforced polymer composites (FRPCs). This printer utilizes a dual nozzle extruding technique, where one nozzle extrudes the polymer (nylon) and the other extrudes different types of fibers. The closed-source printer is intended for use with specific types of proprietary fibers such as carbon fiber, glass fiber, and Kevlar which are associated with the printer. For the objectives of the present study, carbon fiber was used because it has the highest thermal conductivity of the available fibers provided by Markforged. Nylon was used as the polymer matrix for these samples because of its transparent color which helps to differentiate between the matrix and the fibers under the microscope.

To characterize the effective thermal conductivity of the FRPCs printed by the MarkOne, samples were printed with different fiber volume fractions and fiber directions. Two main fiber-polymer configurations were utilized in this study and are shown in Figure 1. These two configurations were selected to investigate the fiber orientation effect on the effective thermal conductivity of the composite. In the series configuration, the fibers were aligned perpendicular to the direction of heat flow as shown in Figure 1(a). In the second configuration, fibers were aligned in a direction parallel to the direction of heat flow through the sample (Figure 1(b)). Specimens with three different fiber volume fractions were fabricated for each configuration to characterize the effect of fiber volume fraction on the effective thermal conductivity.

The sample geometry was defined using CAD software and dimensions selected to fit the available measurement facility with a testing area of 40 x 40 mm. Thereafter, a generated STL file was uploaded to the proprietary, online-based slicing software (Eiger 1.2, Markforged, Somerville, MA) used for Markforged printers. Table 1 summarizes the printing parameters used to print the samples for the present study. Generally, the Eiger software avoids having exposed carbon fibers on the exteriors of the samples. As such, floor layers refer to the pure polymer layers which the printer lays down at the beginning of printing to ensure good bed adhesion while roof layers refer to the pure polymer deposited on the top surface of a part to ensure smooth surface finish. Wall layers refer to the polymer-only shell which encloses the part. The number of concentric fiber rings refers to the quantity of fiber rasters on the outer perimeter of a given later. Since we wish to investigate fiber orientation in only one direction for a given sample, this was set to zero. The slicer software provides information about the total number of fiber and nylon layers in the printed samples which can be used to estimate fiber volume fraction ($v_f$).

![Figure 1. (a) Specimen in flat build orientation resulting in fibers in series and (b) specimen in on-edge build orientation resulting in parallel samples. Fiber orientation with respect to heat flow direction and thermal conductivity notation is also indicated.](image-url)
Each layer of the samples can be defined individually as either fiber or polymer using the Eigersoftware. To evaluate the effect of fiber volume fraction on effective thermal conductivity, samples with a range of fiber volume fractions were fabricated by defining the number of fiber layers for each sample. Three different fiber volume fractions were fabricated for each type of configuration (or build orientation) as shown in Figure 1. The properties of resultant samples are summarized in Table 2 which shows the build orientation, outer dimensions, layer configuration as reported by the slicing software, and the corresponding fiber configuration with respect to the direction of heat flow. These layer configurations were used to ensure the fibers were distributed as evenly as possible in the z-direction given the constraints of the Eiger software. One pure nylon sample (Sample 4) was fabricated using the same printing parameters to quantify the baseline thermal conductivity of the pure polymer matrix.

It can be difficult for the MarkOne printer to print reinforced walls with small thicknesses when the fibers are aligned in the parallel direction (along the x-axis) as can be seen in Figure 2(a). As a result, the length of the fibers in the parallel configuration is less than the designed outer dimension. This may be caused by the movement of the printing head while the polymer within the printed fiber has not yet solidified. When a sample has a larger thickness and, subsequently, fiber length, the polymer within the fiber will have sufficient time to solidify before printing the next fiber line as noticed in the series fiber samples. The Eigertoolpath simulation for a cross-section of a parallel sample is shown in Figure 2(b). Here the regions of the regions of pure nylon wall layer (approximately 1.1 mm thick) are indicated.

### 2.2. Sample preparation and optical measurement

To prepare the samples for thermal conductivity measurements, the sample surfaces normal to the direction of heat flow were ground and polished using a Micro Star StarGrind 200-2V polishing machine. The nylon shell of the samples was removed using a 60-grit silicon carbide grinding disc to ensure that the fibers are in contact with the testing surfaces (i.e. the floor and roof layers for the series samples and the wall layers for the parallel samples). Two more stages of grinding were...
performed using 180-grit and 400-grit silicon carbide discs to further refine the surfaces. Finally, the samples were polished using the 1000/3000-grit polishing disc.

Subsequent to grinding and polishing, the sample thickness was measured at five different positions using a flat anvil micrometer and an average value was recorded for each sample. The cross-section area was measured using the sample length and width at different positions using Vernier calipers.

Because the number of fiber layers within the samples was used to evaluate the total fiber volume fraction in each sample, it was necessary to accurately measure the fiber percentage within the fiber filament itself. To quantify the real fiber volume fraction within the filament, optical microscopic images for the cross-section of the Markforged fiber filament were captured. The fiber filament comes pre-coated with a polymeric material which makes it stiffer compared with the untreated continuous carbon fiber yarns. The fiber filament was sectioned at three locations to gain insight into the consistency and uniformity of the filament. The fiber samples were examined using an optical microscope after going through multiple stages of polishing. The obtained images were thereafter processed using the image processing software ImageJ (National Institutes of Health, Bethesda, Maryland, USA). The images were converted into binary images before the image threshold was adjusted to separate the fibers from the matrix in order to evaluate their volume fraction.

A replicate of the tested samples was sectioned perpendicular to the fiber axes using high-speed abrasive cutting machine (Mecatome T260, PRESI, Hungary). The sectioned samples were grinded and polished in order to be prepared for microscopic imaging. The goal was to have a better understanding of the internal structure of the printed samples and to investigate the existence of air voids within the samples. The LEICA MZ10 F stereo-microscope (LEICA, Germany) was used to capture the cross-sectional images.

### 2.3. Thermal conductivity measurements

The effective thermal conductivity of the samples was characterized using an apparatus developed in [9] which is based upon a modified guarded hot plate technique similar to ASTM C177 [26]. A schematic of this apparatus is shown in Figure 3. Thermal power from the electrical heaters embedded in the primary heater block is conducted through the sample to the primary cold block. The steady-state temperature difference across the sample is measured using resistance temperature detectors.
detectors (RTDs) inserted into each block and the measured thermal resistance of the sample, $R_{\text{meas}}$, is given by

$$R_{\text{meas}} = \frac{(T_{\text{hot}} - T_{\text{cold}})}{Q}$$  \hspace{1cm} (1)

where $(T_{\text{hot}} - T_{\text{cold}})$ is the temperature difference across the sample and $Q$ is the measured input electric power to the primary heaters ($P = IV$).

The measured thermal resistance consists of the sum of the bulk sample resistance and the thermal contact resistance between the sample and the apparatus given by

$$R_{\text{meas}} = R_{c,1} + R_{c,2} + R_{\text{sample}} = R_c + R_{\text{sample}}$$  \hspace{1cm} (2)

$$= R_c + \frac{L}{k_{\text{sample}}A}$$  \hspace{1cm} (3)

where $R_{c,1}$ is the contact resistance between the sample and the main heater, while $R_{c,2}$ is the contact resistance between the sample and the main cooler.

By rearranging Equations (1) and (3), the thermal conductivity of the sample can be calculated as

$$k_{\text{sample}} = \frac{L}{A\left[(\frac{T_{\text{hot}} - T_{\text{cold}}}{Q}) - R_c\right]}$$  \hspace{1cm} (4)

where, $L$ is the thickness of the sample under test and $A$ is its cross-sectional area.

The contact resistance can be obtained by measuring the total thermal resistance for several thicknesses of a given sample which have similar surface properties and extrapolating the measured resistance to zero thickness as in [27–29].

To ensure that all the electrical power applied to the primary heater block flows through the sample, a secondary heater block surrounds the primary block and is temperature-controlled to be identical to the primary heater block temperature, ensuring no thermal gradient exists in any other direction. The primary and secondary (guard) blocks were machined from copper with the primary blocks having a contact area of 40 mm $\times$ 40 mm. Cartridge heaters energized by independently controlled DC power supplies are used to control the temperature of the primary and secondary heater blocks. Temperature-controlled water supplied by a circulator is used to control the temperature of the primary and secondary cooling blocks.

The temperature of all blocks is measured using 1 mm $\times$ 15 mm RTDs (Omega, 1PT100KN1510) inserted into holes at the locations shown in Figure 3 calibrated to within 0.01 K of each other.

The sample under test is clamped between the primary and secondary heating and cooling blocks using a clamping screw mounted to the device frame and the load cell (KAF-S, AST, Dresden, Germany), as shown in Figure 3. Samples were clamped with a pressure of approximately 3 MPa and few droplets of mineral oil were used to minimize thermal contract resistance and to help ensure reparability of the results. The entire assembly was encased with silica aerogel insulation which has a thermal conductivity of 0.014 W/mK. Additional details regarding the data acquisition, temperature control, calibration, and uncertainty analysis are provided in [9].

### 3. Model formulations for effective thermal conductivity

The effective thermal conductivity of composite materials can be calculated using suitable analytical models depending on the filler type, shape, and orientation [30, 31]. In this study, the focus was on investigating the effective thermal conductivity of continuous fibers aligned either in parallel with or perpendicular to the heat flow direction. As such, series and parallel analytical models for effective thermal conductivity were used and are given by

$$k_{\text{eff}} = \left(\frac{1-v_f}{k_p} + \frac{v_f}{k_f}\right)^{-1}$$  \hspace{1cm} Series model (5)

$$k_{\text{eff}} = (1-v_f)k_p + v_fk_f$$  \hspace{1cm} Parallel model (6)

where $k_{\text{eff}}$ is the effective thermal conductivity of the specimen, $k_p$ and $k_f$ are the polymer and fiber thermal conductivities respectively, and $v_f$ is the fiber volume fraction.

The series model was used with the cases when the fibers were arranged in series with respect to heat flow as in Figure 1(a) while the parallel model was used when the fibers are parallel with the heat flow direction as in the parallel fibers case (Figure 1(b)).

The models predict the effective thermal conductivity of the composite as a function of the thermal conductivities of the constituent materials and their volume fractions. As such, the accuracy of the predicted effective conductivities depends greatly on the accuracy of these values.

The thermophysical properties of the carbon fiber are not supplied by Markforged; however, we conjecture that it is a polyacrylonitrile (PAN)-type carbon fiber. The thermal conductivity of these fibers typically ranges from 8.0 to 10.45 W/mK according to carbon fiber manufacturers’ data sheets [32, 33]. The uncertainty in fiber thermal conductivity is included in the model prediction for effective thermal conductivity. The thermal conductivity of the nylon matrix was measured experimentally using Sample 4 which contained no fiber material.

The fiber volume fraction used in the model was quantified based on the microstructure analysis and...
4. Results and discussion

4.1. Filament and 3D-printed sample microstructure analysis

An unprinted Markforged carbon fiber filament used by the MarkOne printer was examined as described above using an optical microscope. A cross-sectional view for three different locations along the length of the fiber filament is shown in Figure 4. The filament appears to be coated with a polymeric material. Although the specification of this was not provided by the manufacturer, it was conjectured to be nylon because this is the base polymer typically used by the Mark One printer. It has a nominal diameter of 0.4 mm and the distribution of carbon fibers within each cross section is non-uniform. It was observed that the fiber pattern inside the filament changes with respect to the location but tends to be distributed in a slight 'S' pattern as shown in Figure 6(a–c). This may be due to the processing or coating techniques used by Markforged or to the fact that the fibers may not be continuous across the whole length of the filament.

Using image processing, the fiber was segmented based on intensity, and the fiber volume fraction was measured as 35.5 ± 4% of the carbon fiber filament itself. This value was slightly higher than the value reported by Blok et al. [34] who reported 20% from a single cross-sectional measurement of the filament and 27% when it was measured within a printed sample.

The measured filament fiber volume fraction was used to determine the overall fiber volume fraction in the printed samples given by

\[ \psi_j = \frac{\text{Number of fiber layers}}{\text{Total number of layers}} \times \text{filament fiber volume fraction (35.5%)}. \]

(7)

where the filament fiber volume fraction was obtained from the microscopic analysis above (35.5%) and the total number of fiber layers was reported by the slicing software (shown in Table 2). The overall fiber volume fractions are summarized in Table 3. However, to accurately quantify thermal contact resistance and to ensure shell layers were not influencing the bulk effective thermal conductivity measurement, the outer layers of the samples in contact with the apparatus were removed. For the
series samples, the floor and roof layers were removed. For the parallel samples, the two wall layers in contact were the apparatus were removed while the floor, roof and walls parallel with the fibers (highlighted in Figure 2(b)) remained. For these reasons, a correction to the fiber volume fraction from on Equation (7) was applied to represent the true quantity of carbon fiber in each sample for the subsequent results.

The cross-sectional view of Samples 5 and 6 perpendicular to the fiber’s axis, is shown in Figure 5 and shows the fiber and polymer layers. Here, small air voids were visible primarily within the fibrous regions of the samples. This may be due to inconsistency in the fiber filament or the nature of the FFF technique. At its highest, the air volume fraction was measured as less than 2% of the total volume of the sample and discrete air voids were discontinuous. Thus, they have little influence on the sample thermal resistance. The fiber percentage obtained by image processing of the captured images showed a good consistency with the fiber volume fraction reported in Table 3.

### 4.2. Effective thermal conductivity

To evaluate the effective thermal conductivity of the samples, any thermal contact resistance between the samples and the apparatus itself must be accounted for. This was accomplished by varying the bulk thermal resistance of each sample (by varying the sample thickness) and backing out the contribution of contact resistance to the measured resistance as described above. The thermal resistance of each sample was measured at different thicknesses by repeatedly grinding and polishing the samples to the desired thickness. The resultant measured thermal resistance is plotted against sample thickness for Sample 4 in Figure 6. Here, the linearity of the results demonstrates good consistency in the surface preparation and contact resistance between the sample thicknesses. The linear best fit line represents Equation (3) and its y-intercept represents the contact resistance (thermal resistance at zero thickness). The effective thermal conductivity of the sample can be evaluated after the thermal contact resistance assessment using Equation (4). It also can be evaluated directly from the plot as the slope represents the inverse of \( k_{sampleA} \) from Equation (3). This procedure was followed to evaluate the contact resistance and effective thermal conductivity for all of the samples.

The parallel samples have a relatively uniform cross-section at each sample thickness because the fibers are perpendicular to this cross-sectional area. As such, the volume fraction does not vary with thickness and both the bulk effective thermal conductivity and contact resistance are similar between thicknesses. For the series samples used in our study, the fiber and sample layers were deliberately frequently alternated to help ensure that the variation of fiber volume fraction with thickness was minimized so as to minimize the effect on bulk effective thermal conductivity. It is more difficult to ensure identical layers are in contact with the apparatus due to the nature of these samples. However, for these samples the contact resistance tended to be relatively similar between the sample thicknesses and quite low with respect to the bulk resistance. As such, the contact resistance had little influence on the measured effective thermal conductivities.

The resulting effective thermal conductivities as a function of fiber volume fraction for the samples arranged in series with the heat flow are shown in Figure 7. The thermal conductivity of the pure polymer (Sample 4) is also plotted and measured as 0.265 W/mK which is in good agreement with the 0.260 W/mK reported in [35]. By incorporating carbon fibers in a series configuration, effective thermal conductivity of the polymer composite is somewhat improved. At the highest volume fraction of 35.5% continuous fiber, the effective thermal conductivity was 0.378 W/mK which represents 42% of an improvement over the pure nylon.

These results further show that, in this series configuration, the effective thermal conductivity is not particularly sensitive to changes in the fiber volume fraction. For example, between Sample 1 and Sample 3, the volume fraction of carbon fiber increased by 50% but only resulted in a 13% increase in effective thermal conductivity of the composite. This is largely due the relatively insulating nylon layers which are in series with the conductive carbon fiber layers.

The prediction for thermal conductivity from the series model (Equation (5)) is also plotted in Figure 7 using the values for fiber thermal conductivities reported in [32, 33]. Overall agreement is good for both cases which indicates that, for fibers arranged orthogonally to the direction of heat flow, the conductivity of the fibers themselves plays a

| Sample | Fiber configuration | Overall fiber volume fraction (v) % | Corrected volume fraction (v) % |
|--------|---------------------|-------------------------------------|-------------------------------|
| 1      | Series              | 21.0                                | 23.6                          |
| 2      | Series              | 26.3                                | 29.5                          |
| 3      | Series              | 31.5                                | 35.5                          |
| 4      | Parallel            | 0.0                                 | 0.0                           |
| 5      | Parallel            | 12.0                                | 11.3                          |
| 6      | Parallel            | 20.5                                | 19.3                          |
| 7      | Parallel            | 34.1                                | 32.2                          |

Table 3. Samples fiber volume fraction based on fiber filament image processing.
minimal role in effective thermal conductivity in this direction.

The effective thermal conductivity for the samples where the fibers were arranged in parallel with the heat flow are shown in Figure 8. In this configuration, the effective thermal conductivity of the composite is more sensitive to the fiber volume fraction with a maximum value of 2.97 W/mK at a volume fraction of 32.2%. This represents an order-of-magnitude increase in thermal conductivity over the pure nylon. The corresponding model predictions from Equation (6) are also plotted. Here, the lower value for carbon fiber thermal conductivity \( k_f = 8.0 \text{ W/mK} \) best predicts the trend in effective thermal conductivity for the composite.
The model also shows that, in contrast to the series configuration, increasing the thermal conductivity of the fiber should increase the composite effective thermal conductivity for a given volume fraction.

### 4.3. Handlay-up sample and future outlook

The results from the parallel samples and the associated model predictions demonstrate the sensitivity of fiber thermal conductivity on the effective thermal conductivity of the composite in this direction. The effective thermal conductivity of these 3D-printed composites was limited by the relatively low thermal conductivity PAN carbon fibers which we estimated to be \( k_f = 8.0 \text{ W/mK} \) based on the results in Figure 8. To investigate the potential of using a higher conductivity fiber to increase the effective thermal conductivity of the composite, a parallel fiber composite sample was fabricated using the pitch-based carbon fiber Mitsubishi DIALEAD K13D2U (Mitsubishi Chemical Carbon Fiber and Composites, Inc.). The specified thermal conductivity of these fibers in the axial direction is 800 W/mK [36] which is significantly higher than PAN carbon fibers.

The sample was fabricated to mimic the 3D-printed components in the previous section by using handlay-up technique where the pitch-based carbon fibers were sandwiched between several layers of rectangular PLA coupons using a clear epoxy as shown in Figure 9. The sample was denoted as Sample 8. The Dialed K13D2U fibers are 11 m in diameter and each tow contains 2000 fibers. By counting the number of tows used to fabricate the sample, the fiber volume fraction was estimated as 4.3 % which is significantly less than the parallel 3D-printed samples used in the previous section.

The sample was cut and polished using the same procedure described previously to prepare the sample for testing. As before, three thickness of the pitch-based carbon fiber sample were measured to quantify and correct for thermal contact resistance. The resulting effective thermal conductivity was measured as 23.6 ± 1.4 W/mK which was significantly higher than the 3D-printed carbon fiber samples, despite having a much lower fiber volume fraction. However, this value is somewhat lower than the \( k_{\text{sample}} = 34.6 \text{ W/mK} \) predicted by the parallel model (based on \( k_{\text{fiber}} = 800 \text{ W/mK} \) and \( v_f = 4.3\% \)). This may be due to several reasons including the uncertainty in the carbon fiber volume fraction or thermal conductivity. Additionally, the DIALEAD fibers are significantly more brittle than PAN fibers and some fiber breakage may have occurred during fabrication.

![Handlay-up sample fabricated with pitch-based carbon fiber (Sample 8).](image)

**Figure 9.** Handlay-up sample fabricated with pitch-based carbon fiber (Sample 8).

![Predicted effective thermal conductivities using continuous fiber additives in the parallel direction.](image)

**Figure 10.** Predicted effective thermal conductivities using continuous fiber additives in the parallel direction.
the hand lay-up and the polishing process which would decrease fiber continuity. Nevertheless, the results from this sample demonstrates the relatively high effective thermal conductivities that can be potentially achieved by using pitch-based carbon fiber or other continuous conductive fibers such as carbon nanotube yarns.

Figure 10 shows the predicted effective thermal conductivity of different continuous fibers in the parallel direction compared with basic metals used for heat exchange and thermal management applications such as copper and an aluminum alloy. From this, a thermal conductivity of 167 W/mK (similar to that of aluminum alloy 6061 which is commonly used for heat sink applications), could be achieved with FRPCs with only 20% pitch-based carbon fibers. Metal fibers and wires such as copper can also been used, as in [23, 24], to improve the thermal conductivity.

The forgoing results demonstrate the potential of continuous fiber polymer composites to achieve significant improvements to effective thermal conductivity with measured thermal conductivities on a similar order of magnitude to that of stainless steels. Potential fabrication using additive manufacturing could further enhance and control fiber placement and orientations to suit specific heat exchange applications.

5. Summary and outlook

The thermal conductivity of 3D-printed continuous carbon fiber composites fabricated using a Markforged MarkOne 3D printer were characterized experimentally and compared against analytical models for effective thermal conductivity. The effect of fiber orientation and volume fraction was investigated. For fibers oriented in a direction normal to the heat flow, the measured effective thermal conductivity of the composite was 0.378 W/mK using a fiber volume fraction of 35.5% which was 42% higher than the pure polymer. In this orientation the effective thermal conductivity is only slightly sensitive to fiber conductivity or volume fraction. However, for heat transfer in the direction of fiber orientation, a similar volume fraction of fibers (32.2%) increased the effective thermal conductivity by approximately one order of magnitude over the pure nylon sample to 2.97 W/mK. This value is significantly higher than any reported 3D-printed composite thermal conductivity.

By assuming the thermal conductivity of the carbon fibers as 8 W/mK (which is typical of PAN carbon fibers) the experimental results were well predicted by the established series and parallel models for effective thermal conductivity. The parallel model demonstrated the sensitivity of FRPC effective thermal conductivity to the fiber conductivity and, to investigate the potential of using higher conductivity fibers, a handlay-up sample using pitch-based carbon fiber was fabricated and tested. The results showed a significantly higher effective thermal conductivity of 23.6 W/mK with only a 4.3% fiber volume fraction which is an order-of-magnitude higher than the PAN carbon fiber FRPCs and slightly higher than stainless steel.

Development of a 3D-printing process which could fabricate pitch-carbon-fiber composite components could significantly improve the effective thermal conductivity of the printed parts and could help realize the additive manufacture of composites with thermal conductivities comparable to aluminum, making them suitable for high-performance heat transfer applications. Moreover, the additive manufacture of these composites would allow for controllable anisotropic conductivities tailored to specific applications, enabling a new generation of lightweight, high-performance, AMFRPC heat exchange technologies.

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