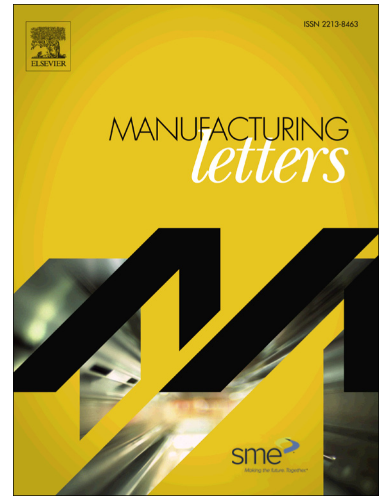

Letters

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PII: S2213-8463(17)30075-5
DOI: https://doi.org/10.1016/j.mfglet.2018.04.001
Reference: MFGLET 150

To appear in: *Manufacturing Letters*

Received Date: 6 December 2017
Revised Date: 9 April 2018
Accepted Date: 21 April 2018

Additive Manufacturing of Continuous Wire Polymer Composites

Yehia Elsayed, Garrett W. Melenka, Roger Kempers*

Department of Mechanical Engineering, York University, Toronto, Canada

*Corresponding Author: kempers@yorku.ca

Abstract

There has been a growing trend towards producing functional components using additive manufacturing (AM). A Continuous Wire Polymer Composite (CWPC) manufacturing method using an open-source desktop 3D printer is presented. The incorporation of continuous wires within AM structures results in a composite structure. The reinforcement of AM components with continuous wires results in improved mechanical properties and wire reinforcement can be oriented in critical locations of AM components. The CWPC manufacturing method will allow for fabrication of thermal and mechanical sensors for temperature and strain, 3D printed heating elements and for high strength components.

Keywords: additive manufacturing, polymer composites, 3D printing, fused filament fabrication,

1. Introduction & Background

There is continuing requirement in many industries for lighter, stronger, and more conductive materials. As such, there has been significant research towards polymer composites (PCs) [1] which can offer superior thermo-mechanical properties by combining a suitable reinforcement within a polymer matrix [2].

Additive manufacturing (AM) has seen significant uptake over the last decade with the goal to create more functional components using this technology. Three-dimensional (3D) printing and specifically fused filament fabrication (FFF) have brought about a new dimension to the fabrication of PCs and offer a straightforward, low-cost manufacturing technique for PC components with a wide range of composite filaments now commercially available [3,4]. Fillers such as metal powders, chopped fibres and graphene pellets have been used to significantly improve mechanical and thermal properties [5,6,7,8]. However, the discontinuous nature of these reinforcement materials within the polymer matrix can restrict maximum achievable performance as interfacial limits become dominant [9,10].

Recent studies have used FFF 3D printing to fabricate PCs with continuous carbon fibers extruded along with a molten polymer during printing the printing process [11,12,13,14]. The resultant components typically yielded significantly improved stiffness and strength [12,14].

A commercially available 3D printer developed by Markforged offers another technique for printing continuous fibre reinforcement and employs two nozzles: one for the thermoplastic and one for the fibre which can be either carbon, glass, or aramid fibers [15,16].

Generally, the focus of these studies was on the enhancement of mechanical properties of the 3D printed components and subsequent mechanical testing. However, continuous fiber reinforced AM structures can also be used to create thermally conductive networks. This approach can potentially greatly improve the effective thermal conductivity of 3D printed polymer composite components.

In the present work, a novel composite material fabrication technique is presented which enables the fabrication of a polymer composites with continuous metal wire reinforcements using a modified low-cost, open-source 3D printer.

2. Methodology

2.1 Nozzle Design and Printer Modification

A FFF 3D printer (Prusa i3 mk3 Prusa Research, Prague, Czech Republic) was modified to print continuous wire polymer composites (CWPCs) in the following way.

A new hot-end was designed to accommodate the introduction of the wire with the molten polymer as shown in Fig. 1. Additionally, A custom hot end holder was designed to account for new orientation of the heatsink and the standard cooling fan was relocated accordingly. The heater block was machined from aluminum to hold the heater and thermistor in the locations shown and an E3D -V6 standard brass nozzle (1 mm ID) and E3D-V6 heat sink were mounted to the heater block as indicated.

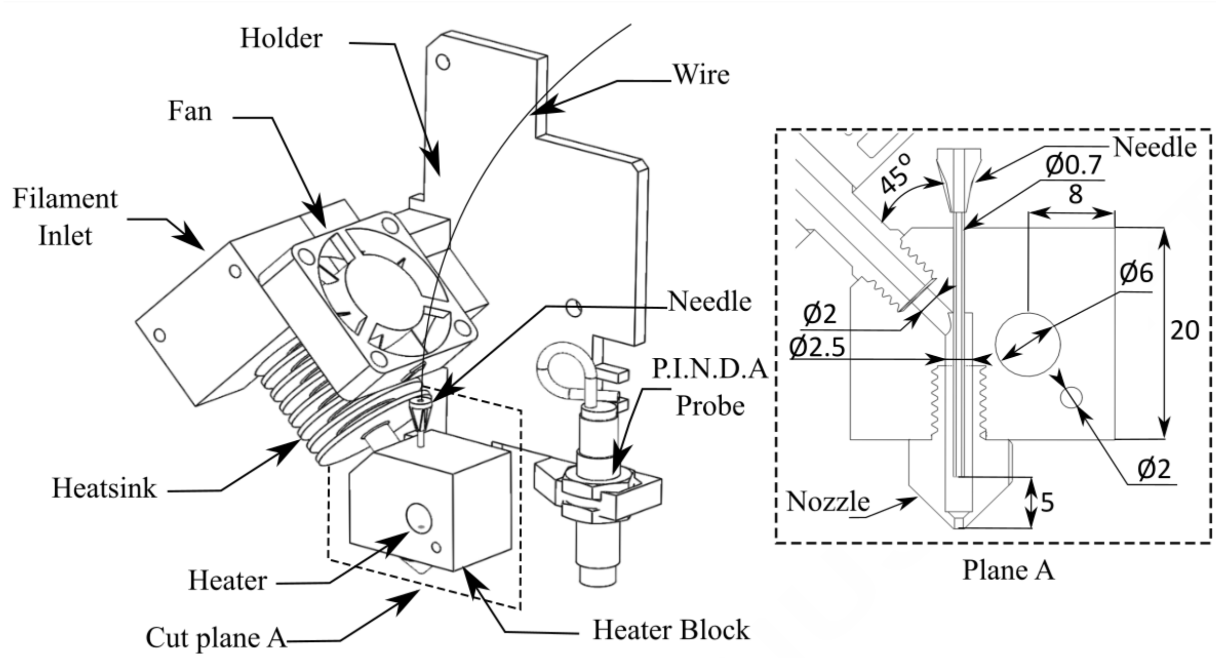

Figure 1: Modified hot end with nozzle critical dimensions

The wire is introduced into the molten filament using a 23 gauge dispensing needle inserted into the top of the heater block. Inside the heater block, the filament flow section begins with a diameter of 2 mm for the first angled part of the block and expands to 2.5 mm in the vertical section to account for the presence of the needle in the vertical section. The needle tip is located 5 mm from the nozzle exit to minimize the polymer flow inside the needle which may causes needle blockage. The advantage of introducing the wire to the polymer using this method instead of using pre-extruded wire-polymer composite filament is the simplicity of the system and the compatibility with different nozzle diameters. In a wire-polymer filament the minimum nozzle diameter is limited to a value close to the filament diameter. Additionally, wires of different materials and diameters can easily be introduced using this process thus allowing for manipulation of the printed composite mechanical and thermal properties.

Finally, the standard filament feeding mechanism was relocated and mounted to the metal frame of the printer and filaments were pushed to the hot end through a 3 mm inner diameter Polytetrafluoroethylene (PTFE) guide-tube. A feeding mechanism for the wires was not required, as the already printed and cooled rasters adhere to the heated bed and exert sufficient traction force to advance the wire from the hot end as extrusion occurs.

2.2 Materials and Printing Parameters

In the present study, polylactic acid (PLA) was used for the matrix material along with two 75 µm diameter reinforcing wires: nickel-chromium wire (McMaster Carr, Ohio, USA) and coated copper magnet wire (Remington Industries, Canada).

Experimentation revealed that for the 1 mm nozzle used, a 0.6 mm layer height, a printing speed of 7 mm/s and nozzle temperature of 175 °C generally ensured repeatable prints when using 75 µm diameter wire.

The printer was controlled using custom G-code to create unidirectional samples with the desired dimensions. This was done to eliminate wires overlapping in the same layer. Printing of these samples begins and one corner of the layer and the print head “serpentines” during printing to the opposite corner of the same layer before advancing to the next layer.

Results & Discussion

Continuous wire reinforcement of AM structures resulted in a composite material. A photograph of two axial reinforced and one alternating axial/transverse reinforced CWPC samples are shown in Fig. 2 (a), (b) and (c) printed with 75µm diameter wires. At the sample ends where the printing head reverses direction to create a new raster, the wire is slightly offset from the edge due to the polymer solidification time required to fix the wire in place. Furthermore, the high thermal conductivity of the metal wire transfer heat from the heater block to the polymer delaying the solidification and causing more wire offset. Extra cooling, especially at the sample edges can reduce this offset significantly.

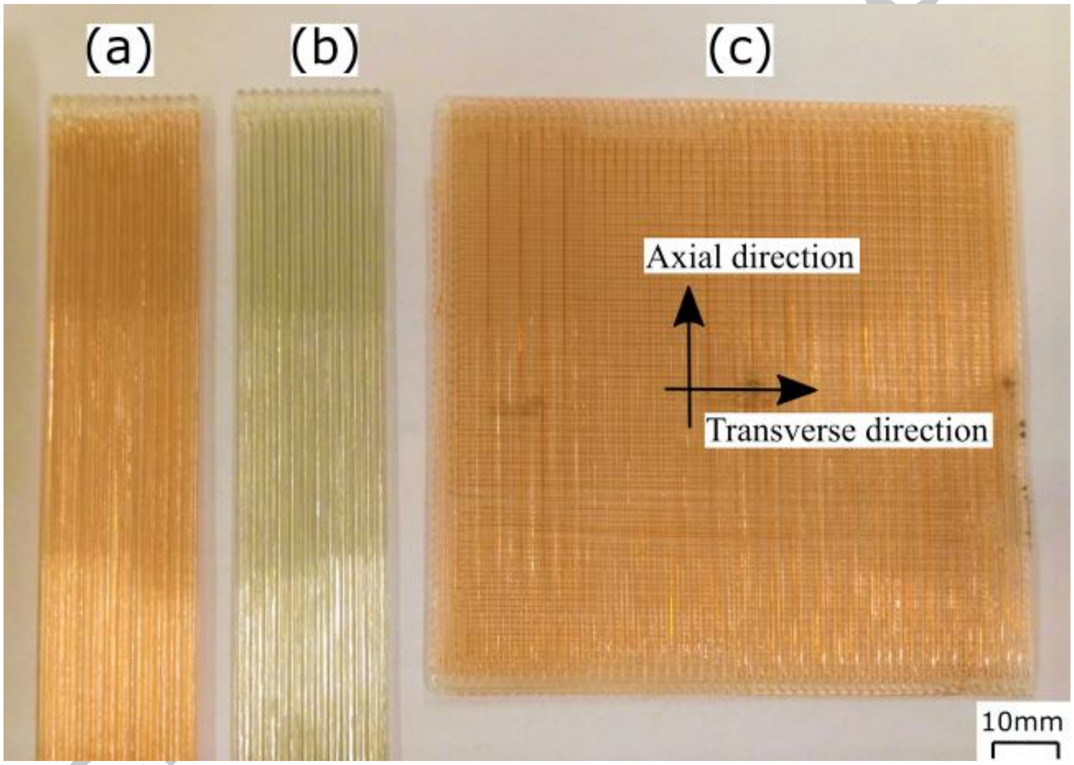

Figure 2: CWPC samples manufactured using a custom 3D printer. (a) Unidirectional Copper reinforced sample with axial reinforcing fibers (b) Nickel-chromium wire reinforced sample with axial reinforcing fibers. (c) Copper wire reinforced sample with alternating axial and transverse fiber reinforcement

The effect of introducing wires within a AM structure is improved mechanical properties when compared to conventional AM structures. Additionally, due to the nature of AM structures the continuous wires can be oriented to align with the critical loading directions of the designed part. Additionally, alternating reinforcement direction as shown in Fig. 2 (c) can result in a quasi-isotropic structure. The result of this manufacturing approach is that functional components can be produced with improved mechanical properties and with reinforcement aligned in the critical loading direction.

Cross-sectional micrographs of manufactured CWPC samples are shown in Fig. 3 which shows the position of the reinforcing wires along with voids or air gaps that exist within the AM structure. The geometry of the extruded thermoplastic material causes voids within the AM structure. Fig. 3 demonstrated that the voids within the AM structure are affected by the size of wire reinforcement. Voids within AM structure will have a negative effect on mechanical properties and therefore should be minimized. It is noted that the wires are not consistently centered in the raster which is believed to be caused the force exerted by the moving printing head. This motion can bias the wire to one side of the raster especially at the corners.

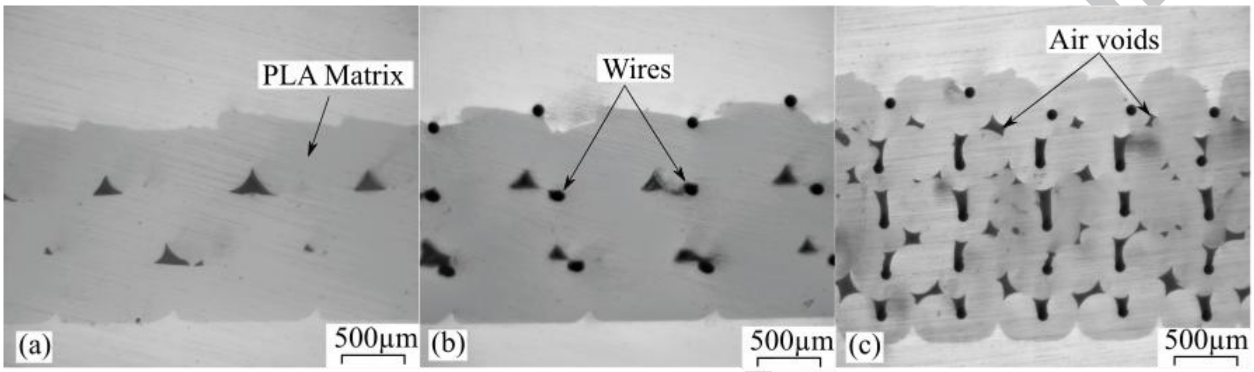

Figure 3: (a) Pure PLA sample (b) 75μm diameter CWPC printed with 1mm nozzle (c) 75μm diameter CWPC printed with 0.6 mm nozzle

A variety of wire diameters were tested with different nozzle diameters and the results showed that the preferred wire diameter is approximately one tenth of the nozzle diameter. We speculated this is because for larger wire-to-nozzle ratios, there is inadequate molten polymer to advance the wire out of the nozzle. Improved quality prints were achieved using a smaller 0.6 mm nozzle with 50 μm diameter wire.

This reinforcing technique is not limited to two- dimensional geometries like the ones shown in Fig. 2. Many available 3D printing slicing programs have a printing mode known as "Vase Mode" which is ideal for producing thin tubular AM structures. The CWPC reinforcement method can be used while manufacturing components in "Vase Mode" resulting in helical reinforcement as shown in Fig. 4. This figure demonstrates that the wire reinforcement occurs around the circumferential direction of the AM structure. The ability to produce continuous axisymmetric components with the CWPC manufacturing method demonstrates the ability to orient wire reinforcement in the critical loading direction of tubular components which will greatly increase the hoop strength of the AM structures allowing for improved performance in radial pressure loading cases.

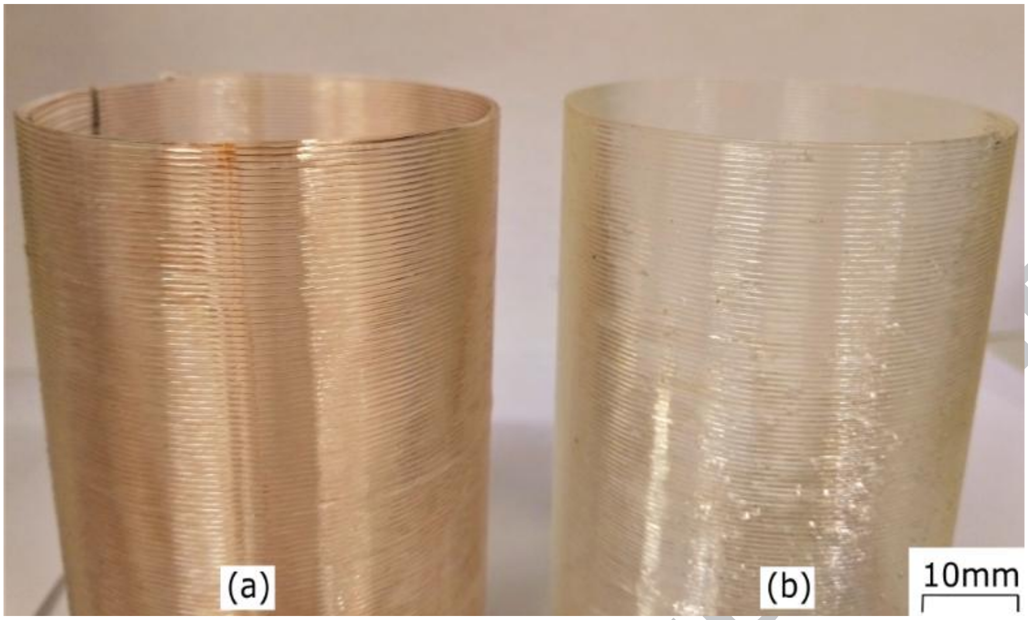

Figure 4: 3D printed geometries created using "Vase Mode" (a) Wire reinforced and (b) non-reinforced structure.

Summary and Outlook

A novel fabrication method has been developed using a low-cost, open-source printer to fabricate CWPC components. Future work will involve mechanical and thermal characterization of these CWPC. As well, this approach will be investigated to fabricate thermal and mechanical sensors and to produce heating elements integrated into 3D printed structures.

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