# Additive Manufacturing of Multifunctional Components Using High Density Carbon Nanotube Yarn Filaments

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## ABSTRACT

Additive manufacturing allows for design freedom and part complexity not currently attainable using traditional manufacturing technologies. Fused Filament Fabrication (FFF), for example, can yield novel component geometries and functionalities because the method provides a high level of control over material placement and processing conditions. This is achievable by extrusion of a preprocessed filament feedstock material along a predetermined path. However if fabrication of a multifunctional part relies only on conventional filament materials, it will require a different material for each unique functionality printed into the part. Carbon nanotubes (CNTs) are an attractive material for many applications due to their high specific strength as well as good electrical and thermal conductivity. The presence of this set of properties in a single material presents an opportunity to use one material to achieve multifunctionality in an additively manufactured part. This paper describes a recently developed method for processing continuous CNT yarn filaments into three-dimensional articles, and summarizes the mechanical, electrical, and sensing performance of the components fabricated in this way.

## 1. INTRODUCTION

Additive manufacturing (AM) offers versatility in component design and broad utility in many applications. For aerospace components, these advantages could lead to significant weight reductions through the reduction in materials used, tailoring location of continuously reinforced composites only where necessary, and net shaped processing of functional and integrated components. Building functionality into the component instead of providing the same with a parasitic external system can lead to lighter systems. Recently, a growing number of aerospace components have been produced using AM technologies. These include parts such as fuel injectors, interior parts, and satellite components [1-3]. These components are typically passive structural parts made from a single material. Some of the potential for weight reduction and simplicity afforded by AM parts can be realized by using traditional composites and nanocomposite materials. Carbon fiber, graphene, and carbon black have been used as reinforcement materials in three dimensional (3D) printable filaments for this purpose [4-7]. Espalin et al. have developed the multi3D system which incorporates a number of subsystems including fused deposition modeling (FDM), also known as fused filament fabrication (FFF), ink dispensing, wire embedding, component placement, and micromachining [8]. This system has been used to successfully produce CubeSat panels, but requires a number of different materials for each function (e.g. structural, electrical, etc.) and processing steps with different machines to complete the part. The MarkOne and MarkTwo printers developed by MarkForged can print continuous fiber reinforcement such as Kevlar and carbon fiber [9, 10]. Multifunctionality can be incorporated into parts printed on these machines by pausing the print, placing components, and then resuming the print; however, this cannot be achieved without manual intervention by the user [11]. These machines also have limited ability to print thermoplastics, especially high strength structural polymers such as polyetherimide (PEI) and polyether ether ketone (PEEK) that require high processing temperatures. Those machines that have the capability to print using high temperature polymers such as PEI do not currently have the capability to build reinforced parts. More recently, Voxel8 has announced a printer specifically for producing multifunctional parts [12]. Interconnects are made using a 3D printed, highly conductive silver ink [13, 14] and large components are placed manually by the user. Small unmanned aerial vehicles (UAV) have been printed using this process. All the machines described above rely on several materials, and in some cases several different pieces of printer hardware, to impart multifunctionality to the printed component. This paper reports on the use of highly densified carbon nanotube (CNT) yarn filament in a 3D printing process. The work presented here demonstrates that the filament possesses sufficient mechanical and electrical properties to be used as both a structural reinforcement and electrical wiring in multifunctional components. In addition, the filament exhibits good conformability, allowing for accurately printed paths and CNT dense structural components.

## 2. EXPERIMENTATION

### 2.1 Material and Hardware

Printable CNT yarn filaments (Figure 1a) were fabricated by continuous solution coating of highly densified CNT yarns (Nanocomp Technologies Inc., Merrimack, NH) with a typical 3D printable polyetherimide [Ultem™ 1010, Stratasys, Eden Prairie, MN; 50 mg Ultem 1010 dissolved in 1 ml dimethylacetamide (DMAc)]. The average width of the Ultem™/CNT filaments was around 350 μm with 10-20 wt.% resin content. Component printing with both neat Ultem™ 1010 and Ultem™/CNT yarn filaments was accomplished using a modified open-source, FFF 3D printer (Aleph Objects, Loveland, CO) equipped with two high temperature hot ends (E3D, Chalgrove, Oxfordshire, UK). A nozzle was dedicated to either neat Ultem™ 1010 or Ultem™/CNT filament (Figure 1b).

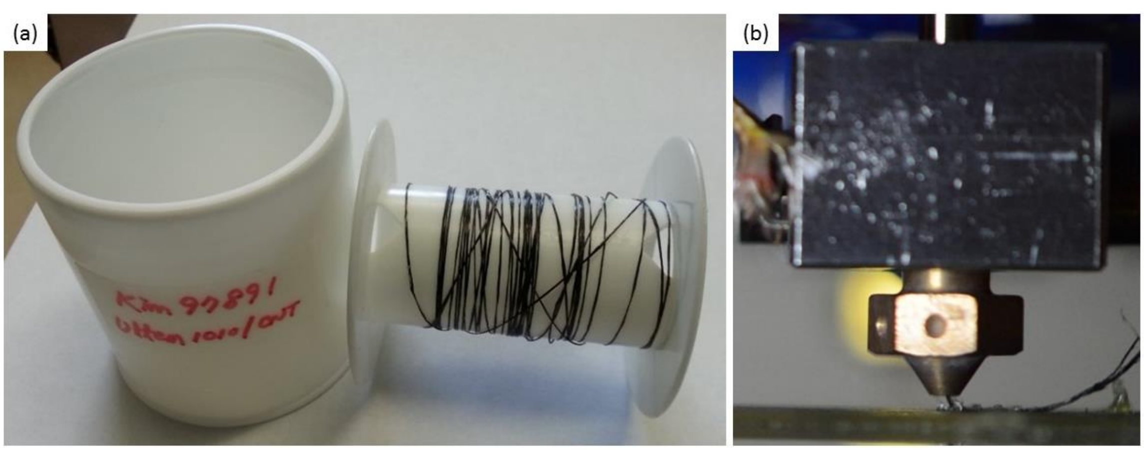

Figure 1. (a) Ultem™/CNT filament before printing. (b) High temperature hot end and nozzle used for Ultem™/CNT filament printing.

## 2.2 CNT Yarn Printing Process

To print a part, an initial layer of Ultem™ was put down on a glass print bed coated with Elmer's Disappearing Purple® glue stick, and either Ultem™ or Ultem™/CNT filament printed on top in subsequent layers. In some tests, an Ultem™ substrate was attached to the print bed and Ultem™/CNT filament print was performed directly on the substrate. The nozzle temperature was set to 375°C for both the neat Ultem™ and Ultem™/CNT yarn print heads. The bed temperature was set at 162°C. Printing the Ultem™/CNT filament was performed using a process called selective compaction mode (Figure 2). In this process, a portion (5-10 mm) of Ultem™/CNT filament was extruded from the nozzle. The nozzle was then lowered to the printing surface at a 45° angle until it made contact with the printing surface. The nozzle was held at the printing surface for one second and then raised vertically (z-axis) 2 mm. Lifting the nozzle allows the Ultem™ to solidify and anchor the yarn in place on the printing surface. The nozzle is again brought into contact with the substrate some distance (typically 1 mm) from the previous contact point. This process was repeated as many times as necessary to ensure a sufficient bond between the Ultem™/CNT filament and polymer substrate. Once a sufficient bond was achieved, the nozzle was brought in contact with the printing surface and moved quickly across to pull the Ultem™/CNT filament out of the nozzle. This selective compaction process was repeated at the beginning of every new line and after any turn with a radius less than or equal to 1 mm.

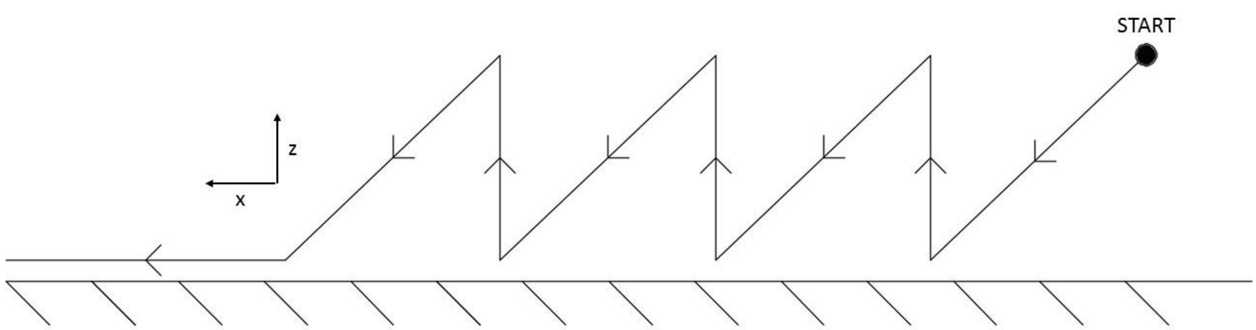


Figure 2. Selective compaction toolpath used for printing Ultem™/CNT filament.

## 2.3 Test Specimen Fabrication

Flat Ultem™/CNT test specimens were printed with both Ultem™ and Ultem™/CNT filament in a unidirectional layup pattern with a spacing of 350 µm between the CNT filament centerlines (Figure 3a). Each specimen contained one layer of Ultem™/CNT filament reinforcement with neat Ultem™ completely encapsulating the reinforcement layer. Specimens consisting entirely of neat Ultem™ were also printed as a control. Dog bone specimens were cut from the printed flat plaques for mechanical characterization. Additional specimens with 1 mm and 350 µm spacing between the centerlines were printed for use in electrical experiments (Figure 3b) using the same method.

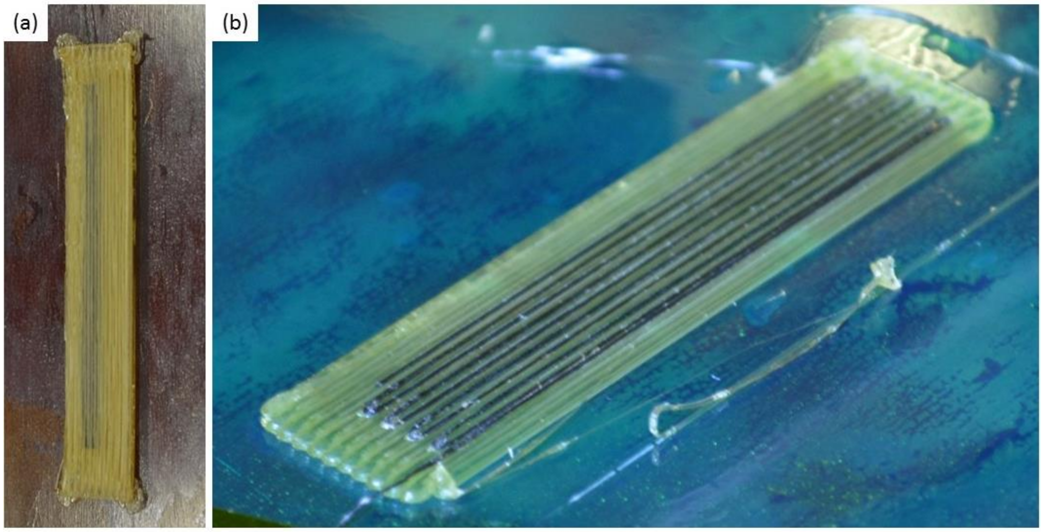


Figure 3. (a) Finished CNT reinforced part before being cut to ASTM D638 standard. (b) CNT reinforced part with 1 mm spacing prior to capping with Ultem™.

### 2.4 Characterization

Optical microscopy of the printed parts was performed with a Leica DM8000 M optical microscope. Tensile tests were conducted using a MTS-858 station with a laser extensometer following the ASTM D638 standard. Electrical properties of the printed components were characterized using the 4-probe method with a Keithley 2400 current source and a Keithley 2000 Digital Multimeter. A VT02 Visual infrared (IR) Thermometer (Fluke Corporation) was used to collect infrared thermographs of the specimen during electrical tests.

## 3. RESULTS

### 3.1 Printing Paths and Resolution

During initial testing, Ultem™/CNT filaments were printed on flat Ultem™ substrates to determine the resolution and evaluate the overall performance of the printing technique. As shown in Figure 4a and 4b, the printed Ultem™/CNT filament maintained a turning radius equal to around half of their width by folding over on themselves during the course of the turn; a result of the high compliance inherent to the dry CNT yarn. Because of this characteristic, the Ultem™/CNT filament can be printed with no visible gaps between adjoining yarn traces (Figure 4c) allowing for structural parts to be printed with high volume of CNTs along the entire part. The shortest Ultem™/CNT filament line that could be printed was around 4 mm in length. This lower boundary was determined by the number of selective compaction stomps needed to ensure adequate bonding between the Ultem™/CNT filament and substrate. Large traces with wider radii were also successfully printed. To demonstrate these capabilities, the word "NANO" was printed with a continuous Ultem™/CNT filament (Figure 4d). Each letter is 10 mm tall by 5 mm wide and contains both sharp and large radius turns up to 2.5 mm.

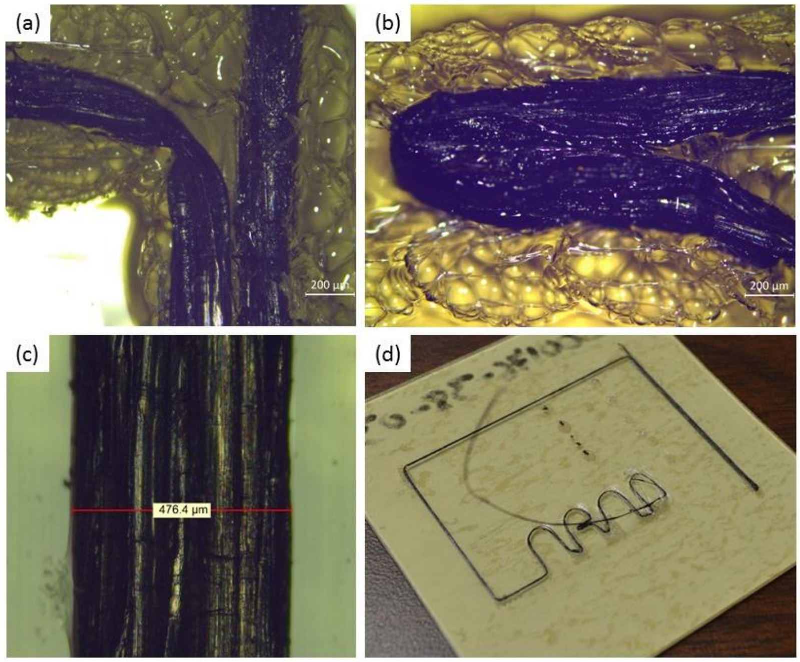


Figure 4. (a) 90° and (b) 180° turn of Ultem™/CNT filament. (c) Two passes of Ultem™/CNT filament showing no visible gap. (d) “NANO” demo test print.

### 3.2 Mechanical Response

Figure 5a shows representative stress-strain curves of the printed CNT yarn reinforced Ultem™ and neat Ultem™ specimens. The ultimate tensile strength of the CNT reinforced parts and neat Ultem™ 1010 parts was 125.30 ± 4.5 and 98.40 ± 8.0 MPa, respectively. The Young’s modulus of both parts was around 3 GPa. The volume content of CNT yarn in the printed parts was calculated to be 4.7%, excluding any voids that may be present in the yarn or neat resin. Values for the ultimate strength were within the range predicted by the rule of mixtures (102.6 and 129.0 MPa) for a 4.7% by volume CNT composite with an as-received yarn strength calculated at 750 MPa. As seen in Figure 5a, the modulus is retained over a larger range of strain (up to 200% relative to the neat Ultem™ sample) in the reinforced samples before failure of the part begins. Inspection of the reinforced parts post-testing revealed CNT residue covering over half of the surface of the Ultem™/CNT interface (Figure 5b). Although tensile load transfer between the Ultem™/CNT filament and Ultem™ matrix was adequate, these results suggest that better wetting through the cross-section of the CNT yarn is needed to improve mechanical performance.

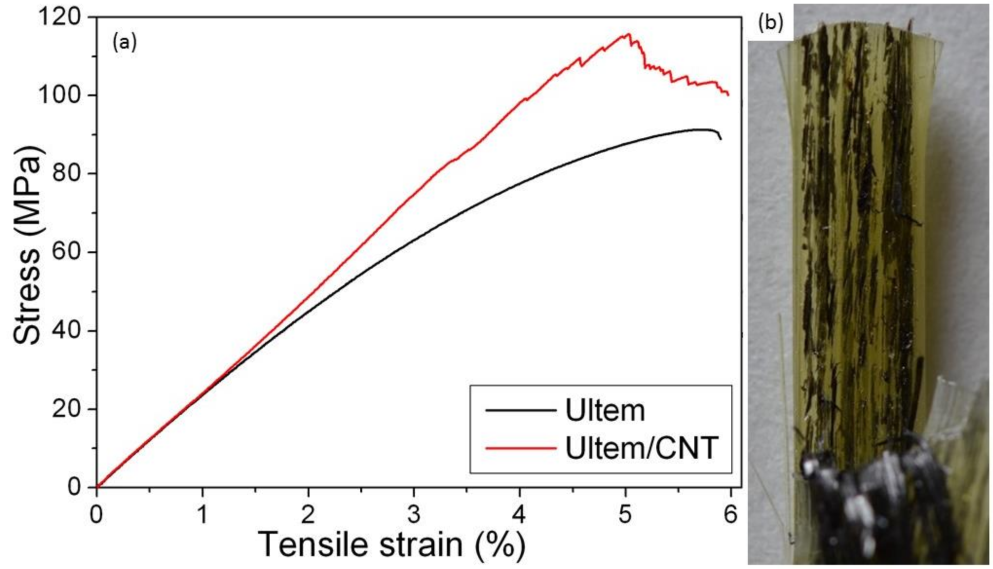


Figure 5. (a) Mechanical response of neat Ultem™ and Ultem™/CNT reinforced tensile specimen. (b) Photo of Ultem™/CNT filament interface after testing to failure.

### 3.3 Electrical and Sensing Performance

Figure 6a shows current-voltage (IV) curves of the current raised from 0 to 0.5 A for printed composites with a 350 µm spacing (identical to the mechanical test specimen) and a 1 mm spacing between the traces. The curves of the composites are linear below 0.2 A with a change in resistance over this point resulting in a change in the slope of the curve. The temperature of the part pushes above 100°C with the application of 5 W of power as shown in the IR thermographs of the composites at maximum current (Figure 6a). These IV curves are congruent with those of the as-received yarns. A demonstration of the functionality of these printed parts is shown in Figure 6b. Here, a 1 W lamp is powered through the same printed part used in the electrical tests.

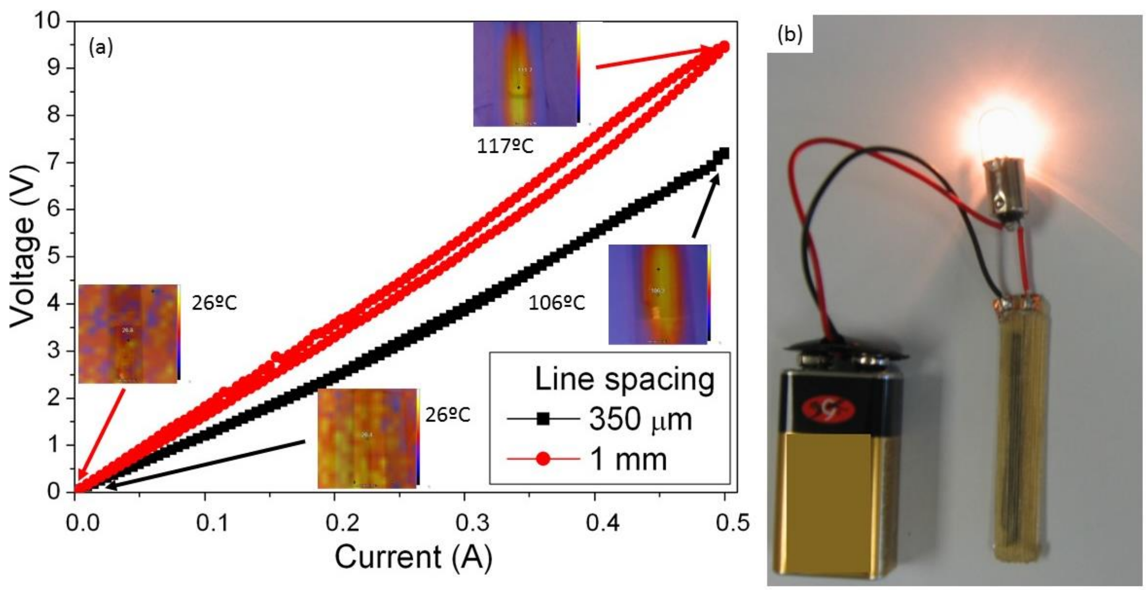

Figure 6. (a) IV curves and related thermographs of Ultem™/CNT filament undergoing Joule heating. (b) One watt bulb powered through Ultem™/CNT filament.

# 4. CONCLUSIONS

This paper demonstrates that multifunctional parts can be produced using high density CNT yarn based materials in conjunction with structural, high temperature aerospace thermoplastics while capitalizing on advantages offered by AM over traditional manufacturing technologies, including those offered by currently available 3D printers. The technology demonstrated enables the production of functional components with reduced mass by utilizing one material for structural, and electrically enabled functions. Potential applications of the Ultem™/CNT filament include but are not limited to strain gauges in structural parts, light-weight embedded data cables, and active heating elements. This manufacturing technology enables the production of parts that take advantage of the benefits offered by advanced part design tools such as topology optimization. This combination of flexible manufacturing and design technologies expand the space of what is possible and can transform the way aerospace components are manufactured providing components with lowered mass, simplifying production (and decreasing cost), as well as increasing reliability.

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