



# Developing enhanced carbon nanotube reinforced composites for full-scale 3D printed components

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Recent research has developed a range of novel nano-enhanced 3D Printer filaments for high-end structural applications. In this research, an enhanced carbon nanotube filament has been formulated with different concentrations of graphitized multiwalled carbon nanotubes. These have been dispersed into an acrylonitrile butadiene styrene polymer matrix under a process of high sheer mixing. This formulation was extruded to form a 1.75 mm diameter filament that was used to 3D print custom full size aerospace components that were later tested and displayed mechanical strength enhancement. In this article the process is detailed which show a method to manufacture 3D printed nanocomposite structures. These polymer filaments can be used on any conventional fused deposition modeling 3D Printing machine for the fabrication of scale components that require mechanical enhancement.

This evolution in enhanced polymer 3D printing filaments allows inventors to produce custom circuit boards, electronic devices, game controllers and custom structural parts [1]. Although this novel type of 3D printing requires slightly more skill due to difficulty in their handling, these materials are now within reach of everyone [2].

The first generation of enhanced filaments used the monomer polycaprolactone (PCL) mixed with conductive carbon black powders [3]. This later evolved into conductive Acrylonitrile butadiene styrene (ABS)-based carbomorph materials that instigated a revolution in home-built consumer electronics fabrication [4]. These 3D printable materials have been investigated as method to produce simple yet important integrated machines, that can be used to detect:

- changes in temperature;
- when water is placed onto a surface;
- applied pressure;
- whether a device is being flexed.

When these actions happen, a difference in electrical resistance is detected. What this means is that devices can now be 3D Printed with integrated functionality which has never before been possible [5]. Further enhancement has been made by adding short

discontinuous lengths of carbon fiber into a polymer matrix to improve structural integrity [6].

Further to this, conventional 3D printing filaments and enhanced filaments can be integrated together in different layers to make multifunctional parts [7]. This advance in low-cost 3D printed, offers the possibility of producing sensors and electronics embedded inside structural 3D printed objects. The uniqueness of this is that devices can be fabricated in a single build. However, one of the major setbacks in enhanced 3D printing filaments is that due to the relatively high concentrations of additions required to reinforce the polymer matrix. This subsequently reduces printability, blocks the nozzle and reduces adhesion to the build platform. Because of this, these formulations are impractical.

During this current research, the objective is to develop a nanostructured 3D printing filament with low concentration additions of MWCNT. These are used to selectively reinforce the underlying polymer matrix at the nanoscale. Due to the high percolation threshold of nanotubes then this results in structures that have complete interconnectivity across the matrix.

In order to generate the filament material, bulk formulations of a test polymer were produced by first dissolving ABS pellets into 2-butanone solvent to form a liquid phase polymer. Mixing was then carried out using high shear impeller mixing at 2000RPM for 4 h to prepare the liquid polymer. Graphitized MWCNT's are

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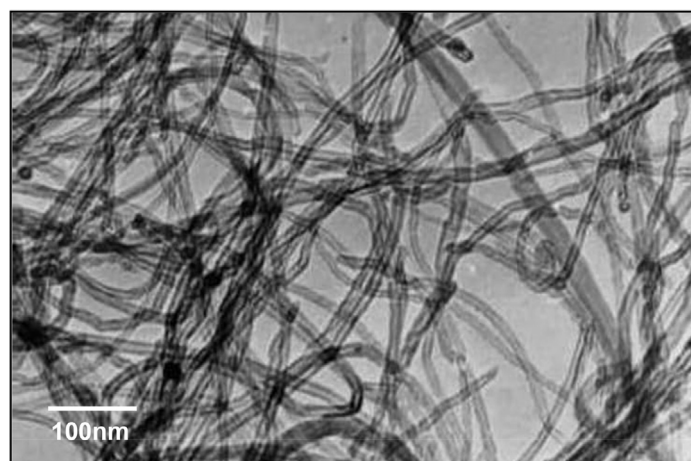


FIG. 1

TEM image of 10–30 nm diameter MWCNT.

shown in the Transmission Electron Microscopy (TEM) image in Fig. 1 were added to the polymer. Graphitized MWCNT 20–30 nm were produced by Catalyzed Chemical Vapor Deposition at 2800 °C to graphitize them. The recorded properties of the MWCNT are displayed in Table 1. Mixing was carried out at 1000RPM for a further 4 h to ensure equal dispersion of the MWCNTs into the matrix. The mixture was then placed into an oven at a temperature of 80 °C for 12 h to remove any remaining solvent and repolymerize the nanostructured enhanced ABS.

The resulting nano-enhanced polymer was then shredded into a 1 mm diameter pellet form and then left to stand at room temperature for a further 24-h. To make the 3D printing filament, an extrusion stage process was undertaken. This involved extruding the pellets down to 1.75 mm diameter continuous filament at 135 °C  $\pm$  2 °C using a hopper and lead-screw with was used to mix, heat and extrude the filament.

The different concentrations of MWCNT that were mixed into the ABS matrix are shown in Table 2. 3-D printing of the nanocomposite filament was carried out using a 3Dynamic Systems Delta FDM printer. This device was used to deposit the material to a layer resolution of 100  $\mu$ m and allowed the fabrication of large

TABLE 1

#### Properties of graphitized MWCNT.

Property	Measurement	Unit
Outer diameter	20–30	Nm
Inside diameter	5–10	Nm
Purity	>99.9	wt%
Length	10–30	$\mu$ m
Specific surface area	55	m <sup>2</sup> /g
Electrical conductivity	>100	S/cm
True density	~2.1	g/cm <sup>3</sup>

TABLE 2

#### Concentrations of MWCNT (wt%) into ABS.

Content MWCNT (wt%)	Matrix Material
1.0	ABS
0.75	ABS
0.5	ABS

TABLE 3

#### 3D printing process parameters.

Printing parameter	Value	Unit
Layer thickness	100	$\mu$ m
Print speed	50	mm/s
Number of shells	4	–
Temperature (extruder)	235	°C
Temperature (build platform)	120	°C
Diameter of extruded plastic	400	$\mu$ m

real-world components. The parameters used to 3-D Print test samples and full sized components are shown in Table 3.

A series of 3D prints using each of the filament formulations was carried out to generate test structures that would act as a reference to analyze the dimensional accuracy of the nanocomposite post 3D printing. This full-sized structure is shown in Fig. 2 displayed good adhesion to the build platform, linear accuracy of  $\pm 0.75\%$  and curved accuracy of  $\pm 0.8^\circ$ .

Fig. 3 shows a WLI scan of a single 3D printed layer. Under high magnification the morphology of the nanocomposite was observed in detail. Here the structure shows that a completely homogeneous structure was formed and that the effect of MWCNT's is of no negative effect towards the print.

The importance of nanocomposite architectures is that due to the increased surface area induced when the MWCNT are added to the matrix polymer. However, as the concentration of MWCNT is increased then this also increases the glass transition temperature

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FIG. 2

A 3D printed nanocomposite full size aircraft wing rib produced to test the dimensional accuracy and a 3D scan showing the layer resolution of the structure with 1% MWCNT.

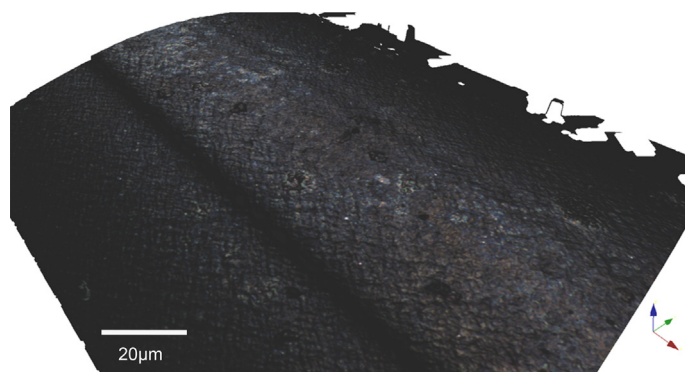


FIG. 3

3D WLI topographical scan of a single layer showing the morphology of the surface structure.

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