Macroporous All-Carbon Scaffolds for Biomedical Applications

Gaurav Lalwani, Andrea Trinward Kwaczala, Shruti Kanakia, Sunny C. Patel, Stefan Judex, and Balaji Sitharaman*

Department of Biomedical Engineering, Stony Brook University, Stony Brook, New York 11794-5281
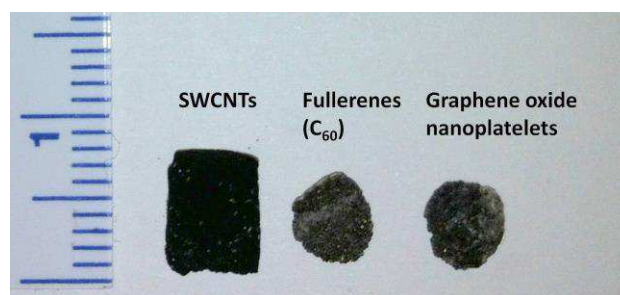

Figure 1: Optical images of unpurified cylinder (5mm diameter, 8mm thickness), and discs (5mm diameter, 3mm thickness) fabricated using SWCNTs, fullerenes and graphene oxide nanoplatelets as starting material.

The assembly of carbon nanomaterials such as carbon nanotubes, fullerenes, or graphene into three-dimensional (3-D) structures is necessary to harness their remarkable physio-chemical properties for a large number of applications such as the next-generation energy storage, catalytic, electro-mechanical, photonic, and biomedical devices.[1-3] Over the last decade, 3-D pristine carbon nanotube (CNT) structures have been fabricated on the sub-micron, micron using various techniques such as chemical vapor deposition, substrate patterning, and capillary-induced self-assembly.[4-6] Macroscopic scale (> 1mm in two or all three dimensions) structures of vertically aligned or entangled networks of pristine CNTs have also been fabricated.[7] However, the suitability of these approaches to form covalent bonds between CNTs; an important feature for many applications,[8] or synthesize 3-D macroscale structures using other carbon nanomaterials such as fullerenes, and graphene still has to be demonstrated. Furthermore, these approaches may present a practical challenge to develop macroscopic-scale (> 1mm in all 3 dimensions) carbon devices; either due to scalability issues, or high operational cost.

We report a facile method to fabricate macroscopic, 3-D, free standing, all-carbon scaffolds (porous structures) using multiwalled carbon nanotubes (MWCNTs) as the starting materials (Figure 1). The scaffolds prepared via radical initiated thermal crosslinking, and annealing of MWCNTs possess macro-scale interconnected pores as determined by microCT, liquid extrusion porosimetry and SEM image processing. They possess robust structural integrity (elastic modulus = 45.72 ± 18.78 MPa, hardness = 3.47 ± 1.73 MPa, determined by nanoindentation), thermal stability (15.06% weight loss between 150-500°C, determined by TGA analysis), and electrical conductivity (2×10^{-1} S cm^{-1}, determined by four-point resistivity measurements). Raman spectroscopic and XPS analysis showed that carbon and oxygen were the primary elements in the scaffolds. Additionally, TEM and HRSEM analysis confirms the crosslinking of carbon nanotubes, forming a macroscopic three-dimensional scaffold.

We also show that the porosity of the three-dimensional structure can be controlled by varying the amount of radical initiator, thereby allowing the design of porous scaffolds tailored towards specific potential applications. Furthermore, this method also allows fabrication of 3-D scaffolds using other carbon nanomaterials such as single-walled carbon nanotubes, fullerenes, and graphene, indicating that it could be used as a versatile method for 3-D assembly of carbon nanostructures with pi bond networks (Figure 2). Additionally, the fabrication process of the scaffolds is rapid, cheap, and scalable, and can be adapted to fabricate scaffolds with various geometries (e.g. cylinders, disks) thereby opening avenues for structure-function studies towards the development of macroscopic all-carbon devices.

References:

[1] H. Dai, Acc Chem Res 2002, 35, 1035
[2] D. M. Sun, Nat Nanotechnol 2011, 6, 156.
[3] B. Sitharaman, Bone 2008, 43, 362.
[4] Z. F. Ren, Science 1998, 282, 1105
[5] M. De Volder, Adv Mater 2010, 22, 4384.
[6] Chakrapani N, Proc Natl Acad Sci U S A 2004, 101, 4009.
[7] M. Xu, Science 2010, 330, 1364.
[8] D. P. Hashim, Sci. Rep. 2012, 2.

Figure 2: Optical images of purified MWCNT scaffolds prepared as cylinders (5 mm diameter, 8 mm length), and disks (5 mm diameter, 4 mm thickness).