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Small but strong: A review of the mechanical properties of carbon nanotube–polymer composites

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Abstract

The superlative mechanical properties of carbon nanotubes make them the filler material of choice for composite reinforcement. In this paper we review the progress to date in the field of mechanical reinforcement of polymers using nanotubes. Initially, the basics of fibre reinforced composites are introduced and the prerequisites for successful reinforcement discussed. The effectiveness of different processing methods is compared and the state of the art demonstrated. In addition we discuss the levels of reinforcement that have actually been achieved. While the focus will be on enhancement of Young's modulus we will also discuss enhancement of strength and toughness. Finally we compare and tabulate these results. This leads to a discussion of the most promising processing methods for mechanical reinforcement and the outlook for the future.

Keywords: Carbon nanotubes; Mechanical properties; Carbon composites

Contents

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1. Introduction

Since their discovery in 1991, carbon nanotubes have generated huge activity in most areas of science and engineering due to their unprecedented physical and chemical properties. No previous material has displayed the combination of superlative mechanical, thermal and electronic properties attributed to them. These properties make nanotubes ideal, not only for a wide range of applications [1] but as a test bed for fundamental science [2].

In particular, this combination of properties makes them ideal candidates as advanced filler materials in composites. Researchers have envisaged taking advantage of their conductivity and high aspect ratio to produce conductive plastics with exceedingly low percolation thresholds [3]. In another area, it is thought that their massive thermal conductivity can be exploited to make thermally conductive composites [4]. However, probably the most promising area of composites research involves the mechanical enhancement of plastics using carbon nanotubes as reinforcing fillers.

The idea of using pseudo one-dimensional fillers as a reinforcing agent is nothing new: straw has been used to reinforce mud bricks since about 4000 BC. In more recent times, fibres made from materials such as alumina, glass, boron, silicon carbide and especially carbon have been used as fillers in composites. However, these conventional fibres have dimensions on the meso-scale with diameters of tens of microns and lengths of order of millimetres. Their mechanical properties are impressive with carbon fibres typically displaying stiffness and strength in the ranges 230–725 GPa and 1.5–4.8 GPa, respectively [5]. In recent years carbon nanofibres have been grown from the vapor phase with diameters of order of 100 nm and lengths between 20 and 100 μm. These small dimensions mean they have much higher surface area per unit mass than conventional carbon fibres allowing much greater interaction with composite matrices. They also tend to have impressive mechanical properties with Young's modulus in the range 100–1000 GPa and strengths between 2.5 and 3.5 GPa [6].

However the ultimate mechanical filler material must be carbon nanotubes. Nanotubes can have diameters ranging from 1 to 100 nm and lengths of up to millimetres [7]. Their densities can be as low as $\sim$1.3 g/cm^3 and their Young's moduli are superior to all carbon fibres with values greater than 1 TPa [8]. However, their strength is what really sets them apart. The highest measured strength for a carbon nanotube was 63 GPa [9]. This is an order of magnitude stronger than high strength carbon fibres. Even the weakest type of carbon nanotubes have strengths of several GPa [10].

However a large amount of work will have to be done before we can really make the most of the exceptional mechanical properties of carbon nanotubes. In this paper we will explore the progress that has already been made to this end. First we will review the properties of carbon nanotubes and the theory of fibre reinforcement. This will lead us to a study of the system requirements in order to achieve reinforcement. The techniques used in the literature to produce polymer–nanotube composites will be reviewed before we look at what levels of reinforcements have actually been achieved. Finally we will discuss the advances made so far and study what needs to be done in the future.

2. Properties of nanotubes

There are two main types of nanotubes available today. Single walled nanotubes (SWNT) [11,12] consist of a single sheet of graphene rolled seamlessly to form a cylinder with diameter of order of 1 nm and length of up to centimetres. Multi-walled nanotubes (MWNT) consist of an array of such cylinders formed concentrically and separated by 0.35 nm, similar to the basal plane separation in graphite [13]. MWNTs can have diameters from 2 to 100 nm and lengths of tens of microns.

Single walled nanotubes can be fabricated in a variety of ways. Early fabrication relied on a modified version of