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Perspectives of carbon nanotubes/polymer nanocomposites for wind blade materials

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A B S T R A C T

The global market for wind energy has increased exponentially in the past few decades, and there is a continuous effort to develop cost-effective materials with higher strength to mass ratio for wind blades. With unique structural and transport properties, carbon nanotubes (CNTs) have attracted much interest as the reinforcement to develop polymer-based nanocomposites delivering exceptional mechanical properties and multi-functional characteristics. In light of previous and current status in carbon-based materials, herein the suitabilities of CNT/polymer nanocomposites for wind blade materials are analyzed. Special emphasis is placed on the mechanical, fatigue, electrical, thermal and barrier properties of CNT/polymer nanocomposites, which are important considerations when selecting suitable materials for wind blades with larger rotary radius. The application of CNT/polymer nanocomposites as sensory materials for the monitoring of defects in composite structures is also discussed. Finally, based on the progress made so far, some suggestions paving the way for the large commercialization of these nanocomposites for wind blades are presented.

Contents

1. Introduction

Wind power, the conversion of wind energy into a useful form of energy, has become an increasingly attractive source of energy generation in past three decades. As an alternative to fossil fuel, wind power is in characteristic of plentiful, renewable, widely distributed, clean, and producing no greenhouse gas emissions during the generation and operation. In 2012 the world wind capacity reached 282 GW, growing by 44 GW over the preceding year, and the distribution by top 10 countries is shown in Fig. 1A [1]. All wind turbines installed by the end of 2012 worldwide can provide 580 TW per annum, which is more than 3% of the global electricity demand [2]. It is predicted that the total wind electricity will increase rapidly in next 15 years, with the fastest development of new capacity taking place in China and India [1,2].

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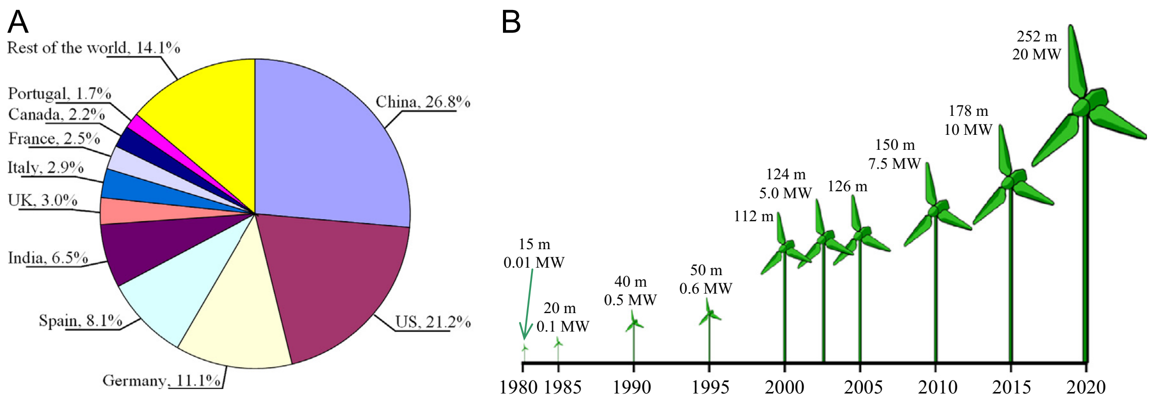

Fig. 1. (A) Distribution of wind power capacity produced by top 10 countries in 2012; and (B) development of wind turbine with larger rotor diameter and higher power capacity since 1980 [1–4].

Table 1
Physical and applicable properties of different carbon-based materials [5].

Properties	Carbon materials				
	Graphite	Diamond	Fullerene	Carbon fiber	CNT
Specific gravity (g/cm^3)	1.9–2.3	3.5	1.7	1.8–2.1	0.8–1.8
Tensile modulus (GPa)	1000[a] 36.5[b]	500–1000	14	100–500	1000
Tensile strength (GPa)	~ 10[a] < 0.01[b]	1.2	N/A	1.0–5.6	> 10
Electrical conductivity (S/cm)	4000[a] 3.3[b]	10^{-2}–10^{-15}	10^{-5}	10^2–10^4	10^2–10^6
Electron mobility ($cm^2/(V\ s)$)	$\sim 10^4$	1800	0.5–6	10^2–10^4	10^4–10^6
Thermal conductivity (W/(m K))	298[a] 2.2[b]	900–2320	0.4	21–180	2000–6000
Coefficient of thermal expansion (K^{-1})	-1×10^{-6}[a] 2.9×10^{-5}[b]	$(1–3) \times 10^{-6}$	6.2×10^{-5}	$\sim 1 \times 10^{-6}$	Negligible
Thermal stability in air (°C)	450–600	< 600	< 600	500-600	> 650
Cost/Price (US$/g)	0.01–0.002	> 100	40–70	0.02–0.1	0.3–10
General content in polymer matrix (wt%)	> 10	> 5	> 1	> 10	< 0.5

[a] In-plane.
[b] *c*-Axis.

In order to achieve the expansion expected in this area, there is a strong need for the development of stronger and lighter materials which enable the manufacturing of wind blades with larger rotors. Theoretical and engineering practices have proven that the larger the area through which the wind turbine can rotate, the more wind energy that can be captured, as schematically shown in Fig. 1B [3]. In addition, leading manufacturers of wind blades generally guarantee that the lifetime of products is approximately 20 years [4]. To extend the working lifetime of blades and enable larger area rotors to be cost-effective, it is necessary to design and optimize blade materials to be much stiffer, stronger, and exhibit better fatigue resistance than currently used ones.

The emergence of nanotechnology as a major field of research, especially based on carbon nanotubes (CNTs), has impacted almost every scientific discipline. Different from other carbon materials, such as graphite, diamond and fullerene (C_{60}, C_{70}, etc.), CNTs are one dimensional carbon materials with a tube-like structure which can have a length-to-diameter ratio greater than 1000. Theoretically, this material can be envisioned as cylinders composed of rolled-up graphite planes with diameters in nanometer scale. The cylindrical nanotube usually has at least one end capped with a hemisphere of fullerene structure [5].

With this unique structure and inherent nature of carbon material, CNTs exhibits some properties which are distinctive from other carbon allotropies. Table 1 summarizes the physical and applicable properties of different carbon-based materials [5]. It is clear that CNTs have many advantages over other carbon materials, offering CNTs great potential to develop high performance material for various applications.

Wood and canvas were used at the early stage of windmills due to their low price, availability, and ease of manufacture. Small blades can also be made from light-weight metals like aluminum and its alloys. These materials, however, require frequent maintenance and limit the blade shape to be a flat plate, which has a relatively low aerodynamic efficiency to capture wind energy [6]. Polymer composites, consisting of additives and polymer matrices including thermoplastics, thermosets and elastomers, are considered to be an important group of relatively inexpensive materials for many engineering applications. These materials are also the fundamental for the structure of modern wind blades. Constituent materials with different properties are selected to fabricate polymer-based composites to improve one or more properties: for example, nature or man-made fibers are introduced into polymer matrices to fabricate composites that have enhanced mechanical and fracture properties. However, there are bottlenecks in optimizing the properties of polymer composites by employing traditional microscale fillers, the reasons are two-folds: (i) The content of conventional filler in polymer composites is generally in the range of 10–70 wt%, giving rise to a higher density than that of the neat polymer matrix; and (ii) stiffness of polymer composites is often traded for toughness, and microscopic defects and voids arising from the high volume fraction of filler often lead to premature failure of the composites [7].

The introduction of nanoscale CNTs as an additive into a polymer resin results in CNT/polymer nanocomposites. Different