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Storing energy and powering small systems with mechanical springs made of carbon nanotube yarn

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ABSTRACT

CNT (carbon nanotube) yarns stretched in tension as mechanical springs are used to drive both electrical and mechanical loads in order to demonstrate the CNT yarns' potential for high power density, their potential for metered energy release, and their application to power practical systems. The energy-storing properties of the CNT yarn are characterized, and the design, operation, and characterization of three demonstration systems that store energy in stretched CNT yarns and release it to drive an electrical or mechanical load are presented. When loaded in tension, the yarn stores energy with an energy per unit length of up to 13.4 mJ/m and an energy density of up to 7720 kJ/m^3 or 6.7 kJ/kg. The CNT spring-driven demonstration systems include a mechanical slingshot and two mechanically-driven electric power supplies. The slingshot releases energy stored in a stretched CNT spring rapidly to launch a projectile, with up to 56% power extraction efficiency. The first electric power supply converts stored mechanical energy into electric power using an escapement-based power regulation mechanism and piezoelectric energy conversion. The second electric power supply uses an electromagnetic conversion system to convert energy stored in the CNT spring to electric output power without regulating the rate of energy release from the spring. The devices demonstrate that CNT yarn can be used to drive mechanical and electrical loads using both quick-release devices that provide high power, and slow-release, escapement-metered systems.

1. Introduction

CNTs (carbon nanotubes) can improve the storage and conversion of energy across a wide range of applications and engineering domains. Research has shown that lithium batteries can achieve improved performance by integrating CNTs into their electrodes (see for example [1–5] as well as [6] and the references therein). It is also well-established that incorporating CNTs into the electrodes of supercapacitors offers performance increases, as shown for example in Refs. [7,8] and in Ref. [9] and its references. However, the energy applications of CNTs are not limited to electrical or electrochemical energy storage. CNTs can act as effective catalyst supports in fuel cells [10,11], enhance heat transfer to speed discharge (i.e. increase power density) of thermal energy storage systems [12], and more.

The storage of energy in elastic deformations in the mechanical domain offers an alternative to the electrical, electrochemical, chemical, and thermal energy storage approaches described above. Part of the appeal of elastic energy storage is its ability to discharge quickly, enabling high power densities. For example, energy stored in stretched elastomer springs was used to propel a jumping microrobot [13]. CNTs offer advantages for this type of elastic energy storage. Indeed, energy storage in springs made of CNTs has the potential to surpass both the energy density of electrochemical batteries and the power density of electrochemical capacitors [14–16] due to the 1 TPa stiffness of CNTs and their high elastic strain limits of up to 13% [17]. Ideal, defect-free CNTs are predicted to have a maximum energy density of 7.7 × 10^6 kJ/m^3 or 5 × 10^3 kJ/kg [15], three orders of magnitude greater than the energy density of conventional springs made of steel and higher than the 2 × 10^6 kJ/m^3 or 730 kJ/kg energy density of rechargeable lithium-ion batteries

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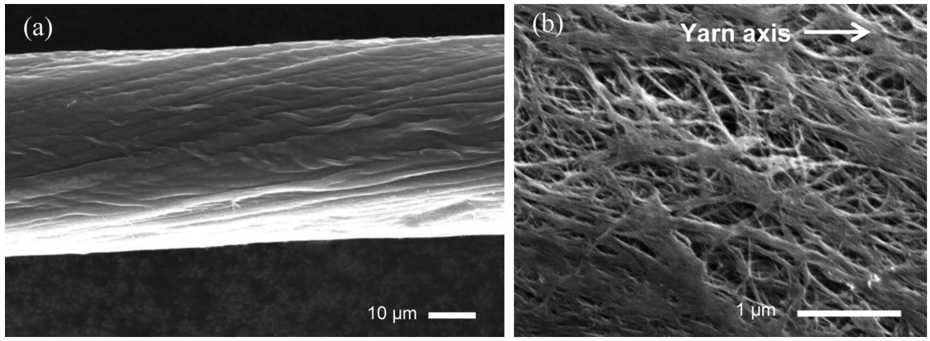

Fig. 1. (a) SEM (scanning electron microscope) image of the yarn and (b) a high resolution SEM image of the yarn surface.

[18]. At the molecular scale, CNTs can function as ideal mechanical springs that store a great deal of energy for their size, but a single CNT does not store a useful amount of energy. Large numbers of CNTs are needed to power macroscopic systems, and the CNTs should preferably be organized into ordered arrays such as yarns.

CNT yarns that were twisted to the point of entanglement have been demonstrated to drive a load in Ref. [19]; as the yarn untwists, a mass suspended at the bottom of the yarn rotates and descends as the yarn elongates. This system's extracted energy density of 8.3 kJ/kg was released over tens of seconds, corresponding to a power density of less than 1 kW/kg. In Ref. [20], twisted CNT yarns infiltrated with a volume-expanding guest (e.g. paraffin wax) were electrically, chemically, and photonically actuated. A power density of 27.9 kW/kg is reported for contractile actuation; the system is also demonstrated to drive rotation of a paddle.

The present research builds on the work of [19,20] by delivering the energy stored in CNT yarns not only to mechanical loads, but also to systems that convert the released energy to the electrical domain to drive an electrical load. The purposes of the research reported here are (i) to store macroscopic amounts of energy in large, ordered arrays of CNTs loaded in tension, (ii) to demonstrate their high power density energy release, (iii) to apply the released power to drive macroscopic mechanical and electrical systems, and (iv) to demonstrate the metered delivery of the released energy to systems where high power density is not desired. The present research employs CNT spun yarn as a spring material because its relatively ordered structure allows many hundreds of millions of CNTs to be strained at once to achieve large-scale energy storage. In addition the amount of stored energy can be tuned by changing the yarn's length and the number of CNTs in the cross-section. Using this material, the current work demonstrates the first use of CNT springs loaded in tension to impart kinetic energy to a mechanical load, as well as the first application of CNT springs to output electrical power. In particular, the design, operation, and characterization of a slingshot and two electric power supplies (effectively CNT spring-driven electric batteries) are presented. The slingshot directly converts the stored elastic energy of a stretched CNT yarn into kinetic energy of a projectile. The first electric battery extracts stored mechanical energy using a metered-release system with piezoelectric energy conversion; the second electric battery uses an unmetered electromagnetic conversion system to convert energy from a CNT spring into electricity. These results are supported by measurements of the storage of energy in and release of energy from the CNT yarns from which the mechanical springs are made.

2. Yarn properties

The yarn (Fig. 1) contains both single-walled and multiwalled CNTs, with most between 3 nm and 8 nm diameter, that are grown by a gas phase synthesis process that incorporates a free-flowing catalyst and spun into yarn. The tested yarn has an average outer diameter of 47 μm and an average linear mass density of 2 tex (1 tex = 1 mg/m). Yarn specimens with average gauge length of 4.8 mm (standard deviation of 0.2 mm) were prepared for tensile test to failure by attaching segments of yarn onto frames made of card stock using epoxy (Pacer Z-Poxy). Tension tests were conducted using an Instron 8848 MicroTester with a 10 N load cell. To measure the displacement and strain in the yarn during tensile testing, small white paint dots were applied to the surface of the yarn. Sequential, high resolution images were taken of the yarn during loading using a Spot Idea camera. Displacement data were extracted using digital image correlation (Vic-2D, Correlated Solutions) and were converted to strain in the regions between the dots. Tension tests to failure were conducted at an extension rate of 0.004 mm/s. The modulus was calculated from the slope of the stress–strain curve between 0 and 1%.

Stress-strain curves of six yarn samples tested in tension to failure are shown in Fig. 2. These yarn samples all have a gauge length of 5 mm ± 0.09 mm. The curves show that the yarn loads non-linearly, with a high initial stiffness and a gradual decrease in stiffness up to the failure strain. The curves also display a distribution of curve shapes, and the measured strength, stiffness and failure strain values vary among samples that are nearly the same length, indicating a degree of variability in the properties of the yarn. Over the 34 samples measured with average gauge length of 4.8 mm, the yarn has an average strength of 1.0 GPa or 0.86 N/tex, with a standard deviation of 0.093 N/tex or 0.11 GPa. The average yarn stiffness is 44.7 N/tex or 51.5 GPa, with a standard deviation of 8.4 N/tex or 9.7 GPa. Correlations are observed between the measured strength and stiffness of the yarn samples and the

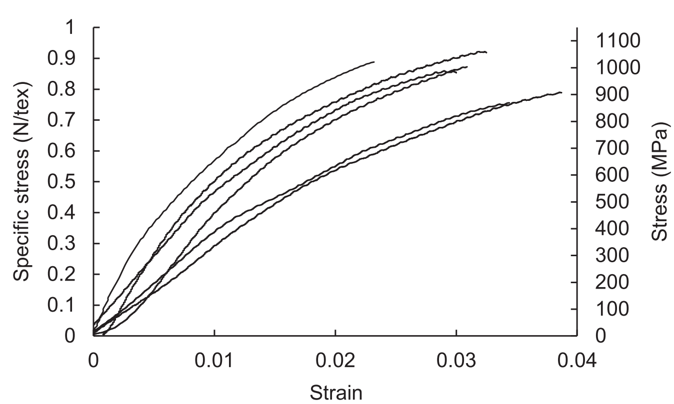

Fig. 2. Sample specific stress vs. strain curves of yarns loaded in tension to failure.