Advanced Continuous Nanofibers and Products

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1. Introduction

Continuous nanofibers possess considerable advantages to discontinuous nanomaterials, such as nanoparticles, nanorods, and carbon nanotubes. These include cost-efficiency, reduced health hazard, and the possibility of integrated nanomanufacturing of nanofiber assemblies. Continuous nanofibers with diameters several orders of magnitude smaller than the diameters of conventional advanced fibers can revolutionize existing and create entirely new applications. Examples include smart textiles, superstrong/tough and transparent composites, tailored coatings, structural elements in MEMS/NEMS, and many others.

Progress in these and other areas depends on the development of reliable methods of nanofiber manufacturing, assembly, and processing into applications, and on our ability to predict and optimize their mechanical and other properties. This lecture reviews the state-of-the-art on an emerging nanomanufacturing technology of electrospinning producing continuous nanofibers with diameters one to four orders of magnitude smaller than diameters available via conventional mechanical spinning processes. Recent breakthroughs on process analysis and control are discussed. Examples of advanced continuous polymer, carbon and ceramic nanofibers are presented and compared to conventional advanced fibers and carbon nanotubes. Applications of continuous nanofibers are discussed. Several unique, structural nanocomposite designs utilizing nanofibers in small quantities are introduced and their manufacturing, testing, and modeling are discussed. Substantial improvements in static, fatigue, and impact properties of these composites are demonstrated. Status and prospects for commercial application of continuous nanofibers are analyzed.

2. Continuous Nanofibers – Next Big Nanotech

Electrospinning is an emerging technology producing continuous nanofibers from solutions in high electric fields [1]. When the electric force on induced charges overcomes surface tension, a thin jet is ejected from a polymer liquid. The charged jet is elongated and accelerated by the electric field, undergoes a variety of instabilities, dries, and is deposited on a substrate as a random nanofiber mat. Recently, the process attracted rapidly growing interest triggered by many potential applications of nanofibers in textiles and nanotechnology. More than two hundreds of synthetic and natural polymers and other materials were processed into fibers with diameters ranging from a few nanometers to microns (Figure 1A). The main advantage of this top-down nanomanufacturing process is its relatively low cost compared to most bottom-up nanomanufacturing methods. The resulting nanofibers are uniform in diameter and do not require expensive purification (Figures 1B and 1C). Unlike submicron diameter whiskers, inorganic nanorods, carbon nanotubes, and nanowires, the electrospun nanofibers are continuous. As a result, this process has unique potential for cost effective electromechanical control of fiber placement and integrated manufacturing of two- and three-dimensional nanofiber assemblies (Figures 1D and 1E). In addition, the nanofiber continuity is expected to alleviate the concerns about the properties of small particles, which have begun to catch the attention of the public. Continuous nanofibers are expected to possess improved mechanical properties combined with very high flexibility. The nanofiber assemblies feature very high open porosity coupled with remarkable specific surface area. Yet, these assemblies posses structural mechanical properties. Uses of nanofibers in textiles, composites, protective clothing, catalysis, electronics, biomedicine (including tissue engineering, implants, membranes, and drug delivery), filtration, agriculture, space and other areas are presently being developed.

Recent breakthroughs in this rapidly evolving field are reviewed in this lecture. Progress on theoretical and experimental analysis and understanding of the nanomanufacturing process is reviewed. Several methods of aligned nanofiber manufacturing are analyzed experimentally and theoretically and their prospects for textile applications are compared. Examples of novel high-performance continuous polymer, carbon, and ceramic nanofibers are presented and compared to commercially available reinforcing fibers and carbon nanotubes. Modeling-based development of integrated methods of controlled nanomanufacturing of nanofiber assemblies is described and examples of highly aligned and ordered 1D, 2D, and 3D assemblies are presented. Pioneering nanomanufacturing of nanocrystalline ceramic (Figure 1F) and carbon nanofibers is discussed.

3. Nanofiber-Reinforced Supercomposites

Several ways to utilize nanofibers economically in advanced structural nanocomposites are introduced and discussed in the lecture. These include nanocomposites with interphases and several hybrid nano/microcomposite designs. A pioneering design of advanced composites with nanofiber-reinforced interfaces is introduced and analyzed in depth. Revolutionary effects

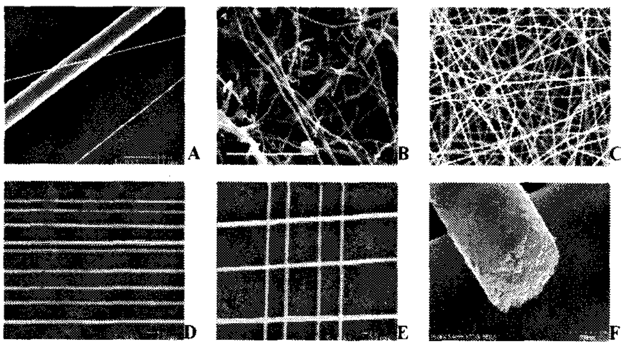

Fig. 1: Comparison of commercial advanced carbon fiber, one of the smallest advanced fibers available, and electrospun continuous nanofibers (A). Comparison of vapor grown commercial carbon nanotubes (B) and electrospun carbon nanofibers (C) showing substantially improved nanofiber uniformity and sample purity. Examples of highly aligned linear and orthogonal assemblies of continuous nanofibers produced by the developed novel method of alignment (D, E). Cross-section of continuous nanocrystalline zirconia nanofiber for potential applications in supertough ceramic nanocomposites with dual nano structure (F).

durability of composites are demonstrated at of nanofiber reinforcement on static and fatigue fracture toughness, strength, and a negligible increase of weight of the composites. Experimental and numerical evaluation of nanomechanisms of improvement is discussed. Recent results on quantitative evaluation of dynamic impact fracture toughness in these novel materials are presented. Current work in progress and prospects for international collaboration in the field are discussed.

4. Conclusions

Continuous polymer, carbon, and ceramic nanofibers have critical advantages for textile and other applications compared to the discontinuous carbon or other nanotubes or nanorods in terms of the cost, health concerns, and the possibility of integrated one-step manufacturing of aligned nanofiber assemblies. Further fundamental experimental and theoretical analysis of the process and resulting nanomaterials are needed in order to develop optimal application designs and flexible and reliable methods of their nanofabrication.

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