PROGRESS ON NOVEL CONTINUOUS NANOFIBERS AND ADVANCED STRUCTURAL NANOCOMPOSITES

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Keywords: *continuous polymer, carbon, and ceramic nanofibers; structural nanocomposites*

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 superstrong/tough and transparent composites and 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 nanocomposites, and on our ability to predict and optimize their mechanical and physical properties. This lecture reviews recent progress on emerging nanomanufacturing technology producing continuous nanofibers with diameters one to three 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 in advanced composites are discussed. Several unique, economic 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 in structural nanocomposites are analyzed.

2 Continuous Nanofibers – Novel Class of Nanomaterials with Critical Advantages for Applications

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 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 methods. The resulting nanofibers are often uniform 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 may alleviate, at least to an extent, the concerns about the properties of small particles, which have begun to catch the attention of the public. Continuous nanofibers can possess extreme mechanical properties combined with very high flexibility. Uses of nanofibers in composites, protective clothing, catalysis, electronics, biomedicine (including tissue engineering, implants, membranes, and drug delivery), filtration, agriculture, space and other areas are presently being developed.

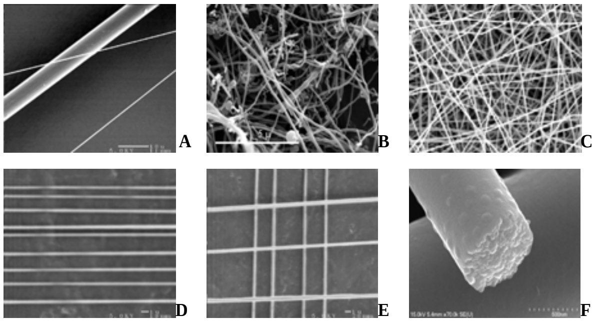

Fig. 1. Comparison of commercial advanced carbon fiber, one of the smallest advanced fibers available, and electrospun continuous nanofibers (A). Comparison of vapor grown commercial carbon nanotubes (B) and electrospun carbon nanofibers (C) showing substantially improved nanofiber uniformity and sample 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).

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. 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 aligned and ordered 1D, 2D, and 3D assemblies are presented. Pioneering nanomanufacturing of nanocrystalline ceramic (Figure 1F) and carbon nanofibers is discussed. A recent breakthrough on direct nanofabrication of highly aligned and dense yarns of continuous nanofibers is presented and discussed.

3 Nanofiber-Reinforced Nanocomposites

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 of nanofiber reinforcement on static and fatigue fracture toughness, strength, and durability of composites are demonstrated at 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 composite 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 horizontally aligned nanofiber assemblies. Fundamental experimental and theoretical analysis of the process and resulting nanomaterials are needed in order to develop optimal nanocomposite designs and flexible and reliable methods of their nanofabrication.

References

[1] Dzenis Y. Spinning Continuous Nanofibers for Nanotechnology. *Science*, 304, 2004, 1917