Breaking High-Performance Fiber Development Paradigm: Continuous Supernanofibers for the Ultratough Structural Composites

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Classical manufacturing techniques for ultrahigh-performance polymer fibers rely on combination of high polymer crystallinity and high degree of macromolecular alignment to achieve superior mechanical properties. As a consequence, advanced fibers such as Kevlar and Spectra possess extraordinary strength but low strain to failure (<3%) and therefore low toughness. Our recent analysis of electrospun polyacrylonitrile (PAN) nanofibers (NFs) in the ultrafine (100-250 nm) diameter range showed extraordinary simultaneous increases in strength, modulus, AND toughness. Finest nanofilaments exhibited strength on the par with the best advanced fibers while exceeding their toughness by more than an order of magnitude. Structural investigations showed that this unique and highly desirable mechanical behavior may be due to high degree of macromolecular alignment in conjunction with *low crystallinity*. We have demonstrated that it is possible to further improve NF mechanical properties by changing nanomanufacturing parameters. Reduction in crystallinity of nanofibers achieved through modified processing resulted in further increases in strain to failure and toughness. Remarkably, it has also resulted in improvements in NF strength and modulus that were attributed to improved polymer chain alignment as a result of increased drawability. Notably, the major improvements in mechanical properties were observed in the intermediate (250-500 nm) diameter range. NFs with these larger diameters are easier to produce and handle, simplifying the upscaling of the nanomanufacturing process. Reported dramatic (2-3 orders of magnitude) simultaneous improvements in mechanical properties of NFs can lead to inexpensive, simultaneously strong and tough composites and structures for safety critical applications. The proposed structural explanation of our discovered NF mechanical behavior challenges the prevailing paradigm in advanced fiber development calling for *high polymer crystallinity* and can lead to the entirely new class of advanced fibers with ultrahigh toughness, in addition to strength. Such fibers can ultimately result in ultralight structures with the strength higher than carbon-epoxy composites (the current state-of-the-art) but much higher toughness rivaling that of metals. Supporting recent results on several other polymer systems and carbon, as well as applications of these novel fibers in hierarchical supercomposites are also demonstrated and discussed.

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Bio Sketch for Y. Dzenis

Dr. Yuris Dzenis is a McBroom Professor of Engineering at UNL. He has earned his PhD in Aerospace and Mechanical Engineering from the University of Texas, PhD in Physics and Mechanics of Polymers from Latvian Academy of Sciences, and MS in Physics (Electrodynamics of Continua) from Latvian

University. He has been a research fellow at the Institute of Polymer Mechanics, Latvian Academy of Sciences, a research scientist at the Institute of Polymer Science, University of Akron and the Institute of Composite Materials, University of Kaiserslautern, and a visiting professor at Doshisha University, Kyoto (twice), University of Canterbury, Christchurch, New Zealand (Erskine Fellow – three times), University of Paris – VI (twice), and University of Trento, Italy. Dr. Dzenis' research interests are in design, manufacturing, modeling, and characterization of advanced nanomaterials, composites, and products. He has been a PI/PD on over 30 federal nanotechnology projects from NSF, AFOSR, ARO, ONR, and DARPA and has developed unique interdisciplinary $4.9M *Advanced Nanomaterials and Nanomanufacturing Laboratories*. Prof. Dzenis has developed and studied a number of unusual advanced materials including composites with aggregating and hollow inclusions, particulate/fiber hybrids, ultra-high-performance continuous polymer, carbon, and ceramic nanofibers, and hierarchical nano/micro composites. He has introduced and developed several nanomanufacturing and hybrid manufacturing technologies to produce advanced nanomaterials. He has introduced a concept of nanoreinforcement of interfaces and pioneered development of cost-effective delamination resistant nanomodified structural composites. Most recent advances included the discovery and explanation of simultaneously high strength and toughness of ultrafine continuous nanofibers. He is currently involved in the development of manufacturing processes and applications for several multifunctional nanofibers, in collaboration with colleagues from various disciplines. Dr. Dzenis is a member of six professional societies and serves on a number of US national panels and committees on nanomanufacturing, advanced materials, and NDE. He has been a plenary speaker at over 30 US national and international conferences on nanotechnology, materials, mechanics, NDE, and composites and has written two invited perspectives on continuous nanofibers and structural nanocomposites for *Science*. He is a Graduate Fellow in the PhD fields of Engineering Mechanics, Chemical and Materials Engineering, and Biomedical Engineering and supervises PhD students in each of these fields. He currently serves as a vice-chair and chair-elect of the NDPD Division of ASME and is an associate editor of the ASME Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems**.**