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Introduction to Nanocomposites

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Nanocomposites are materials that are composed of two or more constituents, with different physical and chemical properties, which remain separate and distinct at the microscopic level but collectively comprise a single physical material possessing any phase dimension of less than 100 nm [1–3]. In the broadest sense, the primary motivation of making a nanocomposite is to integrate one or more discontinuous nano-dimensional phases into a single continuous macrophase to generate "synergistic properties;" that is, the physical/chemical properties of the combined entity are inherently different from, and hopefully superior to, those of the individual material constituents. In this context, one of the combined material's constituents is generally in much greater concentration and forms a continuous "matrix" surrounding the others, which assume the role of a "nanofiller" or "reinforcement." During the nanocomposite formation process, each of the distinct phases is structure- and property-integrated to fabricate hybrid materials that possess multifunctionalities in terms of both structures and material properties. As scientific and societal needs in the late twentieth century drove the demand for higher-performance, sustainable, and multifunctional nanomaterials, more innovative nanotechnology and nanocomposites were increasingly investigated. The advent of new materials and characterization tools in the nanotechnology domain has been paving the way for the latest design of next-generation nanocomposites that not only are easily controllable but also possess multiple intrinsic engineering functionalities.

Based on the different types of matrix materials, nanocomposites can be generally divided into four categories including polymer-, carbon-, metal-, and ceramic-based nanocomposites. Polymers are large molecules or macromolecules composed of repeating structural units, typically connected by covalent chemical bonds; these are generally excellent host matrixes for nanocomposite materials due to their light weight, ease of processing, low-cost manufacturing, and good adhesion to substrates [4, 5]. Polymer nanocomposites (PNCs) are polymer composites using nanostructured materials as reinforcements. Depending on the type of reinforcement material, different properties can be achieved for PNCs. The introduction of inorganic or organic

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nanofillers into polymer systems has resulted in PNCs exhibiting multifunctional, high-performance polymer characteristics beyond those possessed by traditionally filled polymeric materials. Meanwhile, through control of the filler at the nanoscale level, PNCs are able to maximize property enhancement of selected polymer systems or have an exceptional potential to generate new physical phenomena to meet the requirements of military, aerospace, and commercial applications. The properties of PNCs not only are determined by their individual components but also depend on their morphology and interfacial characteristics. In multifunctional PNCs, the reinforcements impart their special mechanical, optical, electrical, and magnetic properties to the composites, whereas the polymer matrix provides support for the reinforcements and retains the properties of the constituent polymer.

Extensive research on PNC materials has already resulted in the development of many various PNCs with multifunctionality that shows substantial improvement in physicochemical properties of the combined material. For example, highly efficient electromagnetic (EM) field absorption at gigahertz frequency (GHz) was reported by He *et al*. in novel magnetic PNCs with *in situ* synthesized $Fe@Fe_2O_3$ core–shell nanoparticles (NPs) or their decorated multiwall carbon nanotubes (MWCNTs) dispersed in a polypropylene (PP). At the same time, *in situ*-formed nanofillers significantly reduced the flammability of PP for a wide range of potential applications [6]. Carbon-based structures as a type of matrix for nanocomposites may contain carbon nanotubes, carbon nanofibers, carbon nanoplates, and graphene. The unique chemical and electronic structures of carbon have made carbon-based nanocomposites noteworthy in a wide variety of applications, such as anticorrosion in electronic devices and sensors, magnetic data storage and magnetic imaging, and environmental remediation for heavy metals and other toxic species. For example, Cao *et al*. reported that newly designed fluorine-doped magnetic carbon was used as an adsorbent for Cr(VI) removal, in which as high as 48.78 and 1423.4 mg/g removal capacities in the neutral and acidic solution were achieved, higher than the state-of-the-art adsorbents such as magnetic carbons, activated carbon, and surface-modified adsorbents in environmental remediation [7].

Metal-based nanocomposites refer to materials consisting of a ductile metal or alloy matrix in which a nanoscale reinforcement material is implanted. Metal-based nanocomposites can possess a wide range of matrix materials, including aluminum, titanium, copper, nickel, iron, and so on. Reinforcement materials can be carbides (e.g., SiC, B_4C), nitrides (e.g., Si_3N_4, AlN), oxides (e.g., Al_2O_3, SiO_2), and elemental materials (e.g., C, Si). The excellent physical and mechanical properties that can be obtained from metal-based nanocomposites, such as enhanced specific modulus, strength, and thermal stability, have been investigated extensively. Recently, Li reported that an *in situ* nano-TiB_2-decorated $AlSi_{10}Mg$ composite (NTD-Al) powder was fabricated by gas atomization for selective laser melting (SLM). This metal-based nanocomposite showed a very high ultimate tensile strength (~530 MPa), excellent ductility (~15.5%), and high microhardness (~191 $HV_{0.3}$), all of which were higher than most conventionally fabricated wrought and tempered Al alloys [8].

Ceramics materials generally display good wear resistance and high thermal and chemical stability; however, they are typically very brittle. In order to overcome this limitation, ceramic-based nanocomposites have been gaining attention, primarily due to the significant enhancement of the mechanical properties that can be achieved by the incorporation of energy-dissipating components, such as whiskers, fibers, platelets, or particles within the ceramic matrix. For example, fully dense, isotropic Al_2O_3/10% MWCNT nanocomposites containing sharp starter cracks of various lengths (DC) show modest toughening, with the steady-state toughness reaching 4.6 MPa $\sqrt{m}$.

In order to produce nanocomposites with multiple functionalities, the method in which the nanofiller is dispersed within the matrix and the subsequent processing are crucial in obtaining the targeted properties for advanced applications. The emerging subfield of nanochemical engineering is aimed at the development of a core set of technology enabling the manufacture of large-scale chemical production of multifunctional nanocomposites [9]. The traditional direct mixing method is not able to attain uniform dispersion and retain the strong connection between the filler and the matrix, thus failing to achieve the desired properties. However, the nanochemical engineering and nano-processes to multifunctional nanocomposites are targeted depending on the types of materials as well as the functions of the nanocomposites. For example, the electrochemical polymerization techniques are generally applied for synthesizing conductive nano thin films for electrochromic devices [10] or anticorrosion to protect metal substrate [11], whereas chemical oxidative polymerization techniques are expected to achieve powder-form nanocomposites for electrochemical energy storage [12] or giant magnetoresistance sensor applications [13]. Therefore, the nanochemical engineering and nano-processes can bring innovative products or improved performances, which have been very well explained in the following chapters. Due to the inherent synergistic properties that can be designed into multifunctional nanocomposites, including catalytic, electrical, magnetic, mechanical, optical, sterical, and biological, these relatively new materials have wide applications spanning broad areas such as energy storage, environmental remediation, EM absorption, sensing and actuation, transportation and safety, defense systems, novel catalysts, biomedicine, and so on.

This book is divided into two parts that coincide with how nanocomposites have affected the two main application areas in energy and environment science since the dawn of the twenty-first century. The first part describes the achievements that polymer- and/or carbon-based nanocomposites have precipitated in various segments of energy applications, such as lithium ion batteries, electrochemical capacitors, solar cells, electrochromic devices, electrocatalysts, photocatalysts, biofuels production, and so on. This direction of research has motivated many researchers to explore more innovative and durable nanocomposites to meet or even exceed present requirements of materials and to help broaden their applications. The second part is centered on the effects of nanocomposites on environmental applications, such as vehicle NO_x emission control, nuclear waste management, EM absorption, and wastewater treatment. This research has motivated the development of novel and sustainable nanocomposites to solve increasingly serious global environmental problems against concordant ecological conditions. All the following chapters in this book present recent developments in each relevant field.

Finally, this book also includes with our general assessment and perspectives of multifunctional nanocomposites, especially their potential for energy and environmental applications. Of course, this book does not extensively cover every aspect of multifunctional nanocomposites but rather selectively reports what have been achieved to date.

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