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Reinforcements in multi-scale polymer composites: Processing, properties, and applications

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ABSTRACT

Smart and novel materials require the replacement of conventional composites with superior ones, which requires an advanced class of composites with multi-functionality. Multi-scale composites are advanced composites that are reinforced with nanoscale materials along with macroscale fibers, and these materials have attracted the attention of researchers as well as various industries. Multi-scale composites have potential applications in almost every field due to their remarkable features like extraordinary mechanical, electrical, and optical properties; extremely high aspect ratios of the nanomaterial constituents; and the uniformity, flexibility, and stability of the fibers. To optimize the performance of these kinds of composites, it is crucial to understand the selection of appropriate reinforcements, processing, and utilization of these advanced materials. Most reviews in this area concentrate only on CNTs, while this review considers other nanomaterials too. Additionally, various methods to improve the dispersion of nanomaterials into the matrix are also discussed. Overall, this article focuses on the components of multi-scale composites, key challenges related to their processing, and the multi-functionality of designed multi-scale composites.

1. Introduction

Researchers are constantly striving to make human life more convenient and to develop advanced technologies. Therefore, the demand for smart and novel materials has increased, and existing technologies are often replaced by more advanced options. Polymeric materials have already replaced conventional materials such as metals and ceramics due to their lightweight, easy processing, and low cost [1]. Moreover, polymers possess outstanding corrosion stability and good mechanical properties (ductility). However, there are some drawbacks associated with polymer components, such as low thermal stability, inferior chemical (e.g., acid) and environmental stability (UV), and low conductivity [2]. To avoid these kinds of issues, polymer composites were designed by reinforcing the matrices with a wide range of filler materials. Based on the desired performance of the final material, the polymer matrix can be reinforced with many kinds of fillers (particles, fibers, or platelets, synthetic or natural, organic or inorganic) at any scale (macro, micro, or nano) [3–6]. The performance of the final product synergistically depends upon the characteristics of the filler as well as those of the host material. Regardless, the performance of polymers decreases with time due to various causes such exposure to UV, high temperature, pH, and humidity [7]. Fiber-reinforced polymer composites with remarkable properties were designed to overcome these problems and advance the overall performance of composites.

In fiber-reinforced polymers (FRPs), fibers provide a unique set of properties such as good length to width ratio, environmental stability, uniformity, and flexibility, while the host matrix protects the fibers against unfavorable environmental conditions and maintains their position throughout the matrix [8]. Many studies show that FRPs can substitute for conventionally used materials. Currently, various kinds of synthetic or artificial fibers are used to reinforce the polymer matrix in order to improve the performance of the final materials [9]. These FRPs are often used in various industrial applications, including automobiles, military vehicles, sports equipment, and aerospace products, because of the their low weight, low cost, high durability, and high strength. However, there is always room for improvement, and researchers are constantly trying to advance the field of composites. To improve the out-of-plane performance of composites, more than one filler material is required [10]. Regardless, weight is a very crucial factor for many applications such as aircraft and automobiles, and large-scale fillers give rise to weight and voids, which subsequently narrow the scope of reinforcement in the matrices [11]. Hence, nano-fillers are broadly preferred as a reinforced material over macro-scale fillers.

Over the past two decades, nanotechnology has been utilized in a

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wide range of applications. The extremely small dimensions of these materials give rise to their outstanding characteristics, such as exceptionally high aspect ratio and near zero weight (in comparison to the host material), that attract many researchers as well as industries. The desired composite material can be designed by exploiting the characteristics of reinforced nanomaterials that fluctuate with size, shape, type, dimensions, and production route [12]. Numerous studies have reported the enhanced mechanical, thermal, and electrical properties of nanoparticle-reinforced composites [13–15]. Composites constructed using reinforcing fibers (carbon, basalt, glass, aramid, natural fibers) together with nano-dimensional filler materials (graphene, carbon nanotube, nanoclay, metal nanoparticles) are known as multi-scale composites [16–18]. These kinds of composites are also known as multifunctional composites because they possess conventional load-sharing properties of the reinforced fibers as well as the additional functional properties (conductivity, sensing, thermal resistivity) associated with the particular nanomaterial. Moreover, the nanomaterials interact with the host resin to improve interactions and change texture and color. The field of nanotechnology has its own sets of challenges that hinder the development and commercialization of nanomaterial-reinforced composites. Processing issues, including homogenous dispersion and unsatisfactory interfacial interactions, are a major concern [19]. To obtain optimal composite performance, researchers have made efforts to alter the surface morphology or structure of the reinforced materials by incorporating chemical moieties that both improve the dispersion quality and the interfacial interactions between matrices and reinforcements [20–22].

This review focuses on the different components of the multi-scale polymer composites and different types of nano-reinforcements and their structures and properties. Further, critical issues regarding processing are discussed. Finally, the improved properties of multi-scale composites along with various applications are discussed.

2. Polymer matrix

The matrix is a main component in a composite that protects fibers or fillers against abrasion and harsh environmental conditions. Moreover, it holds the fibers/fillers together and provides strength to the composite by absorbing energy via deformation during stress. When a load is applied to a composite material, the matrix transfers it to the reinforced material [23]. Features such as type, characteristics, and processing route need to be considered. Hence, it is essential to choose a matrix that can experience greater strain at break than the reinforced fibers. Thermosets and thermoplastics are two main types of polymer resins [23]. Thermosets can be cured at elevated temperature, and it is impossible to change them into their uncured form again. Thermosets possess strength and stability against adverse conditions because of complex cross-linking in the presence of catalyst. Conversely, thermoplastics are soft, do not cross-link with each other, and melt at higher temperatures. Thermoplastics have limited practical applications compared to thermosets because they have high viscosity and require high temperatures during processing. Commonly used thermosets are epoxies, vinyl esters, phenolic resins, polyesters, and urethanes.

Epoxy resins are extensively used thermosets because of their outstanding thermo-mechanical properties, which improve the performance of the final material. Most epoxy resins have glycidyl ethers and amines and can be cross-linked in the presence of a hardener at room or higher temperatures. Many researchers have reported that the hardener improves the strength of the resin along with the glass transition temperature. Hence, the properties of an epoxy resin can be controlled by varying the type and chemical structure of the hardener, resin to hardener ratio, curing time, and curing temperature. For instance, Konuray et al. used a photobase generator as a curing agent and delayed the cross-linking of an epoxy resin to provide improved processing freedom [24]. However, some articles show that long curing times are unfavorable during nanocomposite processing as nanofillers start aggregating and settle to the bottom as soon as resin stirring stops [25]. Therefore, some researchers have decreased the curing time by using microwaves to accelerate the reaction [26]. Curing aids like microwaves, X-rays, and gamma-rays are more economically efficient and offer promising features like reduced curing time, energy savings, improved processing control, and higher heating efficiency compared to thermal curing [27].

3. Reinforced fibers

Fibers play a crucial role in multiscale composites in determining the end performance of the synthesized material. It is well known that the defects present in a material decrease as the size decreases. Compared to the bulk material, a fiber possesses a larger surface area, a higher aspect ratio, and anisotropy that leads to the advanced performance of the material. Numerous studies report that the characteristics of the final composites are a function of fiber type, fiber length, volume fraction, fiber structure, sizing agent, morphology, and fiber orientation.

Effect of fiber length: Zang et al. studied the effects of fiber length on glass fiber-reinforced poly(butylene terephthalate) composites and found that long fibers exhibit better mechanical properties compared to short fibers [28]. Although short fiber-reinforced composites are easy to process, provide versatility, and are cost-efficient, fiber degradation during the injection molding process results in some degradation in mechanical properties. In contrast, long fiber-reinforced composites are processed via pultrusion and exhibit excellent mechanical properties, fatigue resistance, durability, and impact resistance [28].

Effect of fiber loading: Generally, properties of the composite material increase by increasing the fiber loading in the matrix. However, after reaching a threshold limit, the properties of the composite material start to decrease because of poor mechanical interlocking, which degrades load transfer between the fibers and matrix [29,30]. Liu et al. studied the effects of fiber fraction on crack propagation rate and reported that the crack propagation rate was decreased by increasing the volume fraction of fibers, resulting in an improved crack growth threshold [31].

Effect of fiber orientation: Fiber loading and the method of processing significantly affect the orientation of the fibers in the matrix. Wang et al. studied the effects of fiber orientation on the Young's modulus of unidirectional GFRPs both theoretically and experimentally. They found that Young's modulus was lowest when the fibers were oriented at 45° and 60° for experimental and theoretical studies, respectively. Other factors affecting the properties of composite materials are responsible for this mismatch between theoretical and experimental outcomes [32]. Similarly, the shear strength of GFRPs oriented at 0° and 90° were compared with randomly oriented fibers [33]. The results showed that 0° composites possess higher interlaminar shear strength than that of 90° composites, while randomly oriented fibers showed higher in-plane shear strength. Based on the degree of fiber alignment relative to the loading direction, there are three type of fiber orientations, aligned, partially aligned, and randomly aligned. The strength and stiffness of the composite is highest when the fibers are parallel to the loading direction due to efficient stress transfer between fibers and the matrix [34]. Since the orientation of the fiber is influenced by the processing method, compression molded long GFRPs exhibit better strength than injection molded short GFRPs due to the better orientation in a preferred direction observed in compression molding [35].

Effects of fiber shape and type: Some studies showed that the shape of the reinforced fiber affects the performance of the composite [36]. To improve the compressive strength of composites, Bond et al. studied the effect of triangular-shaped glass-fiber reinforcement on composites and compared their properties with circular-shaped glass-fiber reinforced composites. They found that triangular fiber-based composites possess higher tensile and compression strength than circular fiber-based composites [37]. Similarly, Chandra et al. reported the effects of