Research on the Application of Polymer Nanocomposites in Energy

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Abstract. Polymer nanocomposites (PNCs) integrate the exceptional properties of both polymers and nanomaterials, demonstrating unique optical, mechanical, thermal, and electrical characteristics. They offer high efficiency, multifunctionality, and environmental friendliness. This paper explores the properties and fabrication methods of polymer nanocomposites and their applications in energy storage, energy conversion, energy management, and energy conservation and emission reduction.

Keywords: Polymer nanocomposites; Energy; Energy conservation and emission reduction.

1. Introduction

Materials form the foundation of modern societal development. New materials are strategically positioned as emerging industries and industries of the future in China [1]. Polymer nanocomposites are created by combining nanoparticles (NPs) with polymer materials, significantly enhancing the performance of the polymers. These composites excel in mechanical, thermal, electromagnetic, and optical properties. Comprising a polymer matrix with nanoparticles or nanofibers as the nano-reinforced dispersed phase, polymer nanocomposites facilitate the transfer and dispersion of loads across these phases, thus enhancing the mechanical properties of the materials. They are characterized by their lightweight, high hardness, high toughness, and high strength [2].

Nanomaterials possess an exceptionally high specific surface area and surface activity, enabling them to significantly enhance the mechanical properties of polymer materials, such as strength, modulus, and toughness, as well as thermal stability and flame retardancy [3]. Due to the molecular-level compatibility of nano-fillers with polymer matrices within the nanoscale range, their large specific surface area effectively enhances the interfacial binding force between them, thereby improving the mechanical properties of the composite materials. For instance, studies have shown that graphene can effectively improve various properties of polymer materials. Graphene oxide can be modified through covalent or non-covalent interactions on its surface, endowing graphene nano-reinforced materials with additional functionalities and superior performance, further enhancing the performance of polymer nanocomposites [4]. By incorporating graphene oxide graft modified with poly (L-lactic acid)（GO-gPLLA) as a nano-filler into the PLLA polymer matrix and using methods such as solution mixing and compression molding, high-performance PLLA/GO-g-PLLA nanocomposites are produced. When the mass fraction of GO-g-PLLA added is 5%, the flexural and tensile strengths of PLLA/GO-g-PLLA nanocomposites increase by 114.3% and 105.7% respectively compared to the PLLA matrix [5]. The nanomaterials in polymer nanocomposites serve as barriers, filling the microscopic voids in the polymer matrix, preventing the movement, penetration, and diffusion of gases, liquids, and harmful substances, thus achieving better barrier effects. Due to the uniform dispersion of nano-fillers in the polymer matrix, light scattering and absorption are effectively reduced, enhancing the material's transparency. Consequently, polymer nanocomposites exhibit excellent optical transparency. The addition of nano-fillers also allows for the adjustment of the optical refractive index of polymer nanocomposites. By selecting appropriate nano-fillers and adjusting their content, polymer nanocomposites with specific refractive indices can be fabricated. Moreover, polymer nanocomposites demonstrate good optical stability. The inclusion of nano-fillers improves the light-aging resistance of polymer materials, allowing them to maintain stable optical performance under prolonged exposure to light. Additionally, polymer nanocomposites possess strong environmental friendliness. By incorporating biodegradable nanoparticles or through specific structural designs, their biodegradability can be significantly enhanced, thereby reducing environmental pollution. During the manufacturing process of polymer nanocomposites, optimizing production techniques and formulations can reduce the consumption of raw materials and energy waste, while also lowering emissions of exhaust gases, wastewater, and solid waste, achieving green production. Thus, polymer nanomaterials do not release harmful substances during production and use, ensuring the health of humans and the safety of the environment.

In summary, the nano-size effects of the dispersed phase in nanocomposite materials, along with their large specific surface area and strong interfacial interactions, endow them with unique physicochemical properties. The surface effects, small size effects, quantum effects, and synergistic effects of nanoparticles significantly enhance the comprehensive performance of the composite materials [6]. Polymer nanocomposites not only retain the advantages of the polymer materials themselves but also possess the unique properties of nanoparticles, such as magnetic, electrical, catalytic, and biological performances, demonstrating broad application prospects in the energy sector. For example, they can be used as electrode materials to improve the charge and discharge rates and capacity of batteries, as light-absorbing layers to increase the photovoltaic conversion efficiency and reduce manufacturing costs, and in applications like hydrogen storage materials and fuel cells, providing possibilities for future clean energy applications.

This paper investigates the preparation methods of polymer nanocomposites and their current applications in the energy sector.

2. Preparation Methods of Polymer Nanocomposites

Polymer nanocomposites are primarily prepared through organic synthesis, chemical, physical, or biochemical methods, whereby nanoparticles are uniformly and dispersedly integrated into a polymer matrix to form a new type of material [7]. The nanoparticles referred to here are particles with a size of 1 to 100 nm (also known as ultrafine particles), which possess a large surface area and quantum effects [8]. The preparation of polymer nanomaterials includes: 1) physically pulverizing, chemically treating, and physiochemically blending the nanostructural units directly with polymers; 2) fully utilizing the characteristics of polymers to in-situ generate nanostructural units within the polymer matrix; 3) simultaneously generating nanostructural units and polymers.

2.1 Direct Blending of Nanostructural Units with Polymers

This method involves the structural or grinding mixture of both elements using emulsions, solutions, or conventional bulk materials. For instance, nanoparticles can be prepared using the physical pulverization method through ultrafine grinding techniques. Alternatively, polymer nanocomposites can be prepared using physical vapor deposition (PVD) or chemical vapor deposition (CVD) methods. Physical vapor deposition involves placing the substance to be evaporated into an inert gas and then heating it using high-frequency induction, laser, or resistance methods. As the temperature increases, the material vaporizes. When heating ceases, the temperature within the inert gas drops, causing the gases to condense and subsequently form nanoparticles [9]. Chemical vapor deposition utilizes the rapid condensation of the vapors of volatile metal compounds in a protective gas environment to produce nanoparticles. It is suitable for preparing various types of metal, metal compounds, and non-metal compound nanoparticles, such as nitrides, carbides, borides, etc. [10]. In the CVD process, one or more gaseous reactive substances are transported to the substrate, where they adsorb and chemically react on the surface to form a solid product. This method produces nanoparticles with uniform particle size, high purity, fine granularity, good dispersion, high chemical reactivity, controllable processes, and continuous operation. However, precise control over reaction conditions (such as temperature, pressure, reactant concentration) is necessary to achieve desired nanocomposite material properties. Additionally, some polymers may not easily chemically react with the reactants, leading to preparation challenges.

2.2 In-situ Formation of Nanostructural Units within a Polymer Matrix

The in-situ formation of nanostructural units within a polymer matrix primarily involves utilizing the unique functional groups of polymers for complex adsorption of metal ions and the spatial hindrance of the matrix to reactant movement, or providing nano-scale spatial constraints, thus facilitating the in-situ reaction to form nanocomposites [11]. This method is commonly used for the preparation of functional composite materials of polymers with metallic, sulfide, and oxide nano units. Initially, an appropriate precursor, such as an organometallic compound or metal ions adsorbed on polymer functional groups, is selected. The precursor is then dissolved in a pre-prepared polymer aqueous solution to form a polymer-inorganic metal ion complex. The polymer functional groups through complexation adsorb the metal ions, forming a stable complex. Finally, through various methods such as radiation (e.g., radioactive radiation, ultrasound), heating, light exposure, gas reactions, solution reactions, hydrothermal, and solvothermal reactions, the metal ions in the complex chemically react to form nanostructural units. Mezy and others synthesized various morphologies of ZnO using water-soluble polymers PAM and PAM-PAA, studying the effect of water-soluble polymers on the nucleation of ZnO. It was found that the polymers played a role in adsorbing zinc ions and in-situ nucleation, while the interactions between the polymer and zinc nuclei influenced the morphology of ZnO [12]. Another approach involves forming nano units in-situ within a polymer matrix, where zinc acetate is dissolved in a pre-prepared PVA aqueous solution to form a PVA-Zn^{2+} polymer-inorganic metal ion complex. Subsequently, NaOH is added, and a hydrothermal reaction produces the PVA/ZnO polymer composite functional material.

2.3 Simultaneous Generation of Nanostructured Units and polymers

The simultaneous generation of nanostructured units and polymers involves methods such as intercalative in situ polymerization and sol-gel processes. The intercalative in situ polymerization method utilizes layered inorganic substances (such as silicate clays, phosphates, graphite, metal oxides, and disulfides) as hosts, with organic polymers as guests inserted between the layers of the host. This process creates polymer-based nanocomposites. The sol-gel method is another common approach for preparing polymer nanocomposites. It involves precursors like alkoxide metals or metal salts (either water-soluble salts or oil-soluble alcohol salts) dissolved in water or organic solvents to form a homogenous solution. The solute undergoes hydrolysis to form nanoparticles, creating a sol that, upon evaporation and drying, transforms into a gel. If conditions are properly controlled during gel formation and drying, preventing phase separation of the polymer, polymer-based nanocomposites can be successfully obtained.

3. Performance Characteristics of Polymer Nanocomposites and Their Applications in the Energy Sector

Polymer nanocomposites have a broad application prospect in the energy sector. By controlling the type, size, and distribution of nanoparticles, as well as the structure of the polymer, energy materials with superior performance can be developed, offering robust support for energy storage, conversion, environmental protection, and regulation.

3.1 Applications of polymer Nanocomposites in Energy Storage

Energy storage involves holding energy in a specific form within materials or devices. Polymer nanocomposites are characterized by their chemical stability, toughness, processability, and environmental friendliness, facilitating rapid charging and large capacities. Consequently, these materials are employed in batteries, supercapacitors, and thermal molten salt energy storage [13]. Polymer nanocomposites can be used to construct multiphase composite electrodes. For example, electrodes made from carbon nanotubes and polymer materials enhance the cycle life and performance of batteries. Furthermore, polymer nanocomposites serve as cathode materials for electrodes, electrolytes, or separators. By optimizing the dispersion of nanoparticles and the structure of polymers, the mechanical properties and ion conductivity of separators are improved, enhancing the energy density, safety, cyclic stability, and lifespan of lithium-ion batteries. In fuel cells, polymer nanocomposites play a crucial role in the proton exchange membranes, where controlling the type and distribution of nanoparticles enhances the membrane's proton conductivity and chemical stability, thereby improving fuel cell performance. Polymer nanocomposites can also be used as electrode materials in solar cells, where the introduction of photovoltaic nanoparticles, such as quantum dots and carbon nanotubes, improves the electrode's light absorption efficiency and charge separation efficiency, thus enhancing the photovoltaic conversion efficiency of solar cells.

Super capacitors are a novel type of energy storage device characterized by high power density, rapid charge and discharge rates, long service life, and environmental safety. They store electrical energy through charge migration during the charge and discharge processes, similar to conventional capacitors in energy storage and charging capabilities. Polymer nanocomposites serve as electrode materials, electrolytes, and separators in supercapacitors, enhancing the surface area and conductivity of electrodes. For example, combining conductive polymers such as polypyrrole and polyaniline with nano-carbon materials like graphene and carbon nanotubes results in high-performance electrode materials with excellent electrochemical properties. Nanoengineering the morphology and structure of polymer nanomaterials can optimize electrode performance. For example, fabricating nanostructures like nanofibers and nanotubes increases the contact area between the active material and the electrolyte, improves ion transport pathways, and boosts capacitance. Polymer nanomaterials are also used as electrolytes. By incorporating ion conductors or solvents into the polymer matrix, high-performance polymer electrolytes with superior ion conductivity, low electronic conductivity, and robust mechanical properties are produced, significantly enhancing supercapacitor performance. In supercapacitors, separator materials prevent short-circuiting by isolating the positive and negative electrodes. Polymer nanomaterials, used as substrates or coatings for separators, improve their mechanical strength, chemical stability, and ion conductivity. In practical applications, using graphene/polyaniline composites as electrode materials substantially increases the specific capacitance and cyclic stability of supercapacitors. Thus, polymer nanocomposites offer higher specific capacitance, better cyclic stability, greater energy density, and a broader operational temperature range, meeting the requirements of various high-performance energy storage and conversion devices.

Thermal storage technology is an efficient method of storing thermal energy. Traditional molten salt materials suffer from poor thermal conductivity and relatively low specific heat capacity. However, the addition of nanoparticles like graphene and aluminum oxide to molten salts significantly enhances their thermal conductivity and specific heat capacity. Nanoparticles act as thermal bridges, enhancing the convection and radiative heat transfer of molten salts, accelerating heat transfer, significantly increasing the thermal conductivity, and maintaining stable phase change points and latent heat, thus achieving efficient thermal energy storage and release [14]. In solar thermal power stations, molten salt-based phase change materials combined with metal foam and graphene exhibit excellent heat absorption properties and cyclic stability, maintaining stable phase change characteristics and thermal storage capabilities after multiple cycles, reducing heat storage time, and improving the overall efficiency of the thermal storage system.

3.2 Applications of Polymer Nanocomposite Materials in Energy Monitoring

Polymer nanocomposite sensors are a novel type of sensor that harnesses the superior qualities of both polymers and nanomaterials. These sensors achieve sensitive detection of specific physical, chemical, or biological signals by incorporating nanoparticles or nanostructures into a polymer matrix [15]. With their high efficiency, stability, multifunctionality, and eco-friendliness, these sensors are particularly useful in the monitoring of energy storage. They can monitor vital parameters such as the charging and discharging states, remaining capacity, and cycle life of devices. By tracking these parameters in real-time, the sensors ensure the smooth operation of devices, provide early warnings of potential faults, and thereby enhance the reliability and safety of the systems. In the context of energy transmission and distribution, such as within electric power systems and smart grids, polymer nanocomposite sensors are employed to monitor critical electrical parameters like current, voltage, and temperature of power lines. These sensors provide real-time insights into the operational status of the power system, promptly detect abnormalities, and facilitate interventions to ensure the stable operation and quality of power supply. In industrial production and construction, polymer nanocomposite sensors are used to monitor energy consumption and emissions. By tracking the amount of energy consumed and the types and concentrations of emissions in real-time, these sensors help assess and optimize energy use efficiency, promote energy conservation and emission reduction, and support sustainable development. The integration of polymer nanocomposite sensors with existing energy management systems and devices enables the seamless, intelligent, and automated monitoring and management of energy, facilitating real-time supervision, prediction, and optimization of energy systems. This enhances the efficiency of energy use and the reliability of energy supply.

3.3 Applications of Polymer Nanocomposites in Energy Conservation and Emission Reduction

Polymer nanocomposites have wide-ranging applications in the energy sector, encompassing power batteries, photovoltaics, and wind energy, and extending to hydrogen energy, thermoelectric conversion and release, and energy conservation and emission reduction. These nanocomposites are utilized in creating devices for energy conversion and storage, such as photoelectrocatalytic materials and thermoelectric materials. By modulating the type, size, and distribution of nanoparticles, these materials can facilitate efficient photoelectric and thermoelectric conversions, thus enhancing energy efficiency and contributing to energy conservation and emission reduction. In terms of energy transmission and distribution, polymer nanocomposites are employed to produce high-performance insulating materials for electrical wires and cables. The incorporation of nanoparticles improves the material's heat resistance, weather resistance, and mechanical strength, which in turn extends the service life of wires and cables and increases their safety. Additionally, polymer materials modified with nanotechnology can enhance the safety of hydrogen energy, providing robust support for its application. For instance, nano-modified polymer materials can be employed to produce coatings or sealing materials for hydrogen storage containers, enhancing the containers' seal integrity and hydrogen barrier properties. This reduces the risk of hydrogen permeation and leakage, preventing hydrogen from diffusing through the container walls into the external environment, thereby ensuring safety during storage. Nano-modified polymer materials can also be used to manufacture sensitive components or electrodes for hydrogen sensors, endowing the components with excellent mechanical properties and seal integrity. This allows them to operate stably in harsh environments, enhancing the sensitivity and response speed of the sensors.

4. Conclusion

This paper first outlines the properties of polymer nanocomposites. It then discusses their preparation methods. The basic principles of enhancing energy storage and conversion efficiency, optimizing energy transmission and distribution, and improving material stability and safety in the energy sector are explored. Additionally, the applications of polymer nanocomposites in energy storage, energy management and monitoring, and energy conservation and emission reduction are investigated. As the preparation technologies for polymer nanocomposites become more mature and diversified, their industrialization process will also accelerate progressively, realizing large-scale production and application.

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