
Carbon Fiber-Reinforced Polymer Composites: Enhanced Properties through Nanoparticle and Thin Film Integration

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Abstract

Carbon fiber-reinforced polymer composites (CFRPs) are widely utilized across industries such as aerospace, automotive, sports, and construction due to their exceptional mechanical properties and long-term durability. These composites, consisting of carbon fibers embedded in a polymer matrix, form a robust laminate structure ideal for demanding structural applications. The incorporation of nanoparticles or thin films onto the surface of carbon fibers has been shown to significantly enhance their mechanical properties and durability. These modifications improve the interfacial bonding between the fibers and the resin, resulting in increased interfacial shear strength, as demonstrated in numerous studies (1,2). Enhancements in the surface morphology at the nano- and microscale levels also play a critical role in determining optical and UV reflectivity properties. Materials like Vantablack®, composed of aligned carbon nanotubes (CNTs), exhibit a remarkable absorption rate of 99.96% (3). CNTs grown on surface-activated aluminum (CNT/sa-Al) have achieved an even higher absorption of 99.995% (4). In contrast, natural surfaces like fresh snow demonstrate a high reflectivity of up to 90% for incident radiation due to multiple scattering within its porous crystalline structure (5). These insights underscore the potential for advanced surface modifications to enhance both mechanical and optical properties.

This study investigates two distinct approaches for modifying the interface between carbon fibers and the polymer matrix to enhance mechanical and optical performance. The first method employs electrophoretic deposition (EPD) to deposit silica and silver nanoparticles onto the fibers. In this process, a suspension of nanoparticles is subjected to an electric field, causing the particles to adhere to the carbon fibers. The deposition is controlled by parameters such as voltage and duration, which influence the uniformity and distribution of the nanoparticles.

The second method utilizes physical vapor deposition (PVD) to apply thin films of SiO_x and Ag on the fiber surfaces. PVD involves vaporizing the target material in an ionized gas environment, which is then deposited onto the fibers. This process is optimized using magnetron sputtering, which enhances the ionization rate of the gas to improve the deposition efficiency. Critical parameters such as current, deposition time, and gas flow rate are carefully adjusted to achieve thin films with the desired properties.

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The adhesion performance of the nanoparticles and thin films was assessed using lateral force microscopy (LFM), which measures the binding forces required to detach particles or scratch films from the fiber surfaces. These measurements provide quantitative insights into the strength of the interface modifications (6). Additionally, changes in the mechanical properties of the carbon fiber surfaces, including hardness and Young's modulus, were evaluated using atomic force microscopy-based nanoindentation. Preliminary findings suggest that the adhesion quality and mechanical performance are strongly influenced by the deposition parameters, including the voltage and time in the EPD process and the film thickness in the PVD process.

The optical properties of the modified carbon fibers, incorporated into polymer composites, were analyzed using UV/VIS spectroscopy. The results revealed significant differences in reflectivity depending on the type of coating and the deposition parameters. EPD-modified fibers exhibited enhanced UV reflectivity, while composites with PVD-modified fibers showed a modest increase in reflectivity across the entire spectrum.

This study demonstrates the potential of surface modification techniques, such as EPD and PVD, to improve the mechanical and optical properties of carbon fiber-reinforced composites. By optimizing deposition parameters, significant enhancements in interfacial bonding, durability, and optical performance can be achieved. These findings provide valuable insights for advancing the development of high-performance composite materials for industrial applications.

References

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