Materials Science Innovations

RESEARCH PAPER

Preparation Process and Basic Characteristics of Flexible Carbon Fiber Composite Sheets

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Abstract: This research successfully developed a composite material that integrates a flexible carbon fiber fabric (CF) with copper nanoflakes (Cu) and an Ethylene Vinyl Acetate (EVA) layer (P-EVA/Cu@CF), designed for superior electromagnetic interference (EMI) shielding and self-healing capabilities. The material's innovative preparation process involves the integration of carbon fiber fabric (CF) as the base, copper nanoflakes for enhanced conductivity, ethylene-vinyl acetate (EVA) for flexibility and self-repair, and polytetrafluoroethylene (PTFE) for a hydrophobic surface. The CF fabric is sprayed with a copper nanoflake suspension, followed by lamination with EVA mesh and the application of a PTFE layer to create a robust, hydrophobic epidermal layer. This meticulous fabrication method ensures a layered structure that is pivotal for the material's multifunctional properties. The P-EVA/Cu@CF material exhibited remarkable EMI shielding effectiveness, with over 40 dB across the X-band frequency range, making it highly effective in blocking electromagnetic waves. This exceptional performance is attributed to the synergistic effects of the conductive copper nanoflakes and the carbon fiber fabric. Mechanical testing revealed a fracture strength of 1600 MPa and a Young's modulus of 3.8 GPa, indicating that the added components did not compromise the material's inherent mechanical strength. Moreover, the material's self-healing capability was demonstrated through the rapid restoration of its hydrophobic state within 30 s under a 9V voltage, showcasing its potential for sustainable and durable applications in extreme environments. In the future, the P-EVA/Cu@CF composite material, with its advanced preparation process and multifunctional attributes, stands out as an ideal candidate for applications in aerospace, automotive, marine, and wind energy sectors where high-performance materials with robust shielding and self-repair functionalities are critical.

Keywords: Carbon fiber, Composite materials, Preparation process, Electromagnetic shielding

1. Introduction

Carbon fiber composite materials have garnered considerable attention due to their exceptional properties, such as high strength-to-weight ratios, fatigue resistance, and superior corrosion resistance. These materials consistently outperform traditional metals across various applications, making them indispensable in industries like aerospace, automotive, marine, and wind energy. Their ability to reduce weight while maintaining structural integrity is critical for improving fuel efficiency and overall performance in these sectors [1].

Recognized for their strength, corrosion resistance, and fatigue performance, carbon fiber composites are ideal for demanding applications [2]. Their matrix plays a vital role in reinforcing the

Received: Oct. 23, 2024
Revised: Nov. 29, 2024
Accepted: Dec. 08, 2024
Published: Dec. 19, 2024

fibers, resulting in composites that are not only lighter but also significantly stronger than their metallic counterparts [3]. Advanced manufacturing techniques, such as vacuum impregnation and through-plane stitching, further enhance the uniformity and mechanical properties of these materials. Our research builds upon these advancements by developing a multifunctional carbon fiber composite (P-EVA/Cu@CF), which introduces rapid self-healing capabilities and superior electromagnetic shielding [4-5], making it a cutting-edge solution for extreme environments where both durability and functionality are paramount [6].

2. Preparation Process of Carbon Fiber Composite Materials

2.1 Raw Material Composition

In this study, the composite material consists of four key components. First, carbon fiber fabric (CF) functions as the skeleton of the composite, providing primary mechanical strength and stability; a 12K carbon fiber fabric with a thickness of 0.28 mm and a weight of 200 g/m² is used. Second, copper nanoflakes serve as the neural layer, attached to the surface of the carbon fiber, enhancing the material's conductivity and aiding in the absorption of electromagnetic waves. Third, ethylene-vinyl acetate (EVA) functions as the dermal layer [7], encapsulating the carbon fiber fabric and providing flexibility and self-healing capabilities. Finally, polytetrafluoroethylene (PTFE) serves as the outermost epidermal layer, provides excellent hydrophobic properties to the material. The synergistic integration of these components is schematically depicted in Figure 1, which illustrates the layered structure of the composite material, showcasing the distinct roles of each layer in contributing to the overall performance of the material.

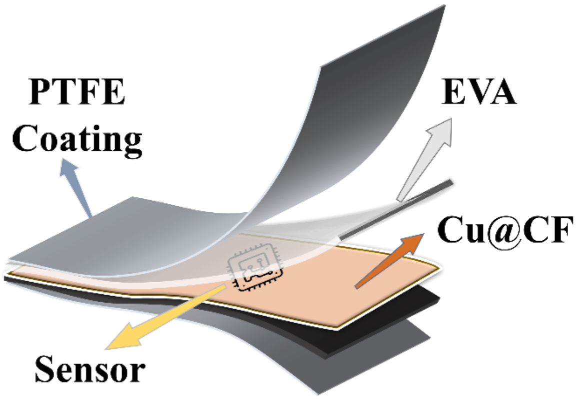

Figure 1. Schematic diagram of carbon fiber composite material structure.

The entire composite material presents a layered structure, where each layer plays a specific role. From the base layer of carbon fiber cloth, to the neural layer of copper nanosheets, to the dermis layer of EVA and the epidermis layer of PTFE, each layer is tightly combined to form a high-performance composite material system. Additionally, the cross-section of the composite material shows clear layering, where the texture of the carbon fiber cloth, the distribution of copper nanosheets, the bonding effect of the EVA layer, and the uniformity of the PTFE layer can all be observed under a microscope. These characteristics collectively ensure the mechanical properties, sensing capability, electromagnetic shielding effect, and self-healing ability of the material.

2.2 Preparation Steps

The preparation of the carbon fiber composite materials involves several key steps. First, the carbon fiber (CF) fabric is cut into 100 mm × 100 mm pieces and uniformly sprayed on both sides with a 5 wt% Cu/Cetyltrimethylammonium bromide suspension for 5 s from a distance of 5 cm. After spraying, the fabric is air-dried at room temperature for 24 h, resulting in a golden-yellow Cu@CF fabric that serves as the neural layer. Next, four layers of EVA mesh are laminated on both sides of the Cu@CF fabric, with the option to embed strain gauges or pressure sensors. This assembly undergoes hot pressing under vacuum at a pressure of 100 N and a temperature of 100°C for 15 min using a hot press, leading to the formation of EVA/Cu@CF composite membranes. Following this, a 60 wt% isoamyl acetate suspension of PTFE particles is prepared and evenly sprayed on both sides of the suspended EVA/Cu@CF membrane, creating the PTFE epidermal layer. Finally, the samples are air-dried, resulting in a P-EVA/Cu@CF composite membrane [8]. Figure 2 provides a visual narrative of these stages, capturing the essence of the material's construction.

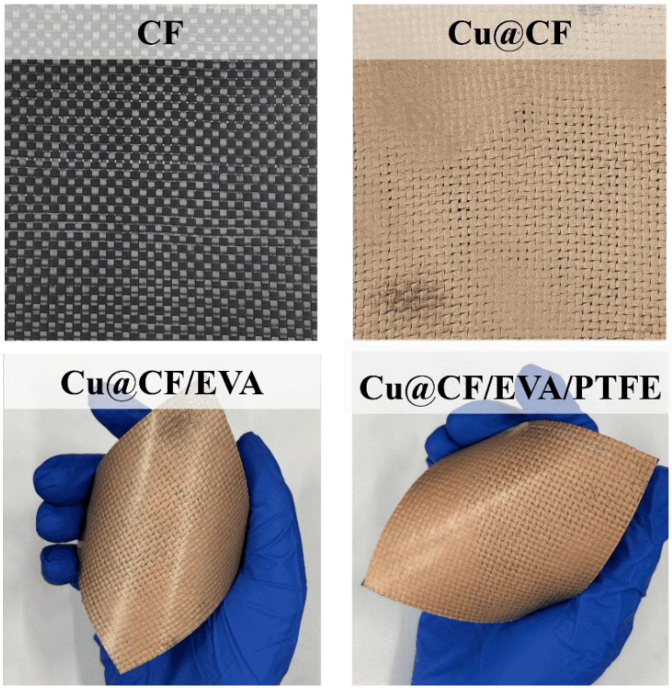

Figure 2. Physical images of various stages of the carbon fiber composite material.

2.3 Processing Methods

The processing of carbon fiber composite materials involves several critical steps to ensure optimal performance. First, a spray coating technique is used to apply both the Cu/CTAB suspension and the PTFE suspension evenly across the surface of the carbon fiber fabric. This step is crucial for creating the conductive and hydrophobic layers of the composite. Next, the laminated material undergoes hot pressing under vacuum conditions, a technique that promotes strong bonding between the layers. The vacuum environment is particularly important for removing trapped air bubbles, which would otherwise compromise the material's density and mechanical strength. By eliminating these air pockets, the vacuum pressing process ensures a more uniform and dense composite structure. Finally, the composite is air-dried to allow the copper nanoflake layer to solidify, completing the formation of the final P-EVA/Cu@CF composite material. This process results in a high-performance material with enhanced electrical conductivity, mechanical strength, and hydrophobic properties [9].

3. Material Characteristics and Testing Analysis

3.1 Microscopic Analysis

Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) are utilized to examine the surface morphology of the carbon fibers and the interface between the fibers and the matrix. These techniques help evaluate the quality of bonding and the surface characteristics of the fibers, crucial for understanding the overall material performance [10]. SEM analysis, conducted at an accelerating voltage of 10 kV, provides detailed insights into the microstructure of the composite. This includes the distribution and dispersion of copper nanoflakes as well as the infiltration of EVA into the carbon fiber fabric. AFM is particularly useful for studying finer details at the fiber-matrix interface, revealing how well the components are integrated. Additionally, elemental mapping was performed to assess the distribution of elements across the sample, ensuring uniform composition and effective bonding throughout the composite [11]. Figure 3 integrates these microscopic examinations, showcasing the composite's microstructural attributes. The SEM images, captured at an accelerating voltage of 10 kV, reveal the intricate distribution of copper nanoflakes across the carbon fiber fabric.

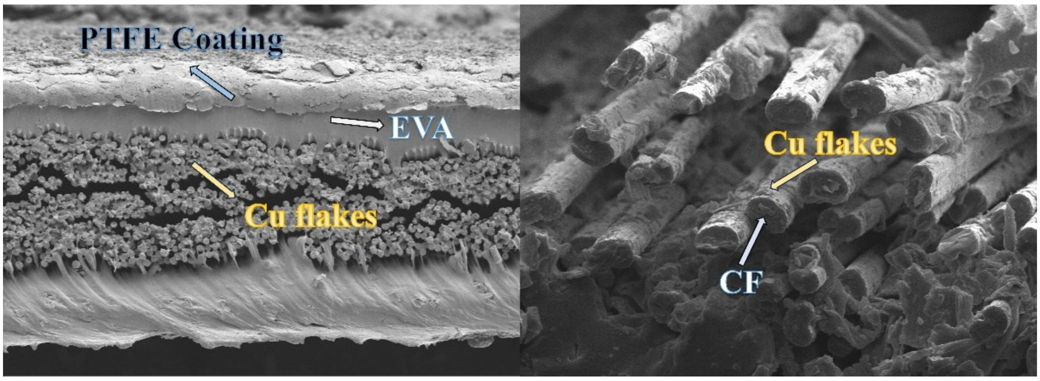

Figure 3. Cu-nanoflakes on the CF surface**.**

3.2 Mechanical Testing

The mechanical properties of the composites, such as tensile strength, flexural strength, and impact resistance, are assessed using standardized tests. These properties are crucial for determining the suitability of the composites for various applications. Mechanical properties were determined using a tensile testing machine (EUT5105) coupled with a Keithley 6487 Picoammeter. The fracture strength, fracture elongation, and Young's modulus were measured to evaluate the impact of the composite layers on the base mechanical properties of the carbon fiber fabric. In essence, Figure 4 presents the impact resistance data, which measures the composite's ability to absorb energy from sudden impacts without fracturing. The results in this figure underscore the composite's resilience and its potential for use in environments where impact resistance is a critical factor. The results demonstrated that the introduction of Cu nanoflakes, EVA, and PTFE did not compromise the inherent mechanical strength of the material, demonstrating the composite's robustness under various loading conditions [12].

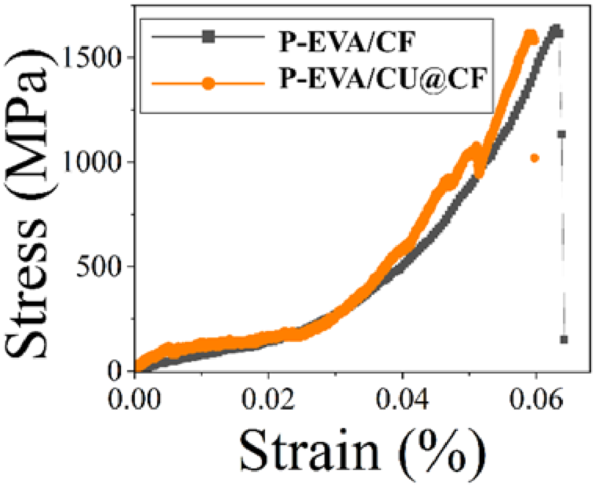

Figure 4. Mechanical test results.

3.3 Thermal Analysis

Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) can be utilized to evaluate the thermal stability and degradation behavior of the composite materials, which is vital for applications in high-temperature environments. Infrared spectroscopy using a Thermo Nicolet iS5 instrument was performed to identify the functional groups present in the composite material. Figure 5 revealed shifts in the infrared spectrum due to the presence of PTFE, indicating its interaction with other components and its role as a barrier to infrared radiation. Thermogravimetrical analysis was executed using a NETZSCH TG 209F3 instrument. The samples were heated to 800 °C at a rate of 10 °C/min in a nitrogen environment to assess their thermal stability. The results indicated a two-stage degradation phenomenon associated with the presence of EVA, and no degradation was observed up to 200 °C for the P-EVA/Cu@CF composite, highlighting its potential for use in high-temperature environments [13].

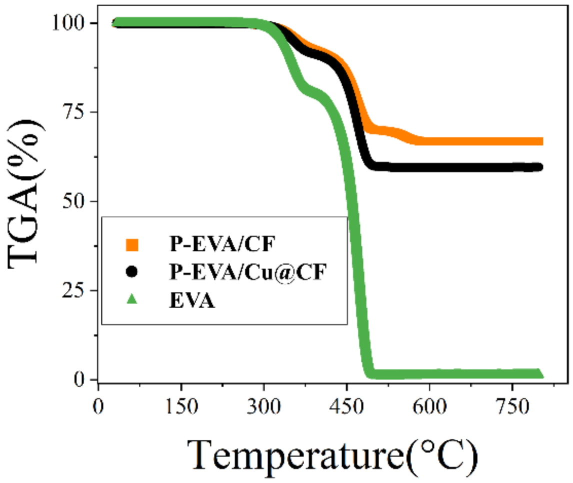

Figure 5. TGA test results.

3.4 Electromagnetic Shielding Properties and Testing

The incorporation of copper nanoflakes in the carbon fiber composite material significantly enhances its electrical conductivity and ability to absorb electromagnetic waves. To characterize these properties, impedance spectroscopy was employed, providing a comprehensive assessment of the material's electromagnetic performance. The EMI shielding effectiveness of the composite material, referred to as P-EVA/Cu@CF, was assessed in the X-band frequency range (8.2–12.4 GHz) using an Agilent E5071c device with waveguide methods. This testing is crucial for evaluating the material's potential in applications requiring protection against electromagnetic interference. The results indicated that the P-EVA/Cu@CF material exhibited exceptional EMI shielding effectiveness, achieving over 40 dB of shielding across the entire X-band range.

Figure 6 succinctly presents the comparative electromagnetic shielding efficiency, demonstrating that P-EVA/Cu@CF outperforms other variants by achieving over 40 dB of shielding across the entire X-band, attenuating electromagnetic waves by more than 99.99%, demonstrating its efficacy in blocking electromagnetic interference [14-16]. The outstanding shielding performance is attributed to the synergistic effects of the inorganic carbon fiber fabric and the metallic copper nanoflakes, which function as conductive elements within the composite structure.

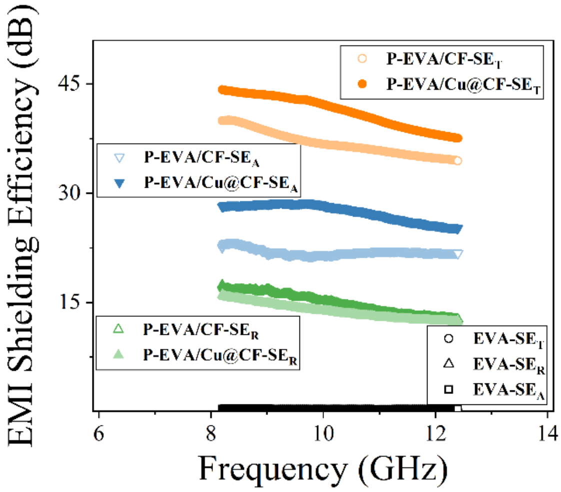

Figure 6. Electromagnetic shielding efficiency of three membranes (P-EVA/Cu@CF, P-EVA/CF and EVA) in the frequency range of 8.2–12.4 GHz.

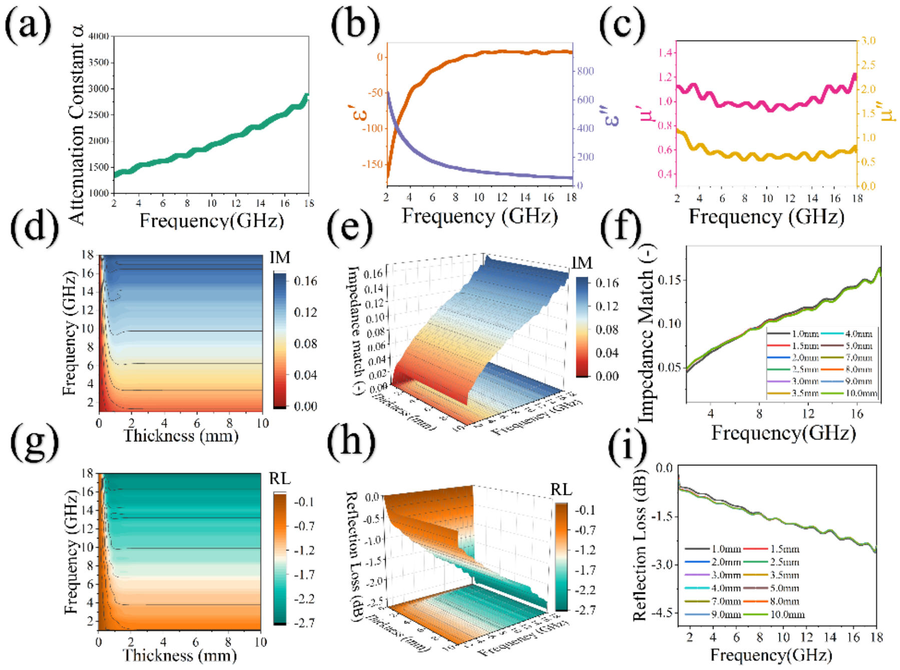

Figure 7. Electromagnetic parameters and attenuation constant α of (a–c) P-EVA/Cu@CF; Impedance Match (d-e) and Reflection Loss (g-h) analysis of P-EVA/Cu@CF composite membranes; Effect of different thicknesses on (f-i) P-EVA/Cu@CF Impedance Match and Reflection Loss.

Our in-depth analysis of the P-EVA/Cu@CF composite's electromagnetic properties, as presented in Figure 7, spans the 2-18 GHz frequency range and utilizes coaxial methods to provide a detailed assessment of the material's absorption capabilities. The attenuation constant α, as depicted in Figure 7(a-c), illustrates a marked enhancement in wave absorption due to the integration of copper nanoflakes, which significantly reduces the attenuation constant by approximately 500 across the entire frequency range. This improvement is primarily due to the superior conductivity of copper, which optimizes the propagation of electromagnetic waves and minimizes energy loss within the material [17]. Furthermore, Figure 7(d-e) display the impedance match analysis, while Figure 7(g-h) present the reflection loss, collectively demonstrating the material's effectiveness in managing electromagnetic interference and its high electromagnetic compatibility. The impact of material thickness on performance is also examined in Figure 7(f-i), showing how varying thicknesses affect the composite's impedance match and reflection loss, which is crucial for customizing the material for specific applications. The P-EVA/Cu@CF composite not only retains the mechanical strength of carbon fiber but also exhibits excellent electromagnetic shielding properties, making it a strong candidate for use in extreme environments where both mechanical resilience and electromagnetic compatibility are vital. The comprehensive overview provided by Figure 7 underscores the composite's versatility and readiness for high-performance applications where electromagnetic shielding is a critical requirement.

3.5 Self-Repairing Investigation and Contact Angle Measurements

The P-EVA/Cu@CF composite's self-healing capabilities were rigorously tested through the induction of artificial scratches and the application of a 9V healing stimulus, leveraging the material's inherent electrical conductivity from the copper nanoflakes to initiate Joule heating. This process effectively melts the surrounding EVA layer, facilitating the self-repair mechanism by reconnecting the damaged areas within a remarkably short span of 30 s.

To further validate the effectiveness of the self-healing process, contact angle measurements were conducted using a KRUSS DSA100 instrument with a 4 μL water droplet [18-20]. Figure 8 provides a visual narrative of the self-healing process and the subsequent recovery of the material's hydrophobic properties. After scratching and subsequent self-repair, the contact angle returned to its original value, demonstrating that the material could not only heal mechanical damage but also restore its hydrophobic surface. This is crucial for maintaining performance in moisture-exposed environments [21-22].

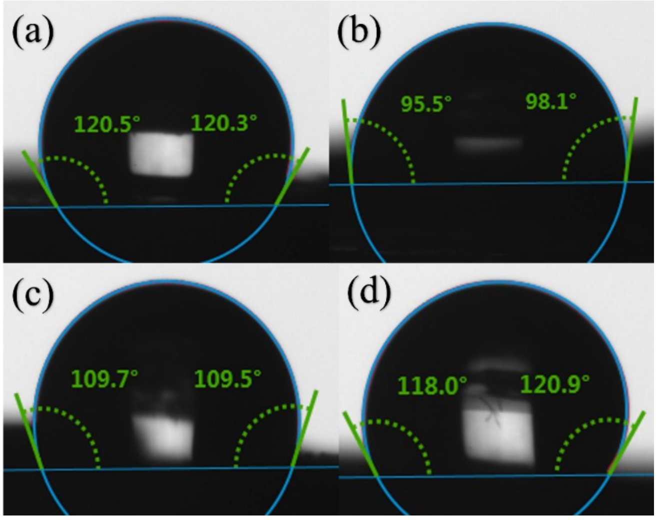

Figure 8. (a) Original contact angle measurement; (b) Contact angle measurement after damage; (c) Contact angle measurement during vertical repair; (d) Contact angle measurement after parallel repair.

Measurements in Figure 8 visually affirm the P-EVA/Cu@CF composite's proficiency in self-healing and the rapid resumption of its hydrophobic state. This dual capability is pivotal for sustaining performance in environments exposed to moisture, underscoring the material's suitability for extreme conditions where durability and adaptability are paramount. The material's autonomous self-repair mechanism not only reduces maintenance costs but also extends the lifespan of devices and structures, solidifying the P-EVA/Cu@CF composite as an advanced material of choice for applications demanding resilience and longevity. Its ability to self-repair without external interventions reduces maintenance costs and enhances the longevity of devices and structures using this advanced material [23].

4. Conclusions

The groundbreaking research presented herein has successfully developed a multifunctional carbon fiber composite material, P-EVA/Cu@CF, which stands out for its exceptional electromagnetic interference (EMI) shielding prowess. This advanced material harnesses the synergistic effects of its conductive components, namely the copper nanoflakes and the carbon fiber fabric, to achieve an impressive electromagnetic shielding effectiveness of over 40 dB across the entire X-band frequency range, equating to a shielding efficacy of more than 99.99%. This level of performance is particularly remarkable, given the material's ability to absorb and shield a broad spectrum of electromagnetic waves, thereby protecting internal structures from radiation and enhancing the durability of electronic devices in extreme environments.

The incorporation of copper nanoflakes has been identified as a pivotal factor in enhancing the material's absorption capabilities, resulting in a significant reduction in the attenuation constant α by approximately 500 across the 2–18 GHz range. This reduction is attributed to the superior conductivity of copper, which optimizes the propagation of electromagnetic waves and minimizes energy loss within the material. Furthermore, the material's impedance match is notably increased in higher frequency bands due to the presence of copper nanoflakes, indicating a more effective adaptation to the external environment and improved compatibility with incident electromagnetic waves.

In summary, the P-EVA/Cu@CF composite material not only maintains the mechanical robustness of carbon fiber but also introduces a new dimension of functionality with its hydrophobic surface and self-healing capabilities. Its electromagnetic shielding properties, as demonstrated, position it as a superior material for applications where resistance to extreme environments and high-performance EMI shielding are paramount. Future work is anticipated to further optimize the material's composition and structure to meet specific design and modulation requirements for advanced electromagnetic wave absorption characteristics.

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