Preparation and Application Research of Conductive Polymer Nanocomposite Coatings

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ABSTRACT Conductive polymer nanocomposite coatings that combine the redox activity of conductive polymers with the structural functionality of nanofillers have broad application prospects in active corrosion protection, electrochemical response, electromagnetic shielding, and microwave attenuation. These coatings are also promising for high-performance fibers, smart weaving materials, and flexible electromagnetic functional surfaces. Based on this background, this study uses polyaniline and polypyrrole as matrix materials and investigates the preparation process, structural control, and service performance of conductive polymer nanocomposite coatings through composite modification with nanofillers. Polyaniline/carbon nanotube composite fillers were prepared by in-situ polymerization, while a polypyrrole/nano-silica composite system was prepared by oxidative polymerization. Composite coatings were then formed on different substrate surfaces by spraying or coating processes. The chemical structure and microstructure were characterized using infrared spectroscopy, scanning electron microscopy, and X-ray diffraction. Conductivity, corrosion resistance, and electromagnetic shielding effectiveness were measured using four-probe testing, electrochemical impedance spectroscopy, potentiodynamic polarization, and waveguide-based shielding tests. The results reveal the synergistic enhancement mechanism between conductive polymers and nanofillers, providing experimental evidence for the rational design of multifunctional coatings with improved durability, corrosion resistance, and electromagnetic-wave shielding performance.

INDEX TERMS conductive polymer, nanocomposite coating, electromagnetic shielding, wave attenuation, functional textiles

I. INTRODUCTION

The functional upgrading of material surfaces is an essential strategy for enhancing the comprehensive performance and expanding the application fields of high-performance fibers and smart weaving materials. This advancement enables the integration of specialized properties—such as electromagnetic shielding and electrochemical responsiveness—directly into the architecture of advanced functional textiles and industrial technical fabrics. Nanocoating technology, through the regulation of micro/nano structures and the combination with functional fillers, can endow the matrix material with diverse functions while maintaining its original properties, and has become a core technology for material surface modification. Among numerous nanocoating systems, conductive polymers, due to their unique intrinsic conductivity, reversible redox properties, and excellent film-forming performance, have gradually become a cutting-edge research hotspot for multifunctional protective coatings. Conductive polymers such as polyaniline and polypyrrole can not only achieve electrochemical responses through doping-dedoping processes, but also promote the formation of passivation layers during metal corrosion, thereby achieving active corrosion protection. However, single conductive polymer coatings still face problems such as insufficient mechanical strength, poor long-term stability, and conductivity degradation in practical applications. The introduction of nanofunctional fillers provides an effective way to solve these problems. Fillers such as carbon nanotubes, graphene, nano-silica, and nano-silicon carbide, with their high specific surface area, excellent mechanical properties, and unique electrical properties, can form a synergistic reinforcing effect with conductive polymer matrices, constructing composite coating systems that combine conductivity, mechanical strength, and protective performance. This study aims to overcome the limitations of traditional coatings that serve only as passive protective layers. By introducing the intrinsic conductivity and redox activity of conductive polymers polyaniline and polypyrrole, and combining them with the synergistic enhancement effect of two typical functional fillers—carbon nanotubes and nano-silica—a multifunctional composite coating system integrating active corrosion protection and electromagnetic shield-

ing is constructed. The study will systematically explore the preparation process parameters, microstructure evolution, conductivity, corrosion resistance, and electromagnetic shielding effectiveness of the composite coating, revealing the structure-property relationship between conductive polymers and nanofillers. The goal is to provide a new theoretical basis and technical pathways for the design and application of intelligent protective coatings and multifunctional surface materials specifically engineered for high-performance fibers and smart weaving materials. These advancements facilitate the development of advanced functional textiles that integrate electromagnetic shielding and active corrosion protection directly into the material architecture.

II. RELATED WORK

Nanocoating technology is an important means of material surface modification. Its core lies in the multifunctional upgrade of matrix materials by regulating micro-nano structures and combining with functional fillers. Abdullah et al . [1] made simple and low-cost improvements to tubular solar distillers. Yang et al. [2] constructed a nanocoating based on graphene oxide and chitosan on the surface of wood by layer-by-layer self-assembly. Yang et al. [3] used micron-sized hexagonal boron nitride and nano-sized alumina as fillers, combined with epoxy resin, and prepared a multifunctional mechanically robust superhydrophobic anti-corrosion coating by spraying. Fast-growing wood is widely used because of its fast growth and low cost, but it has low density and poor durability, especially in outdoor weathering. Rahayu et al. [4] applied TiO2 nanoparticles to the surface of wood by impregnation or spraying, and then carried out accelerated aging tests to compare the effects of the coating on the color change, surface morphology and chemical composition of wood. Li et al. [5] constructed a coating with micro-nano rough structure by chemical modification and spraying process, and systematically characterized its mechanical stability, anti-fouling and self-cleaning properties. Sengottiyan et al. [6] found that the protein crown has a significant effect on the zeta potential of nanoparticles. Considering only the properties of the nanoparticle core or the original coating, it is impossible to accurately predict its actual zeta potential in the biological environment. Chaturvedi and Ramalingam [7] developed a dustproof nanocoating to improve the operating efficiency of photovoltaic systems. Lee et al. [8] proposed to use polydopamine to induce the formation of a uniform ultrathin nanocoating on the surface of nickel-rich cathode materials. Huang et al. [9] combined the concept of green chemistry to design a composite superhydrophobic coating based on nano and micron-sized silica particles. Zolriasatein et al. [10] proposed a nanocoating based on room temperature vulcanized silicone rubber and nano silica particles for coating on the surface of power insulators. While the aforementioned research has made progress in wood protection, photovoltaic efficiency improvement, and battery stability, challenges remain in the field of electromagnetic shielding, particularly for the needs of flexible smart textiles. Recent studies have shown that conductive textiles using graphene/conductive polymers or high-performance MXene coatings can typically achieve shielding effectiveness of 40-80 dB in the X-band, while traditional conductive coatings often struggle to achieve ideal electromagnetic attenuation levels while maintaining fabric flexibility.This paper aims to break through the limitation of traditional coatings as passive protective layers. By introducing the intrinsic conductivity and redox activity of conductive polymers (such as polyaniline, polypyrrole, etc.) and combining the synergistic enhancement effect of nano-functional fillers, a multifunctional composite coating system integrating active corrosion protection, electrochemical response and electromagnetic shielding is constructed. The structure-property relationship of its conductivity mechanism, structural evolution and service performance is systematically studied, so as to provide new theoretical basis and technical path for the design and application of intelligent protective coatings and multifunctional surface materials [11-12] .

III. METHODS

A. PREPARATION OF POLYANILINE/CARBON NANOTUBE COMPOSITE COATING

Polyaniline/carbon nanotube composite fillers were prepared by in-situ polymerization. First, the carbon nanotubes underwent acidification pretreatment: 2.0 g of multi-walled carbon nanotubes were weighed and added to 200 mL of mixed acid (concentrated sulfuric acid to concentrated nitric acid in a volume ratio of 3:1). The mixture was ultrasonically dispersed in a 60°C water bath for 30 min, followed by magnetic stirring and reflux for 4 h. The reaction product was diluted with deionized water and then vacuum filtered through a 0.22 μm polytetrafluoroethylene membrane. The filter cake was repeatedly washed until the pH of the filtrate was neutral. The resulting acidified carbon nanotubes were then vacuum dried at 60°C for 24 h for later use. Aniline monomer was purified by vacuum distillation before use. 0.5 g of acidified carbon nanotubes were dispersed in 100 mL of 1 mol/L hydrochloric acid solution and sonicated for 1 h to obtain a uniform dispersion. 2.0 mL of aniline monomer was added to the dispersion, and the mixture was stirred in an ice-water bath for 30 min to allow aniline to fully adsorb onto the carbon nanotube surface. 20 mL of a 1 mol/L hydrochloric acid solution containing 5.0 g of ammonium persulfate was prepared and slowly added dropwise to the aniline/carbon nanotube dispersion at 0-5°C, with the addition time controlled at at least 30 min. The reaction system was continuously stirred in an ice-water bath for 8 h. After filtration, the product was washed alternately with large amounts of deionized water and anhydrous ethanol until the filtrate was colorless. The resulting dark green precipitate was dried under vacuum at 50°C for 24 h to obtain the polyaniline/carbon nanotube composite filler. The composite coating was prepared using a spraying process. Epoxy resin E-44 was used as the film-

forming base material, and polyamide resin as the curing agent, with a mass ratio of 3:1. Polyaniline/carbon nanotube composite filler was added to the epoxy resin at different mass fractions (0.5 wt%, 1.0 wt%, 1.5 wt%, 2.0 wt%, 2.5 wt%), along with an appropriate amount of xylene and n-butanol mixed solvent (volume ratio 7:3). The mixture was dispersed in a high-speed disperser at 2000 r/min for 30 min, followed by the addition of the polyamide curing agent and continued stirring for 10 min. The resulting coating was filtered through a 200-mesh sieve and then sprayed onto a polished and degreased Q235 carbon steel substrate using a spray gun. The spraying pressure was controlled at 0.4-0.6 MPa, and the spraying distance was 20-25 cm. After spraying, the sample was leveled at room temperature for 15 min, and then cured in a 60°C oven for 6 h. The thickness of the resulting coating was controlled at 40-50 μm [13-14].

B. PREPARATION OF POLYPYRROLE/NANO-SILICA COMPOSITE COATING

Polypyrrole/nano silica composite material was prepared by chemical oxidative polymerization. Before use, the nano silica was surface-modified with a silane coupling agent

KH-570: 5.0 g of nano silica was dispersed in 100 mL of anhydrous ethanol, 1.0 mL of KH-570 was added, and the mixture was ultrasonically reacted at 60°C for 4 h. The product was then centrifuged, washed three times with anhydrous ethanol, and vacuum dried at 60°C to obtain the modified nano silica. 2.0 g of modified nano-silica was weighed and dispersed in 100 mL of 0.1 mol/L p-toluenesulfonic acid aqueous solution, and sonicated for 1 h. Then, 1.5 mL (approximately 1.6 g) of pyrrole monomer (distilled under reduced pressure before use) was added. The calculated mass ratio of polypyrrole to nano-silica in this synthesis system was approximately 0.8:1, aiming to control the packing morphology of polypyrrole through the rigid structure of nano-silica, while avoiding coating brittleness due to excessive polypyrrole content. A 30 mL solution of 0.1 mol/L p-toluenesulfonic acid containing 4.5 g of ferric chloride was prepared. The reaction system was placed in an ice-water bath and reacted for 6 h. After the reaction, the product was centrifuged and washed alternately with large amounts of deionized water and methanol. The resulting black precipitate was dried under vacuum at 40 °C for 24 h to obtain the polypyrrole/nano-silica composite material. Thermogravimetric analysis (TGA) was used to perform precise mass balance analysis on the obtained composite filler. The results showed that the actual mass fraction of polypyrrole in the composite material was about 42%, and the mass fraction of nano-silica was about 58%, which was basically consistent with the feed ratio. The polypyrrole/nano-silica composite coating was prepared by a blending method. Using waterborne polyurethane as the film-forming base material, the polypyrrole/nano-silica composite material was added to the waterborne polyurethane emulsion at different mass fractions (2 wt%, 3 wt%, 4 wt%, 5 wt%, 6 wt%). An appropriate amount of deionized water was added to adjust the viscosity, and 0.5 wt% wetting and dispersing agent and 0.2 wt% defoamer were added. The mixture was ball-milled in a planetary ball mill at 300 r/min for 2 h to ensure uniform dispersion of the filler. After filtering the resulting coating through a 200-mesh sieve, it was coated onto the surface of a polyethylene terephthalate film using a wire bar coater, with the wet film thickness controlled at 80 μm. After drying at room temperature for 24 h, the film was transferred to a 50°C oven for further drying for 12 h, resulting in a dry film thickness of 25-30 μm.

C. STRUCTURAL AND PERFORMANCE CHARACTERIZATION METHODS OF COMPOSITE COATINGS

Microstructure and surface and cross-section structure of the coating by field emission scanning electron microscope (FET) accelerating voltage of 5 ~ 10kV, the sputtering gold treatment of the surface of the gold layer. The crystal structure of the composite material was analyzed through x-ray diffraction (XRD), Cu target K alpha radiation, tube voltage: 40 kV, tube current: 40 mA, scanning range: 5-80 degree and scanning speed: 5 degree/min. The conductivity of the coating was tested with a four probe tester. Five test points were randomly chosen on the surface of the coating and each of the points were tested three times. The average value was considered the conductivity of coating. Before testing, the coating surface must be smooth and dry, and the ambient temperature and the relative humidity must be controlled at 25±1°C and 45±5%. For coatings on insulating substrates, the surface resistivity can be tested directly; for coatings on metal substrates, the coating must be peeled off to form a thin film sample for testing. The anti-corrosion performance of the coating was tested by electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization (PVP) curves. A three electrodes system was adopted, which consists of working electrode (coated carbon steel electrode 1 cm2 exposure area), auxiliary electrode (platinum electrode), and reference electrode (saturated calomel electrode). The electrolyte was 3.5 wt% NaCl solution. EIS measurements were carried out at the open circuit potential with a sinusoidal amplitude of 10 mV and a frequency between 10^5–10^{-2} Hz. PVP curves were made from - 0.5 to + 0.5 (relative to open circuit potential) at a scan rate of 1 mV/s. Samples were immersed in the electrolyte for 30min before testing to attain a stable state. The based electromagnetic shielding effectiveness property of the coating was measured with the waveguide method in the 8.2-12.4 GHz frequency ranges. The coating was applied to the surface of a polyethylene terephthalate (PET) film, dried and cut into rectangular samples of 22.86 mm × 10.16 mm, which were placed in a waveguide fixture. Scattering parameters were obtained by using vector network analyzer and the electromagnetic shielding effectiveness of the coating is calculated. Each sample was tested three times and the average values were

taken. The basic physical properties of the coating are tested such as adhesion, hardness, and impact resistance. Adhesion is tested by GB/T 9286 using cross cutter tester. A grid of 1 mm x 1 mm size is cut on the coating surface with a cross cutting tool. After adherence with special adhesive tape, the extent of peeling of the coating is observed and the level of adhesion is rated by experiments from 0 to 5. Hardness is measured to GB/T 6739 using the pencil hardness method of hardness. of a set of pencils of different hardnesses are then pressed against the surface of the coating at an angle of 45° and the hardness of the most difficult pencil that makes a scratch is noted. Impact resistance is measured according-to GB/T 1732 by an impact tester. The coated sample is laid on the impact tester base and a 1kg hammer is dropped from various heights. The maximum height from which the coating cracks or peels out is observed.

IV. RESULTS AND DISCUSSION

A. STRUCTURAL CHARACTERISTICS AND ELECTRICAL CONDUCTIVITY OF POLYANILINE/CARBON NANOTUBE COMPOSITE COATINGS

Infrared spectroscopy analysis showed that there are characteristic absorption peaks of 1568 cm-1 and 1492 cm-1 for polyaniline/carbon nanotube composite material which correspond to the C=C skeleton vibration of quinone and benzene in polyaniline molecular chain, respectively. The absorption peak at 1298 cm-1 was assigned to the stretch (double bond) vibration of the central nitrogen-carbon (C-N) bond of the aromatic amine and the broad absorption peak around 1120 cm-1 was the characteristic absorption peak of the protonated state of conductive polyaniline, indicating that the polyaniline was in a doped conductive state. Compared with pure polyaniline, the above characteristic peak positions of the composite material had slight shifts, and the intensities of some of the peaks changed, indicating the existence of the π-π interactions between polyaniline and carbon nanotubes. This interaction helps to transfer the charge at the interface between the two. Scanning electron microscopy (SEM) observations showed that the surface roughness declined while the length went down for acid-treated carbon nanotubes, favorable for the dispersion in the polymer matrix. In polyaniline/carbon nanotube composite material, polyaniline uniformly covers the surface of carbon nanotubes and forms typical core-shell structure.This core-shell structure is crucial because the polyaniline coating effectively prevents the highly conductive carbon nanotubes from directly contacting the metal substrate, thereby minimizing the risk of localized galvanic corrosion induced by the carbon nanotubes as a cathode while maintaining the conductivity of the system. In some regions polyaniline forms bridges between the carbon nanotubes and builds up a preliminary three-dimensional network structure. When the composite is dispersed in an epoxy resin matrix, this three-dimensional network structure is partially preserved and the carbon nanotubes constitute conductive pathways in a coating and the channels used by electrons for transport. There is a regular change in the conductivity of the composite coating with the increase of polyaniline/carbon nanotube filler content. At low filler content the particles of the conductor are separated in the coating and do not provide a good contact so conductivity is low. As the filler content increases, the distance between the conductive particles becomes closer, resulting in the formation of localized conductive networks, and a gradual increase in the conductivity. When the filler content approaches the percolation threshold, a through-conductive conductive pathway is formed in the coating, thus improving conductivity greatly. The conductivity test results of the composite coating prepared with various polyaniline/carbon nanotube filler contents are summarized in Table 1.

As shown in Table 1, with filler content increased from 0.5 wt% to 1.5 wt%, three orders of magnitude of increase in the coating conductivity were observed, a fact indicative of the formation of an effective conductive network in this filler content range. At filler content of 1.5 wt%, the coating conductivity was 2.8 * 10-2 S/cm. Further adding filler to 2.5 wt% slightly raised the conductivity to 4.0*10-2 S/cm, which shows that the construction of conductive network was almost complete. At this point, the three-dimensional conductive network built by the carbon nanotubes will synergistically interact with the molecular chain conductivity of polyaniline, which will produce conductivity that is the best possible. The formation of conductive network is the basis for the conductive coating to realize electrochemical response and electromagnetic shielding characteristics.

B. CORROSION RESISTANCE ANALYSIS OF POLYANILINE/CARBON NANOTUBE COMPOSITE COATING

Electrochemical impedance spectroscopy (EIS) results showed that the polyaniline/carbon nanotube composite coating exhibited good anti-corrosion protection against the carbon steel substrate. Initially, all coatings showed high impedance moduli in the 3.5 wt% NaCl solution, indicating their barrier effect against corrosive media. With prolonged immersion, the impedance modulus of the pure epoxy resin coating decreased rapidly, indicating that the corrosive media had penetrated to the coating/metal interface. However, the impedance modulus of the polyaniline/carbon nanotube composite coating decreased significantly less, maintaining a high impedance value even after 480 h of immersion. Potentiodynamic polarization curve testing further quantified the corrosion resistance of the composite coating. Table 2 summarizes the electrochemical parameters of polyaniline/carbon nanotube composite coatings with different filler contents in 3.5% NaCl solution. When the filler content is 1.5 wt%, the corrosion current density is the lowest (3.2 $\times$ 10-7 A/cm2), and the corrosion potential is the most positive (-0.482 V), exhibiting the best corrosion resistance. Compared with pure epoxy resin coatings, the corrosion current density of the 1.5 wt% filler composite coating is

TABLE 1. Electrical conductivity of composite coatings with different polyaniline/carbon nanotube filler contents

Filler content (wt%)	Surface resistivity (Ω·cm)	Electrical conductivity (S/cm)	seepage state
0.5	8.6×10^4	1.2×10^{-5}	No seepage
1.0	2.3×10^3	4.3×10^{-4}	Local seepage
1.5	3.6×10^1	2.8×10^{-2}	Complete seepage
2.0	2.8×10^1	3.6×10^{-2}	Complete seepage
2.5	2.5×10^1	4.0×10^{-2}	Complete seepage

reduced by two orders of magnitude, achieving a corrosion protection efficiency of 98.7%.

To further verify the existence of the passivation layer, cross-sectional SEM characterization was performed on the samples after electrochemical testing (as shown in Figure X). The results clearly show that a dense oxide film with a thickness of approximately 100-200 nm was formed at the interface between the coating and the metal. This passivation layer was induced by the redox reaction between the oxidized polyaniline and the iron substrate at the corrosion potential, forming a second barrier to prevent further ion migration. The anti-corrosion mechanism of the polyaniline/carbon nanotube composite coating can be understood from three aspects: First, the network structure formed by the carbon nanotubes in the coating prolongs the diffusion path of the corrosive medium, enhancing the physical barrier effect of the coating; second, polyaniline has redox activity and can maintain the metal electrode position in the passivation region through interfacial charge transfer, promoting the formation of a dense passivation layer to inhibit anodic dissolution; third, the π-π interaction between polyaniline and carbon nanotubes promotes a rapid electrochemical response. It should be noted that this protection mechanism relies on the precise ratio of filler. When the filler content exceeds 1.5 wt%, incomplete coating may occur in some areas due to filler agglomeration, exposing carbon nanotubes and causing them to come into contact with the substrate. This leads to the appearance of galvanic corrosion and a slight decrease in corrosion resistance.

C. ELECTROMAGNETIC SHIELDING EFFECTIVENESS OF POLYPYRROLE/NANO-SILICA COMPOSITE COATING

The microscopic morphology observation of the polypyrrole/nano-silica composite coating revealed that the modified nano-silica was uniformly dispersed in the polypyrrole matrix and did not form an agglomeration. Polypyrrole was coated on silica surface in a particulate form formed composite structural units. These units connected together inside of the coating, building a network of conductors. The introduction of nano-silica not only enhanced the film-forming characteristics of polypyrrole, but also introduced more interfaces in the coating, which is useful in multiple reflections and absorption of the electromagnetic waves. Electromagnetic shielding effectiveness test results indicate that the polypyrrole/nano-silica composite coating has a good shielding performance in the X-band (12.2-16.4 GHz). Table 3 summarizes the shielding effectiveness and other related parameters of electromagnetic shielding of composite coatings containing various polypyrrole/nano-silica filler contents. The data in the table indicate that the electromagnetic shielding effectiveness of the coating is continuously improved with the increase of the content of the filler. When the filler content is 4 wt%, the average shielding effectiveness of coating in X-band is 22.5 dB, which meets the basic requirement of shielding effectiveness of commercial electromagnetic shielding material of above 10 dB (blocking 90% of electromagnetic wave). Further addition of filler to 6 wt% results in 31.3 dB shielding effectiveness to suppress over 99% of incident electromagnetic waves.

From the aspect of shielding mechanism analysis, the shielding mechanism of the polypyrrole/nano-silica composite coating takes the form of absorption loss, and this accounts for over 70% of the total shielding effectiveness. This characteristic is closely related to the microstructure of the material: on the one hand, as a conductive polymer, the case of the conjugated structure in the molecular chain of polypyrrole can form electric dipole interaction with electromagnetic waves and the conversion of electromagnetic energy into heat energy; and on the other hand, the addition of nano-silica will increase the density of the interface inside the coating, multiple reflections and scattering of electromagnetic waves at the interface will cause the increase of the propagation path of electromagnetic waves inside the coating and increase the chance of absorption. In addition, the heterogeneous interface formed between polypyrrole and silica may also create some interfacial polarization, which may further improve the electromagnetic wave attenuation capability. After 1000 bending cycles, the shielding effectiveness of the coating decreased by less than 5% showing a good flexibility and mechanical stability.The results indicate that, under the condition that the mass ratio of polypyrrole to nano-silica is approximately 0.8:1, the rigid framework of nano-silica effectively suppresses the excessive entanglement of polypyrrole molecular chains, avoids coating embrittlement, and at the same time maintains the continuous conductive network of polypyrrole. This is explained by reinforcing effect of nano-silica as well as good interfacial bonding between polypyrrole and substrate. To quantitatively explain the stability of the composite coating under severe mechanical deformation, adhesion tests were conducted according to GB/T 9286 standard. The results showed that when the polypyrrole/nano-silica filler content was 4 wt%, the coating achieved an adhesion grade of 0 to the PET substrate (completely smooth cut edges with no peeling). This excellent interfacial bonding

TABLE 2. Electrochemical parameters of composite coatings with different polyaniline/carbon nanotube filler contents

Filler content (wt%)	Corrosion potential (V vs. SCE)	Corrosion current density (A/cm^2)	Corrosion protection efficiency (%)
0 (pure epoxy)	-0.687	2.5×10^{-5}	—
0.5	-0.623	8.7×10^{-6}	65.2
1.0	-0.561	2.1×10^{-6}	91.6
1.5	-0.482	3.2×10^{-7}	98.7
2.0	-0.508	5.4×10^{-7}	97.8
2.5	-0.527	8.9×10^{-7}	96.4

TABLE 3. Electromagnetic shielding performance of composite coatings with different polypyrrole/nano-silica filler contents

Filler content (wt%)	Coating thickness (μm)	Average shielding effectiveness (dB)	Absorption loss (dB)	Reflection loss (dB)
2	28	12.2	5.1	3.1
3	27	16.6	8.3	4.3
4	29	22.5	13.2	5.3
5	30	29.8	14.5	5.3
6	28	31.3	15.8	5.5

strength effectively suppressed the generation and propagation of microcracks under repeated bending stress.The polypyrrole/nano-silica composite coating preserves the integrity of the conducting network while having the mechanical properties needed for flexible electronic devices. It is important to note that the electromagnetic shielding performance tests described above were conducted on an insulating polyethylene terephthalate (PET) film substrate. In practical applications, if this coating is applied to a metal substrate (such as Q235 carbon steel), the shielding effectiveness may change due to the secondary reflection effect between the metal and the coating. Specifically, as a good conductor, the metal substrate interacts with the coating in a complex electromagnetic wave interaction mode of reflection-absorption-reflection: the incident electromagnetic wave is first partially absorbed and reflected by the coating; the electromagnetic wave that passes through the coating reaches the metal surface and undergoes a strong secondary reflection, re-entering the coating for secondary absorption. This mechanism generally helps improve the overall shielding effectiveness, but it may also alter the contribution ratio of absorption loss to reflection loss in the shielding effectiveness. Therefore, for practical applications on metal substrates, the shielding effectiveness values measured on PET substrates in this study should be considered conservative estimates; higher shielding effectiveness is expected on metal substrates. Future research will further quantify the specific enhancement of shielding effectiveness by metal substrates.

D. SYNERGISTIC EFFECT AND STRUCTURE-PROPERTY RELATIONSHIP OF COMPOSITE COATINGS

In summary, the results show enhancing synergistic effect between the functional filler and conductive polymer matrix in the conductive polymer nanocomposite coating is significant. For the polyaniline/carbon nanotube system, carbon nanotubes not only serve as conductive fillers to build up a three-dimensional conductive system, but they also electronically couple with the polyaniline molecular chains by means of π-π interactions, enhancing the charge transport efficiency of the entire system. Simultaneously, due to the nanoscale effect of carbon nanotubes, they fill in the gaps between the polyaniline molecular chains, making the coating more dense and giving it better physical barrier properties. Regarding the corrosion resistance, the combination between the redox activity of polyaniline and the conductivity of carbon nanotubes, a double protection mechanism of active inhibition and passive barrier against corrosion is achieved. In the polypyrrole/nano silica system, the function of nano silica is mainly to regulate its structure and improve the interface. The modified nano silica surface has reactive groups that are able to create chemical or physical contact with the polypyrrole molecular chains that promote the homogenous coating of polypyrrole on the surface of the nano silica and form regular composite structural units. Structural units are arranged in the coating to ensure the continuity of the electrical conducting network that passes through it and increases the number of interfaces through which the electromagnetic waves interact.By precisely controlling the mass ratio of polypyrrole to nano-silica (TGA confirmed to be approximately 42:58), coating brittleness caused by excessive polypyrrole content was avoided, while ensuring the effective construction of conductive pathways. The internal conductivity of polypyrrole gives the means to absorb electromagnetic waves and the multiple interfaces which are introduced by nano silica reinforce this phenomenon to reach a shielding of the electromagnetic wave based on absorption phenomena. The correlation between coating performance and filler content has typical percolation features. When the filler content is below the percolation value, the network of the dispersed phase of the functional filler has not formed a continuous network, and the performance is not improved to a large extent. When the filler content is raised to the percolation threshold, there will be a structural abrupt change in the system, the conductive network will be turned into a continuous one and various properties of the system will be significantly improved.

However, theoretically, when the filler content exceeds a certain critical point, excessive filler will lead to agglomeration, resulting in performance degradation. It is noteworthy that within the filler content range examined in this study (up to 2.5 wt% for the polyaniline/carbon nanotube system and up to 6 wt% for the polypyrrole/nano silica system), no decrease in electromagnetic shielding effectiveness was observed. This may be because the critical agglomeration concentration that triggers performance degradation has not yet been reached. This pattern suggests that there exists an optimal filler content range in the design of conductive polymer nanocomposite coatings, which varies depending on the target performance and requires a trade-off between performance requirements and processing technology.

E. THERMAL STABILITY ANALYSIS

The inherent thermal instability of conductive polymers is a key factor limiting their application in high-temperature environments. To verify the feasibility of the prepared composite coating in high-temperature processing or application scenarios related to industrial technical textiles, this study systematically investigated the thermal decomposition behavior of two composite materials, polyaniline/carbon nanotubes (PANI/CNT) and polypyrrole/nano-silica (PPy/SiO2), using thermogravimetric analysis (TGA). For the PANI/CNT composite material, its TG curve showed a typical three-stage weight loss process. The first stage of weight loss (<150°C) corresponds to the volatilization of adsorbed water molecules and residual solvents in the material, with a weight loss rate of approximately 5-8%. The second stage, mainly occurring between 250°C and 450°C, corresponds to the decomposition of the polyaniline backbone, including dopant dedoping and molecular chain breakage, with a weight loss rate of approximately 40-50% in this stage. When the temperature exceeds 500°C, the weight loss tends to level off, and the remaining mass mainly consists of carbon nanotubes and partially pyrolyzed carbon. The initial decomposition temperature (T_onset, 5% weight loss) is approximately 220°C, and the maximum weight loss rate temperature (T_max) is approximately 380°C. For the PPy/SiO2 composite, its thermal stability is slightly lower than that of the PANI system. Its initial decomposition temperature (T_onset) is approximately 200°C, with a major weight loss step occurring between 210°C and 400°C, corresponding to the oxidative decomposition of the polypyrrole backbone. DTG curves show that the maximum weight loss rate temperature (T_max) is approximately 320°C. Due to the excellent thermal stability of nano-silica itself, the char residue of the composite material is as high as 30-35% at 800°C, far exceeding that of pure polypyrrole (approximately 10-15%). In summary, although the conductive polymer matrix begins to decompose significantly above 250°C, the initial decomposition temperatures of both composite coatings exceed 200°C. This allows it to withstand the temperatures of conventional textile finishing processes (such as heat setting and pressing, typically at 150-200°C), meeting the usage requirements of most industrial technical fabrics in non-extreme high-temperature environments. However, for applications requiring long-term operation above 250°C, further improvements in thermal stability are needed through molecular structure design or the addition of flame retardants/heat stabilizers. The TGA data provided in this section offers crucial thermal performance data for evaluating the practical application potential of this composite coating in industrial technical fabrics.

V. CONCLUSION

This study systematically investigates the preparation and application of conductive polymer nanocomposite coatings specifically engineered for high-performance fibers and smart weaving materials. These advanced coatings enable the integration of active corrosion protection and electromagnetic shielding directly into the architecture of advanced functional textiles and industrial technical fabrics. Two composite systems, polyaniline/carbon nanotubes and polypyrrole/nano-silica, were prepared using in-situ polymerization and chemical oxidative polymerization, respectively. Composite coatings were then constructed on different substrates using a spraying process. The microstructure, conductivity, corrosion resistance, and electromagnetic shielding effectiveness of the coatings were systematically characterized .The study revealed differences in percolation behavior among different performance indicators (conductivity, corrosion resistance, and electromagnetic shielding effectiveness). The electromagnetic shielding performance continued to improve even with a filler content as high as 6 wt%, and no performance degradation due to agglomeration was observed. This research provides experimental evidence and theoretical guidance for the application of conductive polymer nanocomposite coatings in active corrosion protection and electromagnetic shielding. Future work can further explore composite systems with multifunctional fillers to expand the application of coatings in intelligent protection fields such as electrochemical response and sensing detection for high-performance fibers and smart weaving materials. These advancements facilitate the integration of responsive molecular architectures directly into the matrix of advanced functional textiles and industrial technical fabrics.

AUTHOR CONTRIBUTIONS

Conceptualization –Yuelong Wang, Cengnan Jiao, Boyi Liang and Shunqiang Guo; methodology – Yuelong Wang, Boyi Liang and Shunqiang Guo; investigation – Yuelong Wang, Cengnan Jiao, Boyi Liang and Shunqiang Guo; writing-original draft preparation – Yuelong Wang, Cengnan Jiao, Boyi Liang and Shunqiang Guo. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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Not applicable.

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