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Development of Corona Prevention Coatings for 750kV Substation in Operation

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Abstract—A single acrylic resin has poor conductivity and toughness, but strong hydrophilicity, which limits its application in high-voltage transmission corona prevention. In response to this issue, this article investigates the preparation of four types of acrylic composite conductive coatings with different additions of carbon fiber powder, multi-walled carbon nanotubes, and nano titanium dioxide. Through experimental testing, compare and analyze the effects of various fillers on the mechanical properties, conductivity, hydrophobicity, and heat resistance of acrylic composite conductive coatings. The experimental results show that the acrylic conductive coating prepared with thermoplastic acrylic resin as the matrix, carbon fiber powder and multi-walled carbon nanotubes as conductive fillers, and nano titanium dioxide as a self-cleaning agent has excellent performance characteristics in all aspects, and is suitable for corona prevention in ultra-high voltage transmission. This acrylic composite coating can be used to repair burrs and scratches on the surface of transmission lines, fill gaps in stranded wires, and achieve the goal of reducing the local electric field of high-voltage transmission lines to prevent wire corona.

Keywords—Anti-corona, conductive coating, acrylic resin, preparation process, construction process, performance testing, electrical properties, mechanical properties, hydrophobicity, heat resistance performance.

I. Introduction

CORONA noise is often generated by the conductors of substations and transmission lines. The main reason for the generation of corona is that the conductors are damaged during transportation and installation, or the design considerations are incomplete, resulting in a thinner conductor diameter. The distribution of wire corona noise sources is extensive, and it is difficult to control them through measures such as setting sound barriers. Therefore, it is necessary to control the noise from the source. The fundamental method for treating corona is to reduce local field strength. The conventional method is to install voltage equalization measures for treatment. However, this method adds more additional mass when there are many corona points on a single section of wire, and the installation method is complex, so it cannot be used on a large area, [1], [2].

Acrylic resin (AA) coating is a new type of coating, widely used in aviation products, military products, light industrial products, instruments, and vehicles due to its excellent adhesion, weather resistance, good light resistance and color retention, bright and full color, durability, gasoline resistance, corrosion resistance, and mechanical properties, [3], [4], [5], [6]. In recent years, its excellent performance has made it one of the hotspots in the research of corona prevention and control measures for transmission lines, [7], [8], [9], [10]. In [11], the authors proposed using composite materials to enhance the corona voltage of conductors. In [12] and [13], the authors analyzed the microstructure and function of coatings filled with carbon nanotubes. In [14] and [15], the authors analyzed the relevant characteristics of modified materials applied to electric fields. However, acrylic resin has poor toughness, poor conductivity, and strong hydrophilicity, [16], [17]. This greatly limits the application of acrylic coatings in ultra-high voltage transmission, [7], [8], [18]. There are three main reasons for this: (1) The high resistivity of acrylic resin makes it difficult to transmit Surface charge, which limits its anti-corona effect, [19], [20], [21]; (2) During the operation of ultra-high voltage substations, the conductors may experience severe shaking, and the mechanical properties of the acrylic conductive coating coated on the conductive surface are poor, which can easily be damaged or even detached by external forces; (3) The operating environment of high-voltage lines is mostly outdoors, and acrylic resin itself has strong hydrophilicity, which is also one of the reasons why acrylic coatings are prone to detachment, [22], [23]. Therefore, the preparation of an acrylic coating with good mechanical properties (strength and toughness) and conductivity, and ensuring that the coating has good hydrophobicity, to meet the requirements of corona prevention in high-voltage transmission processes, has become the key to the application of acrylic coatings in corona prevention composite materials.

This article studies the preparation of a high-voltage transmission line anti-corona coating using thermoplastic acrylic resin as the matrix, carbon fiber powder, and Multi walled carbon nanotubes as conductive fillers, and nano TiO_2 as a self-cleaning agent. This acrylic composite coating can be used to repair burrs and scratches on the surface of wires, fill gaps in stranded wires, and is convenient for on-site construction. Due to the strong plasticity of composite coatings, they can effectively repair damage to the surface of wires. On the other hand, the good flowability of composite coatings can be used to fill the gaps in the wire strands, thereby changing the local morphology of the wire surface and forming a smooth circular surface, which can play an equivalent role in expanding the diameter to a certain extent. These can all serve the purpose of reducing the local electric field of the wire and preventing wire corona. Furthermore, the prepared acrylic composite coating has good hydrophobic and self-cleaning properties, which ensures that the acrylic coating still has a good anti corona effect in complex external environments.

Acrylic resin coatings are widely used in aviation products, military products, and other fields due to their excellent adhesion, weather resistance, and corrosion resistance. However, a single acrylic resin has poor conductivity, toughness, and strong hydrophilicity, which limits its application in corona prevention. In response to this issue, this study prepared an anti-corona conductive coating for ultra-high voltage using carbon fiber powder and multi-walled carbon nanotubes as conductive fillers, and nano titanium dioxide as a self-cleaning agent. On this basis, acrylic conductive films were prepared, and the effects of different additives on the mechanical properties, conductivity, hydrophobicity, and heat resistance of the conductive films were studied.

II. Experimental Materials and Preparation Methods

A. Raw Materials and Reagents

Table 1 lists the main raw materials and reagents required for the preparation of anti-corona coatings.

Table 1. Raw materials and reagents used in the experiment

Raw material name	Purity	Main parameters	producing area
Acrylic acid resin (AA)	Industrial grade		Guangzhou Yongyi Chemical Co., Ltd
Carbon fiber powder (CF)		500 mesh	Xiangsheng Carbon Fiber Technology Co., Ltd
Multi walled carbon nanotubes (MWCNT)		D=10-20 nm	Xianfeng Nano Materials Technology Co., Ltd
Nano TiO2		800 mesh	Shaoxing Lijie Chemical Co., Ltd
3-Aminopropyltriethoxysilane (KH550)	Chemically Pure		Macklin Company
Toluene	Analytical reagent		China National Pharmaceutical Group Corporation
Ethyl acetate	Analytical reagent		China National Pharmaceutical Group Corporation
Leveling agent BYK-4511	Industrial grade		BYK Corporation, Germany

B. Instruments and Equipment Used

Table 2 lists the main instruments and their models used in the preparation of anti-corona coatings.

Table 2． Basic instruments and models used in the experiment

Instrument	Model	Manufacturer
Ultrasonic oscillator	ES35 B	Kunshan Ultrasonic Instrument Co., Ltd
Constant temperature magnetic stirrer	KQ5200DB	Beijing Labtech Instruments Co., Ltd
Universal testing machine	Instron 5967	Instron Corporation
Four-probe dual electrical tester	RTS-9	Guangzhou Four Probe Technology Co., Ltd
Hack Rheometer tester	MARS III	Thermo Fisher Scientific
Scanning electron microscope	JSM-6700F	Japanese Electronics Company
Contact angle measuring instrument	JY-PHa	Chengde Youte Testing Instrument Co., Ltd
Thermogravimetric analyzer	Q50	TA Instruments
Desktop circulating water vacuum pump	SHB-III	Zhengzhou Great Wall Science and Technology Trade Co., Ltd

C. Preparation of Anti Corona Coatings

Firstly, the pretreated carbon fiber powder is ultrasonically dispersed in an acetone solution, followed by 1 hour of ultrasound, filtration, and water washing to obtain purified carbon fiber powder. Then, the carbon fiber powder is placed in a toluene solution of pre prepared silane coupling agent KH550, stirred and heated to 60℃, reacted for 4 hours, and filtered to obtain coupling agent modified carbon fiber powder. Subsequently, a certain amount of carbon nanotubes was placed in ethyl acetate solvent and sonicated for 1 hour to obtain a 5wt% carbon nanotube ethyl acetate dispersion, which is called dispersion A.

Secondly, dissolve the acrylic resin in toluene and stir evenly to obtain a 50wt% acrylic acid solution, called solution B.

Thirdly, nano titanium dioxide is ultrasonically dispersed in toluene to obtain dispersion C.

Finally, take a certain amount of dispersion A, mix solution B with dispersion C, and stir evenly. Add a small amount of leveling agent BYK-4511. The above-mixed dispersion is stirred for 30 minutes to obtain an acrylic composite conductive coating. Apply the coating on a flat plate of polytetrafluoroethylene and wait for the solvent to completely evaporate to obtain a 120μ m thick acrylic conductive film.

To analyze the influence of various fillers on the performance of composite conductive films, this article mainly prepared four types of acrylic coatings: (1) pure acrylic resin, denoted as (AA); (2) A composite coating of acrylic resin (50wt%) and carbon fiber (50wt%), denoted as (AA+CF); (3) A composite coating of acrylic resin (45wt%), carbon fiber powder (50wt%), and multi-walled carbon nanotubes (5wt%), denoted as (AA+CF+MWCNT); (4) A composite coating of acrylic resin (40wt%), carbon fiber powder (50wt%), multi-walled carbon nanotubes (5wt%), and nano titanium dioxide (5wt%), denoted as AA+CF+MWCNT+NanoTiO_2. The specific content of each component is shown in Table 3.

Table 3. Sample names and distribution ratios of each group (unit: wt%)

Sample type	AA	CF	MWCNT	Nano-TiO2	BYK-4511
AA	100	0	0	0	0.1
AA+CF	50	50	0	0	0.1
AA+CF+MWCNT	45	50	5	0	0.1
AA+CF+MWCNT +NanoTiO2	40	50	5	5	0.1

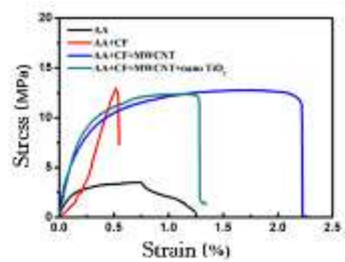
D. Characterization of Anti-Corona Coatings

The tensile properties of the acrylic conductive film were tested using a universal testing machine (Instron 5967). The testing standard is GB/T 1040-2006, and the sample stretching speed is 5 mm/min. The conductivity of acrylic conductive film was measured using the RTS-9 type dual electrical four-probe tester, with each sample tested 10 times, and the final conductivity was taken as the average value. The surface contact angle of the acrylic conductive film is measured using a JY-PHa type contact angle measuring instrument, with a water droplet volume of 3 μ L. The thermal stability of acrylic conductive film was tested by a Q50 type thermogravimetric analyzer. The dispersion state of the nanoparticles in the acrylic film was observed by a JSM-6700F type Scanning electron microscope. Before testing, the sample was first frozen in liquid nitrogen and then brittle fractured, and the microstructure of the cross-section of the acrylic conductive film sample was observed.

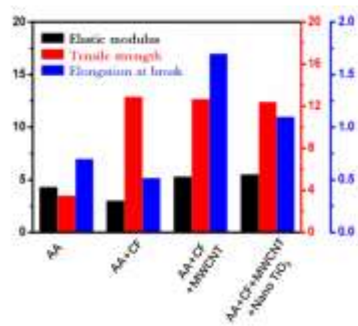
III. Performance Testing and Result Analysis

A. Tensile properties of anti-corona coating film

Firstly, the tensile properties of acrylic conductive composite films were tested, and the experimental results are shown in Fig. 1. As shown in Fig. 1, the elastic modulus, tensile strength, and elongation at the break of the AA+CF composite coating reached 3.0GPa, 12.9 MPa, and 0.5%, respectively. Compared with the pure AA resin (tensile strength: 3.49 MPa) coating, the tensile strength of the composite coating increased by 269.6%, and the elastic modulus and elongation at break decreased by 30.2% and 57.1% respectively. After further adding carbon nanotubes to the composite coating, the toughness of material AA+CF+MWCNT was significantly improved, while the strength was also well maintained. After further addition of nano titanium dioxide, the strength of material AA+CF+MWCNT+Nano-TiO2 remained good, but there was a certain degree of decrease in toughness. This is mainly because titanium dioxide is a nanoparticle, and its addition may increase the defect points in sample tensile testing, resulting in a decrease in toughness. To obtain an acrylic composite coating with excellent comprehensive performance, we need to further analyze and comprehensively examine the other properties of the obtained samples.



(a) Stress-strain curve of Anti Corona Coating Film



(b) Elastic modulus, tensile strength, and elongation at break of anti-corona coating film

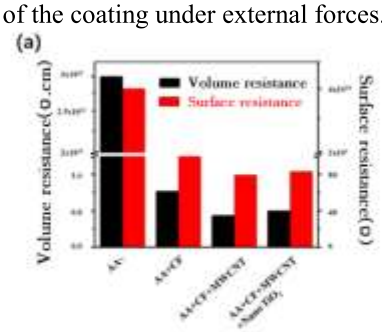
Fig. 1 Tensile properties of four types of acrylic conductive films (AA, AA+CF, AA+CF+MWCNT, and AA+CF+MWCNT+Nano-TiO2)

B. Conductivity and self-cleaning ability of anti-corona coating film

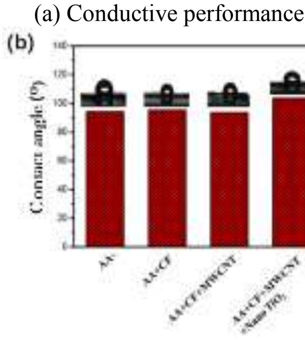
The conductivity of different acrylic conductive films was further tested in the experiment, and the experimental results are shown in Fig. 2 (a). As shown in Fig. 2 (a), after adding CF, the conductivity of material AA+CF increases. Further addition of MWCNT results in the highest conductivity of material AA+CF+MWCNT. This is mainly due to the addition of carbon nanotubes, which further form a bridging structure directly on the carbon fiber, which is conducive to charge transfer, thus greatly improving its conductivity. However, after further addition of Nano-TiO2, the conductivity of the composite coating AA+CF+MWCNT+Nano-TiO2 slightly decreased, with its volume resistance and surface resistance reaching 0.8 Ω.cm and 83.2Ω, respectively.

In addition to the conductivity of conductive coatings, their hydrophobic self-cleaning ability is also an important parameter for acrylic coatings. Therefore, the experiment further studied the hydrophobic self-cleaning ability of conductive films. The hydrophilicity and hydrophobicity of acrylic conductive films were experimentally tested. From Fig. 2(b), it can be seen that the addition of nano CF and MWCNT can improve the hydrophobicity of the material to a certain extent. However, the composite coating with Nano-TiO2 has the best hydrophobicity. The contact angle of AA+CF+MWCNT+Nano-TiO2 composite film reaches 103.7 °, meeting the hydrophobicity requirement (contact angle>90 °), and the contact angle is increased by 10.8% compared to AA+CF+MWCNT type composite film. This may be due to the formation of micro nanostructures on the surface of the coating by Nano TiO2, resulting in the material having good hydrophobicity.

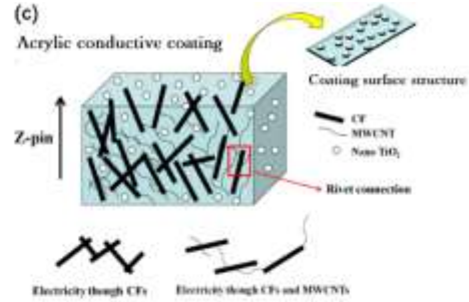
From the above, it can be seen that the mechanical properties, conductivity, and hydrophobicity of the AA+CF+MWCNT+ Nano-TiO2 composite film meets the requirements for the use of anti-corona coatings while meeting the requirements for material anti-corona protection. This is mainly because CF and MWCNT construct a three-dimensional conductive network in the coating and exhibit alternating connections, as shown in Fig. 2 (c). The three-dimensional conductive network in the AA+CF composite system is only formed through the contact between carbon fibers, so the conductivity and efficiency of AA+CF+MWCNT+Nano-TiO2 are higher than those of AA+CF. In addition, there may be a certain degree of riveting effect between CF and MWCNT in the coating system. On the one hand, this plays a crucial role in improving its tensile performance. On the other hand, in environments with high wind speeds, this riveting effect can improve the conductivity stability of the coating under external forces.



(a) Conductive performance



(b) Surface contact angle

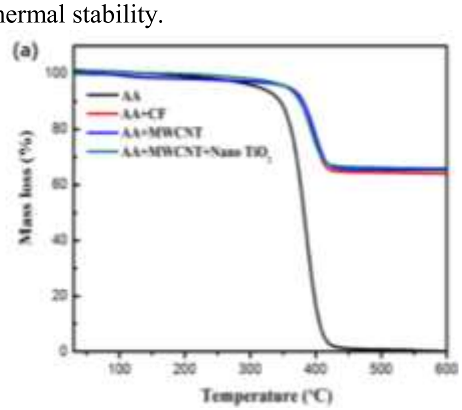


(c) Possible conductive network structure

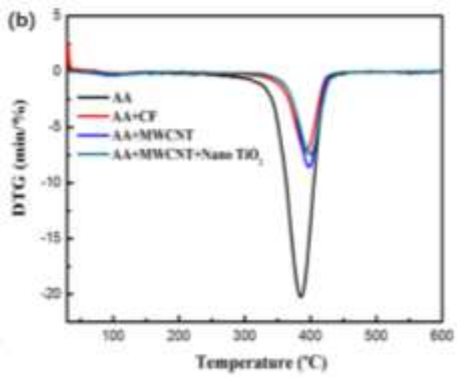
Fig. 2 Conductivity performance, surface contact angle, and possible conductive network structure of four types of anti-corona coating films

C. Heat resistance of anti-corona coatings

For pure acrylic resin and its composite materials, in addition to the basic indicators mentioned above, their thermal stability is also one of the key indicators for evaluating their application as coatings. The thermal stability of the composite film was further studied through thermogravimetric analysis in the experiment, as shown in Fig. 3. From Fig. 3, it can be seen that AA+CF, AA+CF+MWCNT, and AA+CF+MWCNT+ Nano-TiO2 composite conductive films all have good heat resistance. Their maximum decomposition temperatures increased from 385.0°C of pure AA to 390.1°C, 396.1°C, and 400.2°C, respectively, which were 1.3%, 2.9%, and 3.9% higher than AA, respectively. This is mainly due to the following three reasons: (1) The added CF, MWCNT, and Nano TiO2 themselves have better thermal stability than AA. (2) The added CF, MWCNT, and Nano TiO2 also can capture free radicals, which greatly delays the degradation of the composite material. For example, nano titanium dioxide can be used as a flame retardant and heat stabilizer in polymer composite systems, and its addition will further improve the thermal stability of the material. (3) In addition, the carbon fiber (CF) surface modified by the silane coupling agent has more amino groups, which can react with hydroxyl and carboxyl groups in acrylic resin to form a stable Chemical bond so that the interface between nanofiller and AA is enhanced. Moreover, nanofillers form a more stable three-dimensional network structure inside AA, and changes in the internal structure of the material also improve the thermal stability of the material. In summary, the AA+CF+MWCNT+Nano-TiO2 composite conductive film has the best thermal stability.



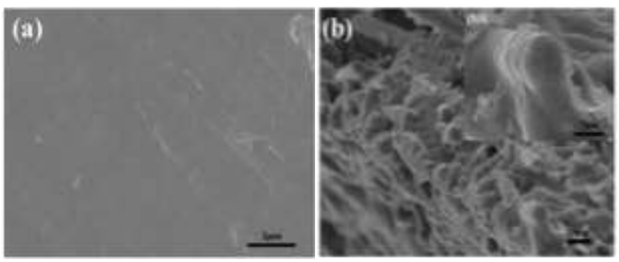
(a) Thermal mass loss curve



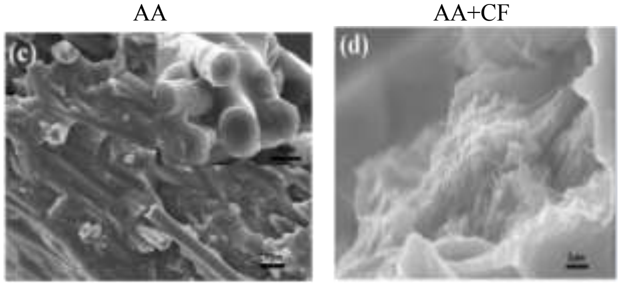
(b)Derivative thermogravimetric(DTG) curve

Fig. 3 Thermal mass loss and DTG curves of four types of anti-corona coating films

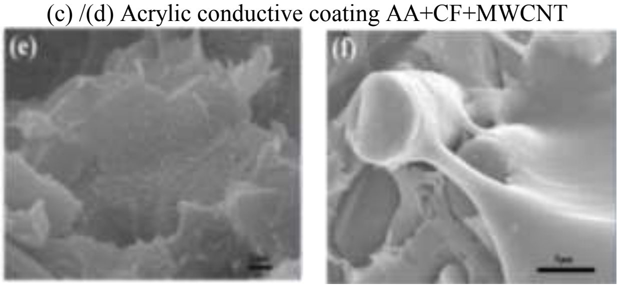
D. *Microscopic Morphology of Anti-Corona Coatings*



(a) Acrylic pure resin coating AA (b) Acrylic conductive coating AA+CF



(c) /(d) Acrylic conductive coating AA+CF+MWCNT



(e) /(f) Acrylic conductive coating AA+CF+MWCNT+Nano-TiO2

Fig. 4 SEM images of brittle sections of four anti-corona coatings

Based on the previous experimental results, we believe that the electrical properties, mechanical properties, and hydrophobicity of composite materials are closely related to the distribution of nanofillers in acrylic acid. Therefore, the experiment further tested the distribution of nanofillers in acrylic conductive composite films, and the experimental results are shown in Fig. 4. From the SEM image of the brittle cross-section of the thin film shown in Fig. 4 (a), it can be seen that pure AA brittle fracture occurs. In Fig. 4 (b), the surface of the AA+CF composite film is coated with a significant amount of acrylic resin, indicating a strong interfacial interaction between carbon fibers and acrylic resin. In Fig. 4(c), (d), (e), and (f), the cross-sections of AA+CF+MWCNT and AA+CF+MWCNT+Nano-TiO2 are uniformly dispersed in the acrylic resin, forming a three-dimensional network structure. After brittle fracture, the acrylic resin exhibits layered fracture. In Fig. 4 (f), a clear wire drawing phenomenon can be observed, indicating that the addition of composite fillers improves the toughness of the composite conductive film.

IV. Construction Technology of Anti-Corona Coatings

Table 4 shows the scope of application, required equipment and materials, construction conditions, process steps, and quality standards involved in the construction of acrylic conductive coatings.

Table 4. Construction Process of Acrylic Conductive Coatings

Applicable scope	Spraying on parts such as galvanized layer scum and local wires with burrs
Equipment and tooling	Air compressor, paint spray can
Auxiliary materials	Cleaning agent, brush, tape
Coating thickness	0.1 ~ 0.8mm
Environment condition	1. The coating area should be clean and free of dust and oil stains 2. Environmental temperature -50℃~400℃ 3. The construction site is well ventilated
Process steps	1. Clean the area that needs to be coated with a cleaning agent, separate the non-coated area with tape, and let it dry naturally. 2. Before using the coating, shake thoroughly and stir evenly to prevent chromatography. 3. Spray or brush coating can be applied uniformly. 4. It can be sprayed and brushed in batches to the desired thickness.
Quality standard	1. The coating layer is evenly distributed, with a smooth surface and no protrusions or burrs. 2. The coating layer shall have no holes, bubbles, or wrinkles.

V. Conclusion

A single acrylic resin has poor conductivity, toughness, and hydrophilicity, which limits its application in high-voltage transmission corona prevention. In response to this issue, this article investigates the preparation of four types of acrylic coatings with different additions of carbon fiber powder, multi-walled carbon nanotubes, and nano titanium dioxide: ① pure acrylic resin, denoted as AA; ② Composite coating of acrylic resin (50wt%) and carbon fiber (50wt%), denoted as AA+CF; ③ A composite coating of acrylic resin (45wt%), carbon fiber powder (50wt%), and multi walled carbon nanotubes (5wt%), denoted as AA+CF+MWCNT; ④ A composite coating of acrylic resin (40wt%), carbon fiber powder (50wt%), multi walled carbon nanotubes (5wt%), and nano titanium dioxide (5wt%), denoted as AA+CF+MWCNT+Nano-TiO2. Through experiments, compare and analyze the effects of various fillers on the

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mechanical properties, conductivity, hydrophobicity, and heat resistance of acrylic composite conductive coatings.

After experimental testing, it has been shown that:

1. Firstly, in terms of the tensile performance of anti-corona coatings, compared to pure AA resin, the tensile strength of AA+CF composite coatings is significantly improved, while the elastic modulus and elongation at break decrease significantly. After adding carbon nanotubes, the strength of the material (AA+CF+MWCNT) remains unchanged, but the toughness is greatly improved. After further addition of nano TiO2 particles, the toughness of the obtained material is reduced to a certain extent. This does not mean that it is not suitable, we need to comprehensively analyze and examine the other properties of the obtained samples.

2. Secondly, in terms of the conductivity of the anti-corona coating, among the four conductive films, the material (AA+CF+MWCNT) has the highest conductivity. This is because the addition of carbon fibers makes it easier for the material to form a bridging structure that is conducive to charge transfer, thereby significantly improving its conductivity. By testing the hydrophilicity and hydrophobicity of acrylic conductive film, it can be concluded that the composite coating with added nano TiO2 has the best hydrophobicity, with a contact angle of up to 103.7 °. This is because nano TiO2 can form micro nanostructures on the surface of the coating, giving the material good hydrophobic properties.

3. Thirdly, in terms of heat resistance performance of anti-corona coatings, AA+CF, AA+CF+MWCNT, and AA+CF+MWCNT+Nano-TiO2 composite conductive films all have good heat resistance performance, among which AA+CF+MWCNT+Nano-TiO2 composite conductive films have the best thermal stability.

4. Finally, in terms of the microstructure of the anti-corona coating, it can be seen from the SEM image of the brittle section of the film that pure AA is brittle and prone to fracture, but the addition of composite fillers improves the toughness of the composite conductive coating film.

Substation and transmission line conductors often generate corona noise, and the basic treatment method is to reduce local field strength. Usually, voltage equalization measures are installed to control it, but this method adds a lot of extra weight when there are many corona points on a single section of wire, and the installation method is complex, so it cannot be used on a large area. Therefore, applying composite materials to prevent corona discharge in transmission lines has become one of the research hotspots in recent years.

This article uses carbon fiber powder and carbon nanotubes as conductive fillers and nano titanium dioxide as a self-cleaning agent added to a thermoplastic acrylic resin matrix to study and prepare an anti-corona acrylic composite conductive coating for high-voltage conductors. From the above characteristic analysis, it can be seen that it has excellent performance characteristics in all aspects and is suitable for corona protection in ultra-high voltage transmission. It can be used to repair burrs and scratches on the surface of transmission lines, fill gaps in twisted wires, and achieve the goal of reducing the local electric field of high-voltage transmission lines to prevent wire corona. This study provides a direct solution for the application of anti-corona coatings in high-voltage anti-corona applications.

However, due to various reasons, the coating is still in the experimental testing stage and has not yet entered the field for application testing. The practical application of this coating on transmission line sites to solve corona discharge is a task that we need to continue to complete in the future.

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We confirm that all Authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

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