

Interface Mechanism and Electrical Conductivity Optimization of Graphene Textile Fiber Composite Materials

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ABSTRACT Against the backdrop of rapid development in emerging fields such as flexible electronics, smart wearables, and electromagnetic shielding, conductive textile materials that combine high conductivity, flexibility, breathability, and mechanical stability have become a research hotspot. Graphene, as a two-dimensional nano conductive material, has ultra-high conductivity, excellent mechanical properties, and chemical stability. It can be combined with textile fibers to prepare high-performance conductive composite materials. However, there are fundamental challenges such as poor interface compatibility, low bonding strength, and uneven dispersion between graphene and textile fibers, which lead to rapid degradation of the conductivity and insufficient mechanical stability of composite materials, severely restricting their large-scale application. The interface-regulated conductive network supports applications such as flexible electrodes, smart fabrics and electromagnetic shielding textiles.

INDEX TERMS graphene, textile fiber composites, interface mechanism, electrical conductivity, electromagnetic shielding

I. INTRODUCTION

A. RESEARCH BACKGROUND

As a core foundational material in the fields of flexible electronics, smart wearable devices, electromagnetic shielding, wearable sensors, etc., flexible conductive materials need to simultaneously meet multiple requirements such as high conductivity, good flexibility, breathability, mechanical stability, and environmental adaptability. Textile fibers have become an ideal substrate for flexible conductive materials due to their natural advantages such as lightweight, flexibility, breathability, braiding, and large-scale preparation. However, pure textile fibers (such as cotton, polyester, nylon) have extremely poor conductivity (volume resistivity is usually greater than $10 \Omega \cdot \text{cm}$), and conductive functional modification needs to be achieved through composite conductive fillers [1-3].

However, the practical application of graphene/textile fiber composites faces primary constraints: Firstly, the interface compatibility is poor. The surface of graphene is inert and has weak interface interactions with polar textile fibers (such as cotton fibers) or non-polar textile fibers (such as polyester fibers), which can lead to aggregation and delamination, resulting in discontinuous conductive pathways in composite materials; Secondly, the dispersibility of graphene is insufficient. There is a strong van der Waals force between the layers of graphene sheets, which is prone to agglomeration and difficult to form a uniform conductive

network on the surface or inside the fibers;

Thirdly, the stability of conductivity is poor. The interface bonding strength is low, and in practical use scenarios such as bending, stretching, and washing, graphene is prone to detachment from the fiber surface, leading to rapid degradation of conductivity;

Fourthly, the composite process is complex and costly. The existing composite processes, such as solution coating and chemical deposition, have problems such as low utilization rate of graphene, high environmental pollution, and difficulty in large-scale production [4].

Research significance

Theoretical significance

(1) The system reveals the interface interaction mechanism between graphene and different types of textile fibers, clarifies the contribution mechanism of interface forces such as van der Waals forces, hydrogen bonds, covalent bonds, etc., and enriches the theoretical system of interface science in nanocomposites;

(2) Establish a correlation model between graphene dispersibility, interfacial bonding strength, fiber structure parameters, and electrical conductivity, clarify the formation and evolution laws of conductive networks, and improve the theory of conductive mechanisms in conductive composite materials;

(3) Propose a theoretical framework for multidimensional interface regulation and performance optimization, provid-

ing methodological references for the research of similar nano filler/textile fiber composite materials [5].

Practical significance

(1) Develop efficient, green, and scalable interface modification and composite processes to solve the persistent obstacles of poor compatibility and uneven dispersion between graphene and textile fibers, and reduce production costs;

(2) Realize the synergistic improvement of the conductivity and mechanical stability of graphene/textile fiber composite materials, meeting the practical application needs in fields such as flexible electronics and smart wearables;

(3) Provide technical support for the industrial production of conductive textile materials and promote the development of emerging industries such as flexible electronics, smart wearables, and electromagnetic shielding;

(4) Expand the application scenarios of graphene in the textile field, enhance the high added value and technological content of textile materials [6-7].

B. CURRENT RESEARCH STATUS ABROAD

Research on graphene/textile fiber composite materials started earlier in foreign countries, mainly focusing on three directions:

(1) Research on interface modification technology, using plasma treatment, coupling agent modification, polymer grafting and other methods to improve interface compatibility;

(2) Innovation in composite processes, developing new composite processes such as in-situ polymerization, electrospinning, and chemical vapor deposition (CVD) to enhance the dispersibility and bonding strength of graphene;

(3) Performance optimization and application exploration, targeting scenarios such as electromagnetic shielding and flexible sensors, to optimize the conductivity and mechanical properties of composite materials.

The advantages of foreign research lie in advanced process equipment and comprehensive characterization methods, but there are also shortcomings: the microscopic analysis of interface interaction mechanisms is not deep enough, the synergistic optimization of modification and composite processes is insufficient, and some processes (such as CVD) have high costs and are difficult to apply on a large scale.

C. CURRENT RESEARCH STATUS IN CHINA

Domestic research has developed rapidly in recent years, with extensive exploration focused on graphene/textile fiber composite materials

(1) In terms of interface modification, scholars have used silane coupling agents, dopamine, plasma and other methods to improve interface compatibility, but the stability and repeatability of the modification effect need to be improved;

(2) In terms of composite technology, processes such as solution coating, ultrasound assisted composite, and melt blending have been developed, but the dispersibility and utilization rate of graphene are still relatively low [8].

D. RESEARCH APPROACH

This article follows the technical route of “theoretical construction mechanism analysis strategy design process optimization empirical verification conclusion optimization”:

1. Systematically analyze the interfacial chemical properties and microstructure of graphene and textile fibers, and reveal the mechanism of interfacial interactions;

2. Design multidimensional interface control strategies (surface modification, dispersion optimization) for different types of textile fibers (cotton, polyester, nylon);

3. Optimize the composite process parameters (graphene content, composite temperature, time, pressure) to achieve uniform dispersion of graphene and firm interface bonding;

4. Build a collaborative optimization model for conductivity and mechanical stability, and identify key influencing factors;

5. Verify the effectiveness of interface control strategies and process optimization schemes through experimental characterization and performance testing;

6. Summarize the research conclusions and propose optimization suggestions for the industrial application of composite materials.

E. RESEARCH METHODS

To achieve the research objectives, the study first utilized a:

(1) Literature research method to Systematically review the theoretical achievements and technical methods in the fields of graphene composite materials, interface science, textile material modification, etc., laying a theoretical foundation;

(2) Experimental characterization method incorporating SEM, TEM, AFM were used to characterize the dispersion and interfacial microstructure of graphene; Using XPS and FTIR to analyze interfacial chemical interactions; Use a four probe tester to test the conductivity performance; Using a universal testing machine to test mechanical properties;

(3) Comparative experimental method: Design comparative experiments with different surface modification schemes, dispersion conditions, and composite processes to determine the optimal parameters;

(4) Model construction method: Establish a correlation model between graphene dispersibility, interfacial bonding strength, and conductivity to elucidate the conductivity mechanism;

(5) Statistical analysis method: Using tools such as Origin and SPSS to perform statistical analysis on experimental data and quantitatively evaluate the performance optimization effect.

Innovation points

(1) Theoretical innovation: Systematically revealing the interface interaction mechanism between graphene and different types of textile fibers, clarifying the synergistic mechanism of van der Waals forces, hydrogen bonds, and covalent

lent bonds, and establishing a correlation theory between interface interaction and conductivity;

(2) Technological innovation: Develop a multidimensional interface control strategy of “plasma modification+coupling agent modification+ultrasonic dispersion” to achieve a strong bond and uniform dispersion between graphene and textile fibers;

(3) Process innovation: Optimize the in-situ polymerization and coating deposition composite process, propose green, efficient, and scalable preparation schemes, and improve the utilization and production efficiency of graphene;

(4) Practical innovation: Through systematic experimental verification, the synergistic improvement of conductivity (volume resistivity as low as $1.2 \times 10^{-3} \Omega\cdot\text{cm}$) and mechanical stability (500 bending attenuation rate of 7.3%) has been achieved, forming a technology solution that can be industrialized and promoted.

II. CORE CONCEPTS AND THEORETICAL FOUNDATIONS

A. DEFINITION OF CORE CONCEPTS

Graphene

Graphene is a two-dimensional honeycomb shaped crystal material composed of a single layer of carbon atoms with sp² hybridized orbitals, with a thickness of only 0.335nm. It has ultra-high conductivity, excellent mechanical properties, large specific surface area, and good chemical stability, making it an ideal conductive filler. This article uses reduced graphene oxide (rGO) prepared by reduction of graphene oxide (GO) and natural graphene flakes as composite fillers, balancing cost and performance [9-10].

1) Interface Mechanism

The interface interaction mechanism refers to the interface interaction mechanism formed between graphene and textile fibers during the composite process, including van der Waals forces, hydrogen bonds, covalent bonds, electrostatic attraction, etc., which are the core factors determining the interface bonding strength and composite material properties [11-12].

2) Optimization of Conductivity Performance

Conductivity optimization refers to the use of interface control, dispersion optimization, process improvement, and other means to enhance the continuity and stability of the conductive pathways in composite materials, reduce volume resistivity, and improve mechanical stability and environmental resistance [13].

B. THEORETICAL BASIS

1) Interface Science Theory

Interface science theory studies the structure, chemical composition, and interactions of interfaces between different phases, including:

Interface tension and wetting theory: determining the spreading and adhesion ability of graphene on fiber surfaces;

Interface force theory: the formation mechanism and contribution of interface forces such as van der Waals forces, hydrogen bonds, covalent bonds, and electrostatic attraction;

Interface bonding strength theory: Evaluation methods and influencing factors of interface bonding strength, including mechanical meshing, chemical bonding, diffusion bonding, etc [14].

2) Theory of Conductive Mechanism

The conductive mechanism of conductive composite materials mainly includes:

Tunnel effect: Electrons transition through the potential barrier between nanofillers;

Conductive pathway theory: Nanofillers form a continuous conductive network in the substrate, and electrons are transmitted along the network;

Seepage theory: When the filler content reaches the critical percolation threshold, the conductivity of the composite material undergoes a sudden change, forming a continuous conductive network.

3) Dispersion and Aggregation Theory

The dispersion and aggregation of nanoparticles are determined by both interparticle forces and external forces. Balance between van der Waals forces and electrostatic repulsion: van der Waals forces between nanoparticles cause agglomeration, while electrostatic repulsion (such as surface charges) inhibits agglomeration;

Dispersant action theory: Dispersants form steric hindrance or electrostatic repulsion by adsorbing on the surface of particles, preventing agglomeration;

Ultrasonic dispersion theory: The cavitation effect generated by ultrasonic vibration destroys particle aggregates and achieves uniform dispersion [15-16].

4) Surface Modification Theory

Surface modification theory refers to changing the surface properties of materials through physical or chemical methods to enhance interfacial compatibility. The core includes:

Physical modification: By means of plasma, irradiation, etc., the surface morphology and roughness are changed to enhance the mechanical meshing effect;

Chemical modification: Introducing active functional groups through coupling agent modification, graft polymerization, and other means to enhance chemical bonding;

Surface energy regulation theory: By modifying and adjusting the surface energy of materials, the compatibility with other materials can be improved [17].

III. THE INTERFACE INTERACTION MECHANISM BETWEEN GRAPHENE AND TEXTILE FIBERS

Analysis of Interface Chemical Properties between Graphene and Textile Fibers

A. SURFACE CHEMICAL PROPERTIES OF GRAPHENE

The surface of graphene (rGO) mainly contains oxygen-containing functional groups such as hydroxyl (OH), epoxy (O), and carboxyl (COOH) groups (the higher the degree of reduction, the lower the content of functional groups), with a surface energy of about $45\text{--}60\text{mJ}\cdot\text{m}^{-2}$ and weak polarity; The surface of natural graphene layers has no oxygen-containing functional groups and is inert and non-polar, with a surface energy of approximately $30\text{--}40\text{mJ}\cdot\text{m}^{-2}$ [18].

Surface chemical properties of different textile fibers

The surface chemical properties of four typical textile fibers are shown in the following table 1:

Analysis shows that:

The surface of cotton fibers is rich in hydroxyl groups, with strong polarity and high surface energy, making it easy to form hydrogen bonds with graphene containing oxygen-containing functional groups;

The surface of polyester fibers is ester based, non-polar, with low surface energy, weak interface interaction with graphene, and the worst compatibility;

The amide groups on the surface of nylon fibers contain amino and carbonyl groups, which can form hydrogen bonds with graphene and have moderate interfacial compatibility;

The surface of carbon fiber contains a small amount of oxygen-containing functional groups, and it has conductivity itself. The interface interaction with graphene is mainly the synergistic effect of van der Waals forces and conductive networks [19-20].

B. SYSTEMATIC ANALYSIS OF INTERFACE MECHANISM

Van der Waals force effect

Van der Waals force is the fundamental force at the interface between graphene and all textile fibers, including dispersion force, induction force, and orientation force. Its contribution depends on the surface polarity of the fibers and the surface properties of graphene. The van der Waals forces between non-polar fibers (such as polyester fibers) and graphene are mainly dispersion forces, with weak interaction strength (about $5\text{--}10\text{kJ}\cdot\text{mol}^{-1}$);

The van der Waals forces between polar fibers (such as cotton fibers) and graphene containing oxygen-containing functional groups include orientation and induction forces, with a high strength of action (about $15\text{--}25\text{kJ}\cdot\text{mol}^{-1}$);

The range of action of van der Waals force is $0.3\text{--}1\text{nm}$, which is the basis of interface bonding, but it is difficult to form a firm bond when acting alone and is prone to delamination.

Hydrogen bonding

Hydrogen bonding is an important interaction force at the interface between polar textile fibers and graphene.

The formation conditions are: the fiber surface contains hydrogen bond donors (such as OH, NH) or acceptors (such as C=O, O), and the graphene surface contains corresponding complementary functional groups:

Cotton fiber and graphene: OH in cotton fiber acts as a hydrogen bond donor, while COOH and OH in graphene act as hydrogen bond acceptors, forming OH... O hydrogen bonds with a bond energy of approximately $20\text{--}30\text{kJ}\cdot\text{mol}^{-1}$;

Nylon fiber and graphene: The NH of nylon acts as the donor, while the C=O of graphene acts as the acceptor, forming NH... O hydrogen bonds with bond energies of approximately $15\text{--}25\text{kJ}\cdot\text{mol}^{-1}$;

Polyester fibers and graphene: The C=O of ester groups on the surface of polyester can serve as hydrogen bond acceptors, but graphene has few donor functional groups and weak hydrogen bonding interactions (bond energy $<10\text{kJ}\cdot\text{mol}^{-1}$);

Hydrogen bonding can significantly improve interfacial compatibility, but it is greatly affected by environmental humidity and lacks stability.

C. COVALENT BOND INTERACTION

Covalent bonding is the strongest interfacial bonding force (bond energy of approximately $100\text{--}400\text{kJ}\cdot\text{mol}^{-1}$), which requires surface modification to introduce active functional groups. While van der Waals forces provide the initial physical contact and universal adhesion (the basis), covalent bonds act as high-energy 'anchor points' that stabilize the interface. These forces are additive; the introduction of covalent bonding does not negate van der Waals contributions but rather provides the necessary mechanical integrity to prevent the delamination that occurs when only weak physical forces are present.

After modification with silane coupling agent, the COOH of graphene reacts with the amino group of the coupling agent, and the alkoxy group at the other end of the coupling agent hydrolyzes and condenses with the OH group of cotton fibers, forming a COC covalent bond;

After plasma treatment, free radicals are generated on the surface of the fibers, which undergo free radical polymerization reactions with functional groups on the graphene surface, forming covalent bonds; Covalent bonding can significantly enhance the interfacial bonding strength and stability, but the modification process is complex and requires precise control of reaction conditions.

Electrostatic attraction effect

The electrostatic attraction effect originates from the charge difference between graphene and the surface of textile fibers:

Graphene is negatively charged on its surface after being treated with dispersants (such as sodium dodecyl benzenesulfonate (SDBS) adsorption), while textile fibers are positively charged on their surface after plasma treatment, forming electrostatic attraction;

Electrostatic attraction can promote the adsorption and dispersion of graphene on fiber surfaces, with a strength of about $10\text{--}15\text{kJ}\cdot\text{mol}^{-1}$, but it is prone to decay in aqueous solutions or high humidity environments.

Comparison and Summary of Interface Mechanisms of Different Fibers

TABLE 1. Surface Chemical Properties of Different Textile Fibers

Textile Fiber Type	Chemical Composition	Surface Functional Groups	Surface Polarity	Surface Energy/Crystallinity
Cotton Fiber	Cellulose (C ₆ H ₁₀ O ₅) _n	Hydroxyl (-OH)	Strongly Polar	65–75 mJ·m ⁻² ; 70–80%
Polyester Fiber (PET)	Polyethylene Terephthalate	Ester Group (-COO-)	Non-Polar	40–45 mJ·m ⁻² ; 40–50%
Nylon Fiber (PA6)	Polycaprolactam	Amide Group (-CONH-)	Weakly Polar	50–55 mJ·m ⁻² ; 50–60%
Carbon Fiber	Carbon (Graphite-like Structure)	Hydroxyl (-OH), Carboxyl (-COOH)	Weakly Polar	55–60 mJ·m ⁻² ; 85–95%

The comparison of the contribution of interfacial forces between four types of textile fibers and graphene is shown in the following table 2:

The summary indicates that:

1. In the unmodified state, cotton fiber and nylon fiber have better interfacial compatibility with graphene than polyester fiber and carbon fiber due to their multiple polar functional groups;

2. Surface modification can significantly enhance interfacial binding energy by introducing covalent bonds, with polyester fiber modification showing the most significant increase in interfacial binding energy (about 8 times);

3. Single interface forces are difficult to achieve strong bonding, and multidimensional regulation is needed to achieve the synergistic effect of van der Waals forces, hydrogen bonds, and covalent bonds;

4. The interface compatibility level is positively correlated with the total interface binding energy. When the total interface binding energy is $\geq 80 \text{ kJ}\cdot\text{mol}^{-1}$, the interface compatibility level is “excellent” and can meet practical application needs.

IV. INTERFACE CONTROL AND PROCESS OPTIMIZATION OF GRAPHENE/TEXTILE FIBER COMPOSITE MATERIALS

A. INTERFACE CONTROL STRATEGY DESIGN

Based on the analysis of interface mechanism, design a multidimensional interface control strategy of “surface modification dispersion optimization interface cross-linking”, and develop targeted plans for different types of textile fibers according to their characteristics.

Surface modification strategy

1. Plasma modification

Using air plasma to treat textile fibers, two major effects are achieved by bombarding the fiber surface with high-energy particles:

Physical effect: Etching the surface of fibers, increasing roughness and specific surface area, enhancing mechanical engagement with graphene;

Chemical effect: It generates active functional groups such as hydroxyl, carboxyl, and free radicals on the surface of fibers, providing sites for subsequent chemical bonding.

Based on preliminary screening and existing literature regarding fiber surface activation, the process parameter optimization range is set at: processing power of 80–120W, processing time of 3–10min, gas flow rate of 10–20sccm.

2. Coupling agent modification strategy Selecting silane coupling agents (KH550, KH560) and dopamine as mod-

ifiers to achieve chemical bridging between graphene and fibers:

Silane coupling agent modification: The amino group of KH550 reacts with the carboxyl group of graphene, and the alkoxy group hydrolyzes and condenses with the hydroxyl group of the fiber to form covalent bonds;

Dopamine modification: Dopamine self polymerizes under weakly alkaline conditions to form a polydopamine (PDA) coating. The catenol group in PDA forms coordination bonds with graphene and forms a strong bond with the fiber surface.

Process parameter optimization: coupling agent concentration of 1–5wt%, reaction temperature of 30–60 °C, reaction time of 2–6 hours.

3. Polymer graft modification

Adopting in-situ polymerization method to graft hydrophilic or hydrophobic polymers on the surface of fibers, regulating surface polarity and interfacial interactions:

Cotton fiber grafted with acrylic acid: enhances surface hydrophilicity and strengthens hydrogen bonding with graphene;

Polyester fiber grafted with polyethylene glycol: introducing polar functional groups to improve compatibility with graphene.

Process parameter optimization: monomer concentration of 5–10wt%, initiator concentration of 0.5–1wt%, polymerization temperature of 60–80 °C.

Graphene dispersion optimization strategy

1. Ultrasonic peeling+dispersant synergistic dispersion

Adopting the “ultrasonic exfoliation+dispersant” composite dispersion method to suppress graphene agglomeration:

Ultrasonic exfoliation: Probe ultrasound (power 200–300W, time 30–60min) or water bath ultrasound (power 100–150W, time 60–120min) is used to break the interlayer van der Waals forces of graphene sheets;

Dispersant selection: Choose dispersants based on the characteristics of graphene and fibers, such as anionic dispersant SDBS, nonionic dispersant Tween 80, and amphoteric dispersant dodecyl betaine;

Mechanism of dispersant action: Suppressing agglomeration through electrostatic repulsion (anionic type) or steric hindrance (non-ionic type), while enhancing the compatibility between graphene and fibers.

Process parameter optimization: dispersant concentration of 0.5–2wt%, graphene concentration of 0.1–1mg·mL⁻¹, ultrasound power and time matching to avoid damage to graphene layers.

2. Graphene surface modification dispersion

TABLE 2. Contribution of Interfacial Interactions for Different Fibers

Textile Fiber Type	Van der Waals Force Contribution (%)	Hydrogen Bond Contribution (%)	Covalent Bond Contribution (%)	Electrostatic Force Contribution (%)	Total Interfacial Binding Energy (kJ·mol ⁻¹)	Interfacial Compatibility Grade
Cotton Fiber (Unmodified)	45	50	0	5	35–45	Good
Cotton Fiber (Modified)	30	35	30	5	85–100	Excellent
Polyester Fiber (Unmodified)	90	5	0	5	10–15	Poor
Polyester Fiber (Modified)	40	10	45	5	90–110	Excellent
Nylon Fiber (Unmodified)	55	40	0	5	40–50	Good
Nylon Fiber (Modified)	35	30	30	5	80–95	Excellent
Carbon Fiber (Unmodified)	85	10	0	5	25–35	Moderate
Carbon Fiber (Modified)	40	15	40	5	95–115	Excellent

Surface modification of graphene to reduce interlayer forces:

Reduction modification of graphene oxide: control the degree of reduction, retain appropriate oxygencontaining functional groups, balance dispersibility and conductivity;

Surface grafting modification of graphene: grafting polymers such as polyethylene glycol and polyacrylic acid to introduce steric hindrance and inhibit agglomeration.

Interface cross-linking strategy

Using crosslinking agents to achieve interface crosslinking between graphene and textile fibers, enhancing bonding strength:

Selecting glutaraldehyde and isocyanate as crosslinking agents, the active groups of the crosslinking agent react with the oxygen-containing functional groups of graphene and the active functional groups on the fiber surface to form a three-dimensional crosslinking network;

Process parameter optimization: crosslinking agent concentration of 0.5-2wt%, crosslinking temperature of 40-80 °C, crosslinking time of 1-3 hours.

B. COMPOSITE PROCESS OPTIMIZATION

Optimize three mainstream composite processes based on the characteristics of different textile fibers to achieve uniform dispersion of graphene and firm interface bonding.

Solution immersion coating composite process

The solution immersion coating process is suitable for hydrophilic fibers such as cotton and nylon. The process is: preparation of graphene dispersion → fiber pretreatment → immersion coating → drying → reduction (only applicable to GO).

Optimize parameters:

Graphene dispersion concentration 0.2-0.5mg·mL⁻¹, dispersant concentration 1wt%;

Dip coating temperature 25-40 °C, dip coating time 10-30 minutes, dip coating frequency 2-4 times; Drying temperature 60-80 °C, drying time 2-4 hours;

Reduction process (GO specific): Hydrazine hydrate reduction (concentration 5wt%, temperature 80 °C, time 2h)

or heat treatment reduction (temperature 150-200 °C, time 1h) is used.

In situ polymerization composite process

The in-situ polymerization process is suitable for synthetic fibers such as polyester and nylon. The process is: monomer preparation → graphene dispersion → in-situ polymerization → fiber forming.

Optimize parameters:

Graphene concentration 0.1-0.5wt% (relative to monomer mass);

Aggregation temperature: Polyester 260-280 °C, Nylon 230-250 °C;

Aggregation pressure: Polyester 0.5-1MPa, Nylon 0.3-0.8MPa;

Dispersion method: Ultrasonic dispersion+mechanical stirring (rotation speed 500-1000rpm).

Coating deposition composite process

The coating deposition process is suitable for various types of fibers, especially for surface modified fibers.

The process is: graphene coating preparation → coating → curing.

Optimize parameters:

Coating formula: 0.5-2wt% graphene, 10-20wt% binder (such as polyurethane, acrylic ester), 78-89.5wt% solvent (such as ethanol, water);

Coating method: Scraper coating (thickness 50-100 μm) or spray coating (pressure 0.3-0.5MPa); Curing temperature 80-120 °C, curing time 1-2 hours.

Targeted optimization schemes for different fibers

Develop targeted optimization plans for four types of textile fibers based on the interface mechanism and fiber characteristics:

V. EMPIRICAL RESEARCH DESIGN AND RESULT ANALYSIS

A. EMPIRICAL RESEARCH DESIGN

1) Experimental Materials and Equipment

1. Experimental materials

TABLE 3. Targeted Optimization Schemes for Different Fibers

Textile Fiber Type	Interface Regulation Scheme	Composite Process	Core Optimization Objectives	Key Parameters
Cotton Fiber	Plasma Treatment (80 W, 5 min) + KH560 Coupling Agent Modification (2 wt%, 40 °C)	Solution Dip-Coating	Enhance hydrogen bond and covalent bond interactions; improve dispersion uniformity	Dip-coating times: 3; Reduction temperature: 180 °C
Polyester Fiber	Plasma Treatment (120 W, 10 min) + Dopamine Modification (2 g·L ⁻¹ , 60 °C)	In-situ Polymerization	Introduce covalent bonds; improve compatibility of non-polar interface	Graphene concentration: 0.3 wt%; Polymerization temperature: 270 °C
Nylon Fiber	Air Plasma Treatment (100 W, 8 min) + SDBS Dispersion (1 wt%)	Solution Dip-Coating + Crosslinking	Enhance hydrogen bond and electrostatic interactions; improve stability	Glutaraldehyde crosslinker concentration: 1 wt%; Curing temperature: 60 °C
Carbon Fiber	Plasma Treatment (100 W, 5 min) + Graphene Surface Grafting with Polyethylene Glycol	Coating Deposition	Form conductive network synergy; improve electrical conductivity	Coating thickness: 80 μm; Graphene concentration: 1.5 wt%

Graphene: Reduced graphene oxide (rGO, layer thickness 1-5 nm, lateral size 1-5 μm), natural graphene (layer thickness 1-3 nm);

Textile fibers: cotton fiber (fineness 18.2tex), polyester fiber (PET, fineness 15.6tex), nylon fiber (PA6, fineness 16.5tex), carbon fiber (fineness 12.8tex);

Auxiliary reagents: Silane coupling agents (KH550, KH560), dopamine SDBS, Tween 80, glutaraldehyde, hydrazine hydrate, etc;

Experimental equipment: plasma processor, ultrasonic cell disruptor, universal testing machine, four probe tester SEM, TEM, AFM, XPS, FTIR.

2) Experimental Plan

Selecting cotton fiber and polyester fiber as representative substrates (representing polar and non-polar fibers respectively), a targeted optimization scheme was adopted to prepare composite materials. An unmodified control group and a modified experimental group were set up to compare and analyze the interface structure, conductivity, and mechanical properties.

1. Experimental group 1: Modified cotton fiber/graphene composite material

Interface control: plasma treatment (80W, 5min) + KH560 coupling agent modification (2wt%, 40 °C, 4h);

Dispersion optimization: rGO dispersion (0.3mg·mL⁻¹) + SDBS dispersant (1wt%) + probe ultrasound (250W, 45min);

Composite process: solution immersion coating (immersion coating 3 times, each time for 20 minutes) + drying (70 °C, 3h) + heat treatment reduction (180 °C, 1h);

Graphene content: 0.5wt% (relative to cotton fiber mass).

2. Experimental group 2: Modified polyester fiber/graphene composite material

Interface control: plasma treatment (120W, 10min) + dopamine modification (2g·L⁻¹, 60 °C, 6h);

Dispersion optimization: rGO dispersion (0.4mg·mL⁻¹) + Tween 80 dispersant (1.5wt%) + water bath ultrasound (120W, 90min);

Composite process: In situ polymerization (graphene concentration of 0.3wt%, polymerization temperature of 270 °C, pressure of 0.8MPa);

Graphene content: 0.5wt% (relative to the mass of polyester fibers).

3. Control group 1: unmodified cotton fiber/graphene composite material No interface control and dispersion optimization, directly prepared by solution immersion coating process, with graphene content of 0.5wt%.

4. Control group 2: unmodified polyester fiber/graphene composite material No interface control and dispersion optimization, directly prepared by in-situ polymerization process, graphene content 0.5wt%.

Testing and characterization indicators

1. Interface structure characterization: SEM observation of graphene dispersion and interface bonding state; Analyze the changes in interface chemical elements and functional groups using XPS; Using FTIR to verify the type of interface interaction force;

2. Conductivity testing: Use a four probe tester to test the volume resistivity (test pressure 1N); Test the volume resistivity after bending for 0, 100, 200, 300, 400, and 500 times, and analyze the conductivity stability;

3. Mechanical performance testing: Use a universal testing machine to test the fracture strength, elongation at break, and interfacial peel strength of composite materials (180 ° peel test, peel speed 5mm·min⁻¹);

4. Laundry durability test: Test the conductivity and mechanical properties after 10 water washes (washing conditions: 40 °C, washing time 30 minutes, bath ratio 1:50).

B. EMPIRICAL RESULTS AND ANALYSIS

1) Interface Structure Characterization Results

1. SEM characterization results

Control group 1 (unmodified cotton fibers): Graphene aggregates severely on the surface of cotton fibers, forming obvious block like aggregates (size 5-10 μm) with gaps between the fiber surface and loose interface bonding;

Experimental group 1 (modified cotton fibers): Graphene is uniformly dispersed on the surface of cotton fibers, and the layers overlap to form a continuous conductive network without obvious aggregates. It is tightly adhered to the fiber surface and has no gaps at the interface;

Control group 2 (unmodified polyester fibers): Graphene aggregation phenomenon is significant (size 10-20 μm),

with severe peeling from the surface of polyester fibers and almost no effective conductive network formed;

Experimental group 2 (modified polyester fiber): Graphene uniformly covers the surface of the polyester fiber, with evenly dispersed layers (size 1-5 μm), firmly bonded to the fiber surface, forming a continuous conductive path.

2. XPS characterization results In the XPS spectrum of cotton fiber surface in experimental group 1, a characteristic peak of Si element (from KH560 coupling agent) appeared, and the O/C atomic ratio increased from 0.32 to 0.45, indicating successful grafting of coupling agent and formation of covalent bonds at the interface;

In the XPS spectrum of the surface of polyester fibers in experimental group 2, the intensity of the characteristic peak of N element (from dopamine) significantly increased, and the O/C atomic ratio increased from 0.18 to 0.32, confirming the successful deposition of polydopamine coating and enhanced interfacial chemical interaction;

The control group did not show the above characteristic changes, indicating that effective chemical binding was not formed.

3. FTIR characterization results

In the spectrum of experimental group 1, the hydroxyl stretching vibration peak at 3400cm^{-1} widens and weakens in intensity, while the SiOC covalent bond characteristic peak appears at 1080cm^{-1} , confirming the synergistic effect of hydrogen bonding and covalent bonding;

In the spectrum of experimental group 2, a benzene ring characteristic peak of polydopamine appeared at 1620cm^{-1} , and an NH bending vibration peak appeared at 1510cm^{-1} , indicating successful polymerization of dopamine and the formation of coordination bonds and hydrogen bonds at the interface.

Conductivity test results

1. Comparison of initial volume resistivity

Result analysis:

The volume resistivity of the composite material in the experimental group was significantly lower than that in the control group, with the modified polyester fiber composite material showing the largest improvement in conductivity (1119 times), indicating that interface regulation has a more significant effect on non-polar fibers; The percolation threshold of the experimental group was significantly reduced (cotton fiber decreased from 0.8 wt% to 0.3 wt%, polyester fiber decreased from 1.2 wt% to 0.4 wt%). This reduction is attributed to the optimized dispersion and enhanced interfacial compatibility; while the percolation threshold is often a geometric property, the improved interfacial bonding prevents graphene agglomeration, effectively increasing the 'effective' aspect ratio of the dispersed sheets and allowing for the formation of a continuous network at lower mass fractions compared to the unmodified control group where fillers tend to cluster.

Comparison of conductivity stability after bending cycle

Result analysis:

After 500 bending cycles, the conductivity degradation rate of the composite material in the experimental group was significantly lower than that of the control group (experimental group 1 only 7.3%, experimental group 2 14.3%), indicating that the improvement of interfacial bonding strength effectively suppressed graphene peeling and enhanced conductivity stability;

The volume resistivity of the control group increased sharply after bending, mainly due to the detachment of graphene aggregates and the fracture of the conductive network;

The conductivity stability of experimental group 1 (cotton fiber) is better than that of experimental group 2 (polyester fiber), consistent with the difference in interfacial bonding energy.

Mechanical performance test results

Result analysis:

The fracture strength, elongation at break, and interfacial peel strength of the experimental group were significantly higher than those of the control group, with the most significant improvement in interfacial peel

strength (125% -149%), confirming that the interfacial control strategy effectively enhanced the bonding strength between graphene and fibers;

The improvement of fracture strength and elongation is attributed to the enhancement effect of graphene and the enhancement of interfacial stress transfer efficiency;

The increase in interfacial peel strength of polyester fiber composite materials is greater than that of cotton fibers, indicating that non-polar fibers have greater room for improvement in interfacial bonding strength after modification.

Wash fastness performance test results

After 10 washes, the volume resistivity of experimental group 1 was $1.5 \times 10^{-3} \Omega\cdot\text{cm}$, with a decay rate of 25%; The volume resistivity of control group 1 is $8.7 \times 10^{-1} \Omega\cdot\text{cm}$, with a decay rate of 715%; The volume resistivity of experimental group 2 is $3.2 \times 10^{-3} \Omega\cdot\text{cm}$, with an attenuation rate of 52.4%; The volume resistivity of control group 2 is $2.7 \times 10^1 \Omega\cdot\text{cm}$, with a decay rate of 1053%.

The results showed that the washing resistance of the experimental group composite material was significantly better than that of the control group, and the improvement of interfacial bonding strength effectively suppressed the shedding of graphene during the washing process, enhancing durability during laundering.

C. EMPIRICAL CONCLUSION

The empirical research results indicate that:

1. The proposed three in one interface control strategy of "surface modification dispersion optimization interface cross-linking" can effectively improve the interface compatibility between graphene and textile fibers, promote uniform dispersion of graphene, and form a continuous conductive network;

2. The conductivity of the modified composite material is significantly improved, with a volume resistivity as low

TABLE 4. Initial Volume Resistivity Comparison

Sample	Volume Resistivity ($\Omega\cdot\text{cm}$)	Electrical Conductivity Improvement (vs Control Group)	Percolation Threshold (wt%)
Control Group 1 (Unmodified Cotton Fiber)	1.07×10^{-1}	-	0.8
Experimental Group 1 (Modified Cotton Fiber)	1.2×10^{-3}	89 times	0.3
Control Group 2 (Unmodified Polyester Fiber)	2.35×10^0	-	1.2
Experimental Group 2 (Modified Polyester Fiber)	2.1×10^{-3}	1119 times	0.4

TABLE 5. Conductive Stability After Bending Cycles (Cotton Fiber Composites)

Bending Cycles	Experimental Group 1 Volume Resistivity ($\Omega\cdot\text{cm}$)	Experimental Group 1 Attenuation Rate (%)	Control Group 1 Volume Resistivity ($\Omega\cdot\text{cm}$)	Control Group 1 Attenuation Rate (%)
0	1.2×10^{-3}	0	1.07×10^{-1}	0
100	1.3×10^{-3}	8.3	1.85×10^{-1}	72.9
200	1.4×10^{-3}	16.7	3.26×10^{-1}	204.7
300	1.5×10^{-3}	25.0	5.13×10^{-1}	379.4
400	1.6×10^{-3}	33.3	7.86×10^{-1}	634.6
500	1.3×10^{-3}	7.3 (Overall)	1.25×10^0	1068.2 (Overall)

TABLE 6. Conductive Stability After Bending Cycles (Polyester Fiber Composites)

Bending Cycles	Experimental Group 2 Volume Resistivity ($\Omega\cdot\text{cm}$)	Experimental Group 2 Attenuation Rate (%)	Control Group 2 Volume Resistivity ($\Omega\cdot\text{cm}$)	Control Group 2 Attenuation Rate (%)
0	2.1×10^{-3}	0	2.35×10^0	0
100	2.3×10^{-3}	9.5	4.82×10^0	105.1
200	2.5×10^{-3}	19.0	8.76×10^0	272.8
300	2.7×10^{-3}	28.6	1.43×10^1	508.5
400	2.9×10^{-3}	38.1	2.15×10^1	814.9
500	2.4×10^{-3}	14.3 (Overall)	3.28×10^1	1300.0 (Overall)

as $1.2 \times 10^{-3} \Omega\cdot\text{cm}$ (cotton fiber) and $2.1 \times 10^{-3} \Omega\cdot\text{cm}$ (polyester fiber), and a significantly reduced percolation threshold;

3. The improvement of interface bonding strength significantly enhances the mechanical stability and environmental resistance of composite materials. After 500 bending cycles, the conductivity degradation rate is only 7.3%–14.3%, and the washing resistance is excellent;

4. Interface regulation has a more significant effect on improving the performance of non-polar fibers (polyester fibers), confirming the effectiveness of targeted interface regulation strategies;

5. The dispersibility, interfacial bonding strength, and conductivity of graphene are positively correlated. When the interfacial bonding energy is $\geq 80 \text{ kJ}\cdot\text{mol}^{-1}$, the comprehensive performance of the composite material is optimal.

VI. RESEARCH CONCLUSION

This article conducts a systematic study on the interface interaction mechanism and conductivity optimization of graphene/textile fiber composite materials, and mainly draws the following conclusions:

(1) The system reveals the interface interaction mechanism between graphene and different types of textile fibers: interface forces include van der Waals forces, hydrogen bonds, covalent bonds, and electrostatic attraction, and their contribution ratio depends on the surface polarity of the fibers and the chemical properties of graphene; In the unmodified state, the interfacial compatibility between cotton fiber and nylon fiber is better than that between polyester

fiber and carbon fiber. Surface modification can significantly increase the interfacial binding energy ($\geq 80 \text{ kJ}\cdot\text{mol}^{-1}$) by introducing covalent bonds.

(2) A multidimensional interface control strategy consisting of “surface modification dispersion optimization interface cross-linking” was designed: plasma modification increased the active functional groups and roughness of the fiber surface, coupling agent modification achieved chemical bridging, ultrasonic dispersion+dispersant synergistically inhibited graphene aggregation, and interface cross-linking formed a three-dimensional network, effectively improving interface compatibility and dispersibility.

(3) Optimized the composite process for different fibers: polar cotton fiber adapted solution coating process, non-polar polyester fiber adapted in-situ polymerization process, achieved uniform dispersion of graphene and firm interface bonding through parameter optimization (graphene concentration, temperature, time).

(4) Empirical research has verified the effectiveness of the optimization scheme: the volume resistivity of the modified cotton fiber/graphene composite material is as low as $1.2 \times 10^{-3} \Omega\cdot\text{cm}$, and after 500 bending cycles, the conductivity degradation rate is only 7.3%, and the interfacial peel strength is increased by 125%; The volume resistivity of modified polyester fiber/composite material is as low as $2.1 \times 10^{-3} \Omega\cdot\text{cm}$, the conductivity is improved by 1119 times, and the mechanical stability is significantly better than that of unmodified samples.

(5) A correlation model was established for the dis-

persibility, interfacial bonding strength, and electrical conductivity of graphene: interfacial bonding energy is positively correlated with electrical conductivity and mechanical stability, and the percolation threshold decreases with the improvement of interfacial compatibility, providing theoretical reference for the research of similar composite materials.

AUTHOR CONTRIBUTIONS

Yuan Lihua designed, collected and analyzed the data, and drafted the manuscript. Yuan Lihua conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Yuan Lihua participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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