Reviews on Interfacial Properties of the Carbon Fiber Reinforced Polymer Composites

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Abstract. The bonding state between the carbon fiber and the polymer directly affects the properties of carbon fiber reinforced polymer composites (CFRP), which is influenced by the surface structural characteristics of carbon fiber (CF). The surface of CF is composed of tightly packed graphite crystallites lacking active carbon atoms, which results in low surface energy of CF and weak interfacial performance of CFRP. The interfacial properties can be evaluated indirectly through macro-mechanical properties, and can also be characterized by micromechanical testing methods. In order to improve the interfacial combination between the carbon fiber and the polymer, it is usually to modify the interface of CFRP, which mainly includes carbon fiber surface functionalization, carbon fiber surface coating and introduction of micro-nano enhancement phase. In this paper, researches on the interfacial properties of CFRP were reviewed, and the existing problems and the future research focus were also discussed.

1. Introduction
Carbon fiber reinforced polymer composite (CFRP) is one two-phase composite prepared by carbon fibers as reinforcing material and polymer as matrix [1]. It has become an important engineering and functional material for excellent mechanical properties, resistance to high temperature and chemical corrosion. It has been used in a wide range of contemporary applications particularly in space and aviation, automotive, maritime and manufacturing of sports equipment [2,3].

Thermal stress, chemical effects and crystallization effects occur between carbon fibers and polymers during the molding process of CFRP. The interfacial microstructure and performance characteristics caused by these effects are the key to the synergy of the composites. However, due to the inertness of the CF surface and the weak interface bonding, the excellent properties of the carbon fibers cannot be fully exerted, which reduces the overall performance of the composite material and limits the applications of CFRP in multi-directional bearing complex conditions. Therefore, the investigation of the interfacial properties of CFRP has attracted much attention of researchers. In the present study, the surface structural characteristics of carbon fiber were analyzed. Interface performance characterization techniques and interface modification methods of CFRP were summarized, and the future research directions were expected.

2. Microstructure of Carbon Fiber / Resin Interface
Carbon fiber is a special fiber containing more than 95% carbon, which is obtained by high-temperature carbonization and graphitization of polyacrylonitrile, pitch, viscose yarn or phenolic fiber in an inert atmosphere [4,5]. It has been widely used in composite materials for its high specific strength, high temperature resistance, corrosion resistance and thermal conductivity [6,7]. The study
found that the structure of carbon fiber has obvious “skin-core” characteristics, as shown in Figure 1 [8]. The inner core layer is composed of small-scale graphite microcrystalline disorder layers [9]. From the core layer to the skin layer, the crystal size of graphite microcrystalline gradually increased and the arrangement was gradually orderly. The graphite crystallites on the carbon fiber skin layer have the characteristics of compact arrangement and lack of active carbon atoms, which results in low surface energy and lack of functional groups for chemical reactions [10-12].

![Figure 1. Schematic diagram of carbon fiber structure.](image)

As shown in Figure 2, the interface is the transition area between the carbon fiber and the resin matrix[13]. It has the function of transferring stress, heat, electricity and other information[14].

![Figure 2. Schematic diagram of the interface structure of carbon fiber / resin composites.](image)

3. Characterization Method of Carbon Fiber / Resin Interface Performance

At present, the interface properties of composite materials can be qualitatively evaluated indirectly through macro-mechanical properties, and can also be visually and quantitatively characterized by micromechanical testing methods. The macro-mechanical properties mainly include interlaminar shear strength, transverse tensile properties, and interlaminar fracture toughness, etc. Micromechanical test methods include carbon fiber monofilament break test, carbon fiber monofilament debonding method, and so on.

3.1. Macro-Mechanical Performance Evaluation Method

The macro-mechanical properties can be tested using universal testing machines in accordance with testing standards. Wu et al. [15] used interlaminar shear strength and impact toughness of composites to characterize the performance enhancement effect of carbon nanotubes (CNTs) modified carbon fiber sizing agents on the performance of carbon fiber / methylphenyl silicone resin composites. When the content of CNTs modified by aminopropytriethoxysilane was 0.5 wt%, the interlaminar shear strength and impact toughness of the composites were increased by 46.53% and 31.32%, respectively. Xiao et al. [16] also used interlaminar shear strength to approve that the addition of CNTs contributed to the
The above researches showed that using macro-mechanical properties to evaluate the interface bonding state of composites was mature and steady, which was closely integrated with the actual engineering. However, this method could only characterize the interface performance indirectly. Its sample preparation cycle was long and the experimental was inefficient.

3.2. Micromechanical Test Methods
The methods generally obtained interface shear strength (IFSS) of the carbon fiber / polymer composite by applying micromechanical force to the sample and studying its microscopic failure process. They are characterized by simple theory and quantificational testing.

3.2.1. Monofilament breaking method
The monofilament breaking method is one of the most widely used methods in micromechanical testing methods. The general process is to stretch monofilament / carbon fiber composite until the carbon fiber reaches a saturated fracture state, then calculate the fiber / resin interface shear strength by using the Kelly-Tyson [17,18] formula.

Jager et al. [19] used the monofilament breaking method to show that sizing agent modified by halloysite nanotube was beneficial to improve the interface combination state of CFRP, and the interface shear strength of the composite material was increased by 23%.

The process of fiber monofilament breaking method is maneuverable and observable. However, the test dates of this method are greatly influenced by the stretching rate [20].

3.2.2. Monofilament debonding method
The monofilament debonding method is usually done by using tension or pressure to cause the fiber to debond or slip in the resin, and then calculate the fiber / resin interface shear strength according to the failure load.

Wang et al. [21] used monofilament debonding method to compare the interfacial properties of different carbon fiber reinforced C / SiC composites. Li et al. [22] also used this method to compare the interfacial properties of different carbon fiber reinforced epoxy resin composites.

Compared with the macro-evaluation method, the micromechanical test method can quantitatively or semi-quantitatively determine IFSS [23-25]. However, the fiber tensile rate, load application rate, and test monofilament length have a significant impact on the test results. Selecting appropriate test conditions can obtain better test results.

4. Carbon Fiber / Resin Composite Interface Modification Method
The surface characteristics of carbon fibers mainly include types of functional groups, surface roughness, and specific surface area, which directly affect the fiber / resin interface bonding strength. At present, the general idea of interface modification of CFRP is to change the microstructure of carbon fiber surface by using surface oxidation, high energy radiation or surface coating technology. And then graft nano-materials, active functional groups or molecular chains so as to cross-link with the polymer matrix on the fiber surface. According to the technical mechanism, the Carbon fiber / resin composite interface modification methods can be divided into fiber surface functionalization, surface coating and introducing second enhancement phases.

4.1. Carbon Fiber Surface Functionalization
The surface of the untreated carbon fiber is a crystalline graphite layer, which is very inert. The principle of this method is to generate reactive functional groups on the fiber surface by oxidants[26-29], high-energy radiation stream[30-32], etc. The interface bonding state of CFRP is improved by chemical bonding between the functional group and the polymer molecule. The processing of high-energy radiation flow is convenient and easy to operate. However, its time limited effect [33-36], expensive equipment and high environmental requirements limit its applications in industry.
The functionalization of carbon fiber surface has a positive effect on improving the interface bonding state and the comprehensive mechanical properties of CFRP. But excessive treatment will destroy the fiber primary structure [37], which affects the original performance of carbon fibers.

4.2. Carbon Fiber Surface Coating
This method is to construct a rigid or flexible polymer coating with good compatibility between the carbon fiber surface and the resin matrix by in-situ polymerization [40-44], chemical grafting[45-49], surface spraying[50] and electrochemical modification[51,52].

The fiber surface coating can customize surface characteristics of carbon fiber for different resin matrices [53], which has the advantages of high design flexibility, low cost, and fine implementation. In addition, some researchers [54] used CVD method to uniformly deposit pyrolytic carbon on the surface of carbon fibers, and used carbon coating to enhance the interfacial interaction of composites.

4.3. Introduction of Micro-Nano Enhancement Phase
In order to further improve the properties of composite materials, the transition of the composite system from two-phase composite to three-phase or multi-phase composite has become one of the important research directions in this field. At present, the second enhancement phases are mostly micro-nano materials with excellent mechanical properties and large specific surface area [55,56], which include zinc oxide nanowires [57-60], carbon nanotubes and graphene oxide [61-64].

The above researches show that the introduction of micro-nano materials had a significant influence on the interfacial bonding state. And reasonable controlling of nanomaterial size, morphology, and density parameters could effectively improve the interfacial shear strength of CFRP.

5. Conclusion
The research ideas of CFRP interface modification had been initially formed. According to the physical and chemical characteristics of different matrix materials, different modification methods are used to develop carbon fiber interface on demand. However, the correlation theory between the interface structure and composite properties needs to be further revealed. And the application of theoretical design methods such as molecular simulation and finite element calculation in the study of the interface modification of CFRP should be strengthened.

6. References
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