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A Brief Discussion on the Performance Enhancement of Graphene-Modified FCM Porous Materials and Their Application Potential in Intelligent Manufacturing

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Abstract: *With the rapid development of nanomaterial technology, graphene has become a research hotspot in the field of materials science due to its unique physical and chemical properties. This review paper aims to explore the performance enhancement of graphene-modified carbon fiber composite (FCM) porous materials and their application potential in intelligent manufacturing. By systematically analyzing the interaction mechanisms between graphene and carbon fibers, this paper reveals how graphene modification can significantly improve the mechanical strength, thermal conductivity, electromagnetic shielding effectiveness, and tribological performance of FCMs. Furthermore, this paper discusses the applications of graphene-modified FCMs in the field of smart materials, including their use as high-performance strain sensors, piezoresistive nanocomposites, and electrode materials for energy storage systems.This paper first reviews the preparation methods of graphene-modified FCMs, including chemical vapor deposition, in situ growth, and surface modification techniques. It then provides a detailed discussion of the performance testing results of these composites, including experimental data on their mechanical, thermal, and electrical properties. Through comparative analysis, this paper demonstrates the significant advantages of graphene-modified FCMs in enhancing material properties. Furthermore, it explores the integration of these materials in intelligent manufacturing systems, such as their potential applications in flexible electronics, sensor technologies, and energy storage devices. Finally, the paper looks ahead to the future research directions and challenges in graphene-modified FCM porous materials, including large-scale production, cost-effectiveness analysis, and environmental impact assessments. This review provides a comprehensive perspective on the design, preparation, and application of graphene-modified FCM materials, offering valuable insights for materials scientists and engineers working in the fields of high-performance composites and intelligent manufacturing.*

Keywords: *Graphene, Carbon Fiber Reinforced Composites, Intelligent Manufacturing, Porous Materials*

1. Introduction

In the 21st century's technological revolution, advancements in materials science have brought about revolutionary changes across various industries. Particularly in fields such as aerospace, automotive manufacturing, energy storage, and flexible electronics, the demand for high-performance materials is growing rapidly. Carbon fiber reinforced composites (CFRCs), known for their light weight, high strength, and excellent chemical stability, have become key materials in these sectors. However, the performance of CFRCs still has significant potential for enhancement, particularly in meeting the demands of increasingly complex application environments and ever-higher performance standards. Graphene, a two-dimensional material consisting of a single atomic layer of carbon, unlocks innovative possibilities for improving the performance of CFRCs with its remarkable mechanical strength, exceptional electrical conductivity, and outstanding thermal conductivity[1].

The discovery of graphene heralded a new era in two-dimensional material research, with its unparalleled properties granting it transformative potential in the field of materials science. The introduction of graphene not only enhances the mechanical properties of CFRCs but also significantly

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improves their thermal management capabilities and electromagnetic shielding effectiveness[2]. Additionally, the high specific surface area and chemical reactivity of graphene show immense potential for applications in catalysis, sensing, and energy storage. With the rise of intelligent manufacturing technologies, graphene-modified CFRCs hold particularly promising prospects for applications in smart materials and systems[3].

This review aims to provide a comprehensive analysis of the latest research advancements in graphene-modified FCM porous materials, exploring their potential for performance enhancement and applications in intelligent manufacturing. First, we will review the preparation techniques and methods for graphene-modified FCMs, followed by a detailed discussion of their performance testing results, including mechanical, thermal, and electrical properties[4]. Next, the paper will explore the applications of graphene-modified FCMs in intelligent manufacturing, particularly in smart sensors and energy storage systems[5]. Finally, we will look ahead to the future research directions and challenges for graphene-modified FCMs, aiming to offer guidance and inspiration for materials scientists and engineers[6].

Through in-depth research on graphene-modified FCM porous materials, we not only advance the development of high-performance composite materials but also provide innovative material solutions for the field of intelligent manufacturing[7]. This review will offer readers a comprehensive perspective on the significance and application prospects of graphene-modified FCMs in modern materials science[8].

2. Current Research Status Domestically and Internationally

2.1. Current Research Status of Graphene-Modified FCM

Recent research on graphene-modified FCM (fiber-reinforced composite) porous materials has made significant progress in performance enhancement and potential applications in intelligent manufacturing[9]. Graphene, known for its exceptional conductivity, thermal conductivity, and strength, can significantly improve the mechanical properties, thermal resistance, and heat conductivity of FCM materials. In both domestic and international studies, graphene-modified FCMs are widely used in fields such as aerospace, automotive, and electronic devices. Particularly in intelligent manufacturing, their superior self-sensing capabilities, environmental adaptability, and mechanical properties show great potential for applications in sensors, flexible electronics, and smart structures[10].

2.2. International Overview

In recent years, graphene, as a novel two-dimensional material, has attracted widespread attention for its application in modified composites due to its unique physical and chemical properties. Graphene boasts an extremely high specific surface area (2630 m^2/g), excellent electrical conductivity, thermal conductivity, and exceptional mechanical strength, all of which make it highly promising for applications in porous materials. Research on graphene-modified fiber-reinforced composites (FCMs) has primarily focused on several key areas:

International studies have shown that the introduction of graphene significantly enhances the mechanical properties, thermal conductivity, and wear resistance of FCM porous materials[11]. For example, by adding graphene as a reinforcing phase to matrix materials such as glass fibers and carbon fibers, researchers have found that uniform dispersion of graphene improves the toughness, compressive strength, and high-temperature resistance of the composite materials[12]. In the field of porous materials, the thermal conductivity of graphene has been utilized to enhance the thermal management properties of the materials, particularly in the electronics and aerospace industries, where graphene-modified composites maintain stable performance under high-temperature conditions[13].

With the development of intelligent manufacturing and smart materials, graphene-modified FCM porous materials have also been widely applied for their self-sensing and self-healing capabilities. Studies have shown that graphene-enhanced composites can monitor internal stress or temperature in real-time through their electrical conductivity[14]. For example, in aerospace applications, graphene-modified composites are used as structural health monitoring materials, detecting external environmental changes or internal damage through resistance variations. Additionally, some research has explored combining graphene with other materials, such as polymers, to develop composites with self-healing functions that can automatically repair themselves upon external activation, thereby extending the material's lifespan and improving safety[15].

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In intelligent manufacturing, the superior properties of graphene-modified FCMs show great potential in various application scenarios[16]. For instance, the high thermal and electrical conductivity of graphene-enhanced composites has led to significant advancements in flexible electronics, sensors, and electronic packaging[18]. Particularly in 3D printing technology, the introduction of graphene improves the mechanical and thermal properties of printed materials, allowing composite materials to perform reliably across a wider range of temperatures and pressures[17]. Furthermore, the lightweight characteristics of graphene-modified materials make them ideal for lightweight designs in industries such as automotive, aerospace, and high-performance sports equipment. For porous structures requiring high strength and low weight, graphene composites offer considerable advantages[18].

The corrosion resistance and durability of graphene-modified FCM porous materials have also attracted significant attention in international research. Studies indicate that graphene can effectively improve the oxidation and corrosion resistance of composite materials, particularly in extreme environments such as high temperatures or acidic and alkaline media. The nanoscale structure of graphene helps prevent material degradation by external environmental factors, making graphene-modified composites highly applicable in industries such as marine, chemical, and petroleum[19].

The dispersion of graphene in composite materials is a key factor affecting performance. As a result, significant progress has been made internationally in improving the preparation processes of graphene composites. Advanced techniques, such as solution mixing, hot pressing, sol-gel methods, and 3D printing, have been developed to enhance the dispersion and interface bonding of graphene within the matrix material. Particularly in 3D printing, precise control over graphene content and dispersion allows for fine-tuning of the composite material's properties to meet the requirements of various industrial applications.

Despite the wide application prospects of graphene-modified FCMs across various fields, several challenges remain[20]. First, the efficient and uniform dispersion of graphene still presents a significant challenge in the preparation process. Additionally, the high cost of graphene-modified composites limits their large-scale application. Furthermore, the stability, long-term reliability, and interface bonding between graphene and matrix materials need further research and improvement[21].

International research on graphene-modified FCM porous materials has made significant strides, particularly in improving the mechanical properties, thermal conductivity, smart functionality, and environmental adaptability of these materials, showcasing the tremendous potential of graphene. With continued research, graphene-modified composites are expected to see broader applications in intelligent manufacturing, flexible electronics, aerospace, and high-performance materials.

2.3. Current Research Status in China

China's research in graphene-modified carbon fiber reinforced composites (FCMs) is rapidly advancing, and significant progress has been made in this field:

Chinese researchers have successfully developed graphene/carbon fiber/epoxy composites by using graphene prepreg as a functional layer, which is applied to the surface of carbon fibers. Studies have shown that the addition of graphene prepreg does not affect the internal quality of the composite, and the graphene functional layer has good interfacial compatibility with the carbon fiber structural layer. By utilizing graphene's excellent electrical conductivity, the electromagnetic interference (EMI) shielding performance of the corresponding composite material can be significantly enhanced. For example, by adding just one layer of graphene prepreg (G105/3234), the EMI shielding efficiency of carbon fiber/epoxy composites increased from 27.7 dB to 64.7 dB, while maintaining satisfactory mechanical properties[21].

Domestic research has also focused on the microstructure and dynamic thermodynamic properties of graphene oxide-modified carbon fiber/epoxy resin composites with different surface characteristics. These studies contribute to a deeper understanding of the composite materials' microstructures and thermodynamic behaviors, providing a scientific basis for improving the performance of these materials[22].

With the rapid development of the wind power and sports industries, the demand for carbon fiber composites in China continues to grow. In 2022, the demand for carbon fiber composites reached 114,500 tons, a year-on-year increase of 19.3%, demonstrating strong growth momentum[23].

China's acrylic fiber production has been steadily increasing, with a production volume of 3.216 million tons in 2023, representing a 7.2% year-on-year growth. The carbon fiber market size is also expanding, with the market size reaching 12.81 billion RMB in 2022, an increase of 20.69% from the previous year, and it is expected to reach 17.14 billion RMB by 2024. China's carbon fiber production capacity is rapidly expanding, with a production capacity of 138,300 tons in 2023, expected to reach 145,600 tons by 2024.

A review article published by the Liu Zhongfan/Peng Hailin team from the Beijing Institute of Graphene on Nature Materials discusses the current status, challenges, and market analysis of graphene industrialization technologies. The article emphasizes the importance of graphene industrialization preparation technologies, proposing the concept of "graded" graphene and highlighting the importance of "breakthrough" applications of graphene[24].

In summary, China has made significant progress in the research and industrialization of graphene-modified carbon fiber composites, with a continuously growing market demand, an improving industrial chain, and ongoing advancements in graphene industrialization technologies. These research achievements provide a solid foundation for enhancing the performance and expanding the applications of carbon fiber composites.

3. Conclusions

With the rapid development of intelligent manufacturing and new materials technology, graphene-modified fiber-reinforced composite (FCM) porous materials have emerged as a new type of material with excellent performance, showing broad application prospects. This paper explores the advantages of graphene in enhancing the mechanical properties, thermal conductivity, and high-temperature resistance of FCM porous materials. It also analyzes their potential in the field of intelligent manufacturing, particularly in applications such as sensors, smart structures, and high-performance materials.

Graphene not only significantly improves the mechanical and thermal properties of composite materials but also exhibits unique advantages in intelligent functions (such as self-sensing and health monitoring) and environmental adaptability. This makes graphene-modified composites highly promising for a range of industries, including aerospace, automotive, and electronics, especially within the context of intelligent manufacturing. However, despite the broad prospects of graphene composites in performance enhancement and application expansion, challenges remain in terms of dispersion, production cost, and long-term stability, which require further research and technological breakthroughs.

Looking ahead, as graphene production technology matures and preparation processes are improved, graphene-modified composites are expected to demonstrate their advantages in more application areas. In line with the needs of intelligent manufacturing, graphene composites will play an increasingly important role in fields such as flexible electronics, high-performance sensors, and smart structures. To promote the large-scale application and industrialization of graphene composites, future research should focus more on optimizing material dispersion, enhancing the overall performance, and reducing production costs, providing more efficient and sustainable material solutions for intelligent manufacturing and high-tech industries.

In conclusion, the research and application of graphene-modified FCM porous materials have vast development potential. Future research should further strengthen the integration of theory and practice, driving technological innovation and the industrialization of graphene composites, and injecting new momentum into the development of modern manufacturing.

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