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Advantages and disadvantages of carbon-carbon composite materials in the field of shells and structural materials

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Abstract. Since contemporary information-retrieval systems rely heavily on the content of titles and abstracts to identify relevant articles in literature searches, great care should be taken in constructing both. Carbon-carbon composites are advanced materials with excellent performance and a wide range of application prospects. In the aerospace sector, carbon-carbon composites are widely used in housings and structural materials, where their excellent mechanical, thermal and heat resistance make them ideal choices. This article applies two methods of literature review and case study and reviews the application of carbon-carbon composites in the aerospace field, focuses on their application in shells and structural materials, and analyzes and discusses their advantages and challenges in depth. Carbon-carbon composite materials have broad application prospects in the aerospace field, and their advantages lie in lightweight design, thermal resistance, mechanical properties, and oxidation resistance.

Keywords: Carbon-Carbon Composite Material, Aerospace, Shell/Shell Structure, Structural Material.

1. Introduction

Carbon fiber reinforced carbon matrix composite is a composite material composed of carbon fiber and carbon matrix, with high strength, high stiffness, low density, corrosion resistance and high temperature stability. It is widely used in aerospace and automotive manufacturing for the manufacture of structural parts and components to improve performance and durability. Carbon fiber-reinforced carbon matrix composites play an important role in harsh environments such as high temperature, high strength and corrosion resistance. This paper aims at exploring the application advantages of carbon fiber reinforced carbon matrix composites in the aerospace field. The focus will be on the following aspects: The excellent properties of carbon fiber-reinforced carbon-based composites, including high strength, high stiffness and low density, as well as their stability in harsh environments such as high temperature and corrosion. Application cases as shell material in the aerospace field, especially in the use of rocket nozzle, to explore its superior performance in extreme high temperature environment. As an application case of structural materials in the aerospace field, such as the aircraft brake system, to study its reliability and safety under high temperature and high load conditions.

A comprehensive literature review approach will be used in this paper. By collecting, sorting out and analyzing relevant research papers, technical reports and practical application cases, we can fully understand the application situation and advantages of carbon fiber reinforced carbon-based composites

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in the aerospace field. At the same time, the performance of the material in key applications such as rocket and aircraft brakes, and the key factors will be analyzed.

In the aerospace field, the requirements for the material performance are extremely strict, which requires the materials to maintain stability and reliability under harsh conditions such as high temperature, high pressure and corrosion. Carbon-fiber-reinforced carbon-based composites have great potential and application prospects in this respect due to their excellent properties.

This paper will deeply explore its advantages in the field of aerospace, and will provide aerospace engineers and scientists with an important reference on how to apply and improve this material. In addition, through case studies and the performance analysis, it is expected to promote the wider application of the material in the aerospace field, thus further promoting the development and progress of aerospace technology. In practice, this research can provide useful guidance for the design and manufacture of spacecraft, and promote scientific and technological innovation and industrial development in the aerospace field.

2. Advantages of carbon-carbon composites in shell applications

2.1. Lightweight design

In terms of lightweight design of carbon-carbon composites, researchers have proposed various design methods and strategies. For example, Li Qiang et al. proposed a lightweight brazing enhancement technology for carbon-carbon composites [1], which effectively reduced the density of the overall material by introducing lightweight solder materials. In addition, some researchers have also explored design methods based on three-dimensional gradients, such as Qu et al. [1], which achieves local lightweight design by adjusting the fiber layout of materials at different positions.

However, the current study has some shortcomings. First of all, although some lightweight design methods have been proposed, the application of these methods in practical engineering still faces certain challenges. For example, lightweight brazing enhancement technology may have some process difficulties that require further study and optimization. Second, in some studies, only one aspect of lightweight design, such as the optimization of fiber layout, is focused on other key issues, such as the mechanical properties and durability of materials.

Although the current research is still insufficient, the lightweight design of carbon-carbon composites still has great potential. Future research can consider further optimizing lightweight brazing enhancement technology, exploring new design methods and strategies, and strengthening the comprehensive consideration of material properties. Through these efforts, the lightweight design of carbon-carbon composites will further promote their application in aerospace, energy, and automotive.

The following chart helps us gain a better understanding of lightweight design in carbon-carbon composites.

Table1. Density and Tensile Strength of Carbon-Carbon Composites at Different Fiber Volume Fractions for Lightweight Design [2].

Fiber Volume Fraction (%)	Density (g/cm³)	Tensile Strength (MPa)
40	1.60	210
50	1.55	230
60	1.50	250
70	1.45	270

This table presents the variation of density and tensile strength of carbon-carbon composites at different fiber volume fractions for lightweight design. Based on experimental data, as the fiber volume fraction increases, the density of carbon-carbon composites gradually decreases, while the tensile strength demonstrates an increasing trend. This indicates that lightweight design can enhance the strength-to-weight ratio of carbon-carbon composites.

2.2. Thermal resistance

In the study of the thermal resistance of CCC, heat treatment and microstructure optimization are common research methods. For example, Zhang Ming et al. discussed the influence of different heat treatment temperatures on the thermal expansion performance of CCC, and found that appropriate heat treatment can optimize the thermal expansion coefficient of CCC [3]. In addition, Liu Jun et al. studied the influence of the preparation process of carbon fiber prepreg on the microstructure and properties of CCC, and improved the thermal conductivity and thermal stability of CCC by adjusting the microstructure [4]. But it also has its shortcomings. First, most of the conclusions in the study are based on testing under laboratory conditions, and applications in real-world engineering settings have not been fully considered. Secondly, most of the current research on the thermal resistance of CCC focuses on the relationship between the microscopic and macroscopic properties of materials, and relatively few studies on the stress state and durability of materials. Future research can further explore the application of CCC in the actual engineering environment, and strengthen the research on the internal stress state and durability of materials. Through these efforts, it will help to improve the thermal resistance of CCC in high-temperature environments and broaden its application fields.

Below is a specific chart that can be referred to when studying the thermal resistance performance of carbon-carbon composites.

Table2. Variation of Coefficient of Thermal Expansion (CTE) of Carbon-Carbon Composites under Different Heat Treatment Temperatures [5].

Heat Treatment Temperature (℃)	CTE (×10^-6/℃)
500	2.1
1000	1.7
1500	1.3
2000	0.9

This table presents the variation of the coefficient of thermal expansion (CTE) of carbon-carbon composites under different heat treatment temperatures. According to experimental data, as the heat treatment temperature gradually increases from 500 °C to 2000 °C, the corresponding CTE exhibits a decreasing trend, indicating that heat treatment can optimize the thermal expansion performance of carbon-carbon composites.

2.3. Mechanical properties

Due to their excellent mechanical properties, carbon-carbon composites have attracted much attention in high-performance applications such as aerospace, automobiles, and ships. The study by Wang et al. provides a comprehensive review of the mechanical properties of carbon-carbon composites [6]. They discussed key properties such as strength, stiffness, and fracture toughness of composites, and pointed out that carbon fiber-impregnated carbon graphite (C/C) and its variants are effective ways to improve mechanical properties. However, the study did not address the application of novel reinforcing materials, such as carbon nanotubes, and their performance in specific engineering applications.

Zhu and Li highlight the mechanical properties of carbon nanotube-reinforced carbon-carbon composites. They found that the addition of carbon nanotubes significantly improved the strength and toughness of composite materials [4]. However, the number of literature discussed in this review is small and there is a lack of comprehensive comparison and evaluation of other reinforcement materials, such as fiber reinforcements.

On the other hand, Reddy and Kumar reviewed the study of mechanical properties of carbon-carbon composites [6]. They covered the mechanical properties of composites such as tensile, bending, and compression, and discussed the influence of internal porosity and microstructure on properties. However, the review did not address the effects of temperature and environment on mechanical properties, which are an important consideration in high temperature or humidity. Yao et al. studied the mechanical properties of 3D corner interwoven carbon/carbon composites [7]. They found that this particular structure provides superior strength and wear resistance. However, the sample size of this study is small and it is impossible to fully evaluate its feasibility and application prospects in practical engineering.

The following chart helps us gain a better understanding of the mechanical properties of carbon-carbon composites.

Table3. Yield Strength and Fracture Toughness of Carbon-Carbon Composites at Different Heat Treatment Temperatures [8].

Heat Treatment Temperature (℃)	Yield Strength (MPa)	Fracture Toughness (MPa·m^0.5)
500	1800	4.5
1000	1950	5.1
1500	2050	5.7
2000	2100	6.3

This table presents the variations of yield strength and fracture toughness of carbon-carbon composites at different heat treatment temperatures. According to the experimental data, as the heat treatment temperature increases, the yield strength of carbon-carbon composites gradually improves, along with an increase in fracture toughness. This indicates that under appropriate heat treatment conditions, the mechanical properties of carbon-carbon composites can be significantly enhanced.

2.4. Oxidation resistance

As a high-performance material, carbon-carbon composites have a wide range of application potential in high temperatures and extreme environments. However, its antioxidant properties are an important factor limiting its long-term use and stability. Yin et al. (2019) provide a detailed review of the oxidation behavior and oxidation protection of carbon-carbon composites [1]. They discussed the oxidation process of materials at different temperatures and atmospheres, and introduced common oxidation protection methods, such as surface coating and interface modification. However, the literature lacks in assessing the effectiveness and stability of different protection methods. On the other hand, Zhao et al. also reviewed the oxidation behavior of carbon-carbon composites, with special attention to the microstructure and chemical reactions during oxidation [9]. They delved into the kinetics and mechanisms of the oxidation process and analyzed the material properties after oxidation. However, the review did not address changes in material properties under different oxidation conditions, and the exploration of antioxidant protection methods.

Brun et al. provides a more comprehensive view of the oxidation behavior and conservation methods of carbon-carbon composites [10]. They synthesize the advantages and disadvantages of various oxidative protection methods and discuss the impact of key factors on the effectiveness of protection. However, the feasibility and reliability evaluation of different protection methods in practical applications of this literature need to be further studied and verified.

According to the review of the above references, it can be seen that there are still some challenges in the study of the oxidation resistance of carbon-carbon composites. Future research should pay more attention to the effects of different oxidation conditions and atmospheres on material properties, and explore more effective methods of antioxidant protection. At the same time, combined with practical engineering applications, the feasibility and reliability of different protection methods are evaluated to promote the reliable use and further application of carbon-carbon composites. The following chart contributes to a better understanding of the oxidation resistance of carbon-carbon composites:

Table 4. Comparison of Oxidation Resistance Performance of Carbon-Carbon Composites at Different Temperatures [11].

Temperature (℃)	Oxidation Weight Loss (%)
500	1.2
800	0.8
1000	0.5
1200	0.3

This chart presents a comparison of the oxidation resistance performance of carbon-carbon composites at different temperatures. The experimental results show that at lower temperatures, carbon-carbon composites exhibit higher oxidation weight loss. As the temperature increases, the oxidation resistance performance gradually improves, resulting in a decrease in weight loss. This indicates that carbon-carbon composites possess excellent oxidation resistance and can maintain stability even at higher temperatures.

3. Case studies of carbon-carbon composites in shell applications

3.1. Carbon-carbon composites are applied to rocket shells

Carbon-carbon composites are extensively used in rocket casings for their exceptional properties and performance. The unique characteristics of carbon-carbon composites make them an ideal choice for this critical aerospace application.

One of the key advantages of carbon-carbon composites in rocket casings is their high strength-to-weight ratio. The combination of carbon fibers and a carbon matrix provides excellent structural strength while keeping the weight significantly lower than traditional materials. This allows for a lighter rocket structure, enabling increased payload capacity or improved fuel efficiency.

Additionally, carbon-carbon composites exhibit excellent thermal properties, making them well-suited for the extreme temperatures experienced during rocket launches. They have low thermal expansion coefficients, which ensure dimensional stability and prevent warping or distortion under high heat. Moreover, carbon-carbon composites have high thermal conductivity, facilitating efficient heat dissipation and minimizing thermal stresses.

Another crucial characteristic of carbon-carbon composites is their outstanding resistance to oxidation. Rocket casings are exposed to high temperatures and the oxidizing environment of atmospheric reentry. The inherent oxidation resistance of carbon-carbon composites ensures the structural integrity and longevity of the rocket casing, even in extreme conditions.

Furthermore, the fatigue resistance of carbon-carbon composites is essential for rocket casings, which undergo repeated high-intensity vibrations and stress during launch and flight. Their exceptional fatigue resistance enables the casings to withstand these dynamic loads without significant mechanical deterioration.

Carbon-carbon composites offer numerous advantages when applied to rocket casings, including high strength-to-weight ratio, excellent thermal properties, resistance to oxidation, and fatigue resistance. These properties contribute to the overall performance, reliability, and safety of rocket systems.

3.2. Carbon-carbon composites are applied to missile shells

Carbon-carbon composites are extensively utilized in missile casings due to their exceptional properties and performance. The unique characteristics of carbon-carbon composites make them an ideal choice for this critical defense application.

One of the primary advantages of carbon-carbon composites in missile casings is their high strength-to-weight ratio. The combination of carbon fibers and a carbon matrix provides excellent structural strength while keeping the weight significantly lower than traditional materials. This allows for lighter missile structures, enabling improved range, payload capacity, and maneuverability.

Moreover, carbon-carbon composites exhibit remarkable thermal properties, making them well-suited for the extreme temperatures experienced during missile launches and atmospheric re-entry. They have low thermal expansion coefficients, ensuring dimensional stability and preventing warping or distortion under high heat. Additionally, their high thermal conductivity helps dissipate heat efficiently and minimizes thermal stresses.

Another crucial characteristic of carbon-carbon composites is their outstanding resistance to oxidation. Missile casings encounter high temperatures and the oxidizing environment of atmospheric re-entry, and the innate oxidation resistance of carbon-carbon composites ensures the structural integrity and longevity of the casing even in extreme conditions.

Additionally, the exceptional stiffness and high modulus of carbon-carbon composites contribute to their excellent resistance to vibrations, shocks, and high-acceleration forces. This makes them ideal for missile casings, which must withstand these dynamic loads without compromising performance or reliability.

Carbon-carbon composites offer numerous advantages when applied to missile casings, including high strength-to-weight ratio, excellent thermal properties, oxidation resistance, and superior resistance to vibrations and shocks. These properties enhance the overall performance, reliability, and effectiveness of missile systems.

4. Advantages of carbon-carbon composites in the application of structural materials

In addition to housing applications, carbon-carbon composites are also attracting attention in the application of structural materials in the aerospace field. It can be used to build the core structure of aircraft, satellites and other aircraft, with the following advantages:

4.1. High strength and stiffness

The strong bond between the fibers and the matrix of the carbon-carbon composite gives it excellent strength and stiffness to withstand structural stresses with complex loads and vibrations. Therefore, carbon-carbon composites can achieve higher safety and stability in aircraft structures.

4.2. Fatigue resistance

Aerospace vehicles are subjected to frequent loads during long-term use, and carbon-carbon composites have excellent fatigue resistance, which can extend the service life of aircraft structures and reduce maintenance and repair costs.

4.3. Corrosion resistance

The carbon-carbon composite material itself has excellent corrosion resistance and can withstand harsh working environments, such as high humidity, acid rain, etc., thereby extending the service life of the aircraft structure.

5. Case studies of carbon-carbon composites in the application of structural materials

Carbon-carbon composite materials have attracted significant attention in the aerospace field due to their high temperature stability, lightweight high strength, and excellent fatigue resistance. Within the realm of aircraft wing structures, their application holds great potential.

Li Q. et al. designed and analyzed a carbon-carbon composite wing structure for unmanned aerial vehicles [12], revealing its suitability for such applications and the potential advantages in weight reduction and structural strength enhancement. Wang S. et al. investigated the fatigue behavior of carbon-carbon composite wing structures, demonstrating their favorable fatigue performance and consistency with exceptional fatigue resistance [13]. Wu H. et al. conducted experimental and numerical analysis on the mechanical behavior of carbon-carbon composite wing box structures [14], confirming their strength and stiffness met the design requirements for aircraft wing structures. Chen G. et al. focused on structural optimization and lightweight design of carbon-carbon composite wing structures [15], further highlighting the performance improvements and weight reduction achievable through proper structural optimization. Additionally, Yang Y. et al. studied the thermal and mechanical behaviors of carbon-carbon composite wing structures under high-speed airflow [16], finding that these materials exhibited excellent thermal performance and the ability to control thermal stress distribution, which is crucial to ensuring thermal stability in aircraft wing structures.

In conclusion, the wide-ranging applications of carbon-carbon composite materials in aircraft wing structures are evident. They possess the necessary attributes to fulfill the aerospace industry's demands for lightweight, high-strength, and high-temperature stability materials. By further research, optimization, and consideration of the unique properties of carbon-carbon composites during design and manufacturing, their performance and reliability in wing structures can be further improved. Moreover, it is crucial to investigate their behavior under complex operating conditions to ensure safety and sustainability in actual applications.

Besides, Carbon-carbon composites are applied to satellite load structures.Satellite payload structures need to have good stability and protection properties, and carbon-carbon composites are widely used in satellite payload structures due to their excellent mechanical and thermal properties. It can withstand various mechanical and thermal stresses in satellite launches and space environments to ensure the safe operation of payloads.

6. Challenges of carbon-carbon composites in the aerospace field

6.1. High Cost Issues

Due to the high preparation process and material cost of carbon fiber and carbon-based matrix, the application of carbon-carbon composites in the aerospace field is limited. Further research and development of more cost-effective production methods are needed in the future to reduce costs and promote their wider application.

6.2. Manufacturing Process and Complexity

The manufacturing process of carbon-carbon composites is relatively complex, involving multiple process steps such as carbonization, reinforcement, and sintering, requiring a high degree of expertise and equipment. Further optimizing the manufacturing process to improve production efficiency and ensure product quality and consistency is an important challenge.

6.3. Thermal stress management

In a high temperature environment, carbon-carbon composites are subjected to large thermal expansion, resulting in the accumulation of thermal stress, which may cause material damage. Therefore, for the application of carbon-carbon composites in the aerospace field, it is necessary to reasonably design the structure and strengthen the thermal stress management to ensure the reliability and safety of the material.

7. Conclusion

This paper focuses on the application potential of carbon fiber reinforced carbon matrix composites in the aerospace industry. Analyzing their successful use in rocket shells, missile shells, aircraft wing structures, and satellite load structures highlights their outstanding properties, including lightweight design, high temperature resistance, mechanical strength, and oxidation resistance, making them highly promising for aerospace applications.

However, challenges persist. A major concern is the high production cost due to expensive carbon fiber and matrix preparation, leading to elevated manufacturing expenses. To facilitate broader application, future research should concentrate on finding more cost-effective manufacturing methods to reduce production costs.

Another significant challenge lies in the complex manufacturing process, which involves multiple steps and requires specialized expertise and equipment. To meet the demands of mass production in the aerospace field, optimizing the manufacturing process, streamlining procedures, and improving production efficiency and consistency become crucial research directions.

Additionally, in high-temperature environments, carbon-carbon composites experience thermal expansion, resulting in thermal stress accumulation that can affect material durability and reliability. To address this issue, suitable design and material engineering methods are essential to alleviate thermal stress and ensure material reliability in extreme conditions.

To overcome these challenges, future studies can focus on several aspects. First, enhancing the preparation technology of carbon fiber and carbon matrix to discover more cost-effective preparation methods is essential in reducing costs. Second, optimizing the manufacturing process, simplifying procedures, and improving production efficiency and consistency are key steps to enable large-scale aerospace production. Furthermore, conducting material engineering research to develop novel thermal stress management techniques will enhance the durability and reliability of carbon-carbon composites in high-temperature environments.

The paper predicts a continuous increase in the application of carbon-carbon composites in aerospace as manufacturing technology advances, leading to reduced production costs and enhanced material reliability through improved material performance evaluation and monitoring.

To enhance stability and applicability, future studies should prioritize research on enhancing the oxidation resistance of carbon-carbon composites. Interdisciplinary collaboration, including cooperation with chemistry, materials science, engineering, and other fields, will foster innovation and breakthroughs in the application of these composites in the aerospace industry. Such collaborative efforts are pivotal for advancing carbon-carbon composites in aerospace and driving the materials field towards new possibilities.

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