Review

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A Review of the Structural Characteristics of Aerospace Composites

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Aerospace composite materials' performance and application level are vital symbols for measuring the advancement and dependability of aerospace models, and they are the key materials enabling the development of aerospace models, which define the performance and success of models. This review summarizes recent significant research advances in the fields of thermal structure, heat protection, thermal wave transmission, heat insulation, and structural composite materials, and proposes new materials for extreme environments, reusable anti-thermal insulation materials, third-generation structural composite materials, and new materials for extreme environments. Low-cost and quick composite component manufacturing is an essential avenue for the future development of aerospace composite materials.

Keywords: Functional Composites; Structural Composites; Aerospace Applications; Materials; Temperature Resistance

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AEROSPACE composite materials serve as the foundation for aerospace models and are the industry leader in terms of technology. Their performance and quality level are crucial indicators of the development and dependability of aerospace models. Multiple material systems, including thermal structure, heat protection, wave penetration, heat insulation, and structure, are covered by aerospace composite materials. They are essential materials that assist the development of aeronautical models and determine the performance and success of models by serving in harsh conditions (1). Spacecraft of all kinds, including hypersonic vehicles, aerospace vehicles, and space missions, are currently developing quickly on a global scale. Key components aiding the development of the aforementioned spacecraft are aerospace composite materials. They are indispensable and play a crucial part in the overall functionality and mission realization of the spacecraft.

It is primarily seen in:

i. In order to dig out the material mechanics, physics, or chemistry performance limits, precise design constraints are necessary.
ii. The border of transdisciplinary, the change of material state features, and its performance under harsh use en-

vironments, involve several disciplines.

iii. Reliability, “a minor difference, a thousand miles away,” if the failure mechanism is complex and the safety factor of the materials is low.

iv. Independence is a necessity for the development of a strong aerospace nation, which calls for the achievement of system autonomy, industrial independence, and technological independence.

v. As the aerospace industry expands and becomes more diverse, the demand for materials that are both economically feasible and readily available is rising.

vi. Promoting the growth of fundamental industries as the chemical, metallurgical, and energy sectors Progress and development in fields like engineering thermophysics, mechanics, and physics.

In order to assess the current state of aerospace composite materials and lay the groundwork for its further advancement, this paper reviews the major research advancements made in functional composite materials over the past few years, including thermal structure, heat protection, heat transmission, and heat insulation, as well as resin-based structural composite materials.

Thermally Conductive Materials

The term “thermal structure” refers to a composite material structure that does not rely on a metal structure to support the load and simultaneously performs aerodynamic dimensionality and heat resistance functions. It primarily refers to the aerodynamic shell, end/leading edge, rudder/wing, combustion chamber, etc., and is typically used in aircraft (2). The service environment is a complicated thermal, mechanical, and chemical coupling environment with temperatures above 1,000 ℃ and primary stresses above 100 MPa. One of the key accomplishments of the space shuttle was realizing the safe return and reusability of the craft, which was made possible by the U.S. space shuttle’s development and utilization of the C/C nose cone, wing leading edge, and other thermal components (3). The study and use of ceramic-based thermal structural materials have advanced quickly thanks to the active development of hypersonic vehicles. In order to overcome the brittleness of conventional ceramics and obtain high temperature resistance, low density, high specific strength, high specific modulus, and ablation resistance, ceramic-based thermal structures use continuous fibers. The European Transitional Test Vehicle’s nose cone, windward cover, control rudder, etc. are all made of C/SiC thermal structural elements (4). The nose cone’s component size has grown to 1.4 meters. Additionally, Europe has undertaken study on the ablation properties of C/SiC under various situations, accumulating rich research findings that have paved the way for the continued use of C/SiC materials. Europe has recently conducted research on ceramic matrix composites that can withstand extremely high temperatures, manufactured 300 mm level plate and rudder specimens, and performed evaluation tests on oxygen-acetylene flame devices (5). Ceramic-based thermal structural materials are very customizable and based on the composition of the matrix and the structure of the reinforcement; it is possible to create thermal structural materials with a variety of architectures, components, and qualities.

The development of thermal structural materials is going in the direction of realizing low-cost and quick preparation of large thermal structural composite materials, developing ultra-high temperature (2,500 ℃) thermal structural composite materials, creating new parts and systems, and creating new types of thermal structural materials. The procedure for compounding and manufacturing thermal structural materials, as well as further study on how these materials interact with harsh environments, are all important for ensuring the success and development of thermal structural materials applications.

Heat-Resistant Substance Made of Resin

Heat-resistant materials made of resin are based on organic polymers. The quality of the material is sacrificed in a succession of chemical and physical processes like breakdown, melting, and sublimation in order to remove a significant quantity of aerodynamic heat and fulfill the goal of heat protection. The simplicity of the assembly process is still regarded as the most efficient, mature, and cost-effective form of thermal protection. Three series of glass/phenolic, high silicone/phenolic, and carbon/phenolic have been produced after years of development. As much as 90% of missile warheads in use today have elements that are heat resistant. It has vital special advantages and is also frequently employed in the system. Low-density heat-resistant materials are in high demand because to the requirement for space exploration (6). The SLA-561V honeycomb-reinforced low-density resin-based heat-resistant material, which was successfully developed by Lockheed Martin in the 1970s, has a maximum heat flux limit of 3 MW/m2. The phenolic impregnated carbon ablator (PICA), which was created by NASA Ames Research Center in the middle to late 1990s, was successfully used for the return capsule of the “Stardust” spacecraft and the heat protection of the Mars rover. SpaceX has created PICA-X, a heat-resistant material for Dragon spacecraft, based on PICA. After 2010, NASA concentrated on creating lightweight, heat-resistant materials with gradient structures and 3D hybrid fiber braids that are used to protect deep space probes from heat, and the technology maturity level has now reached level 6 (7, 8).

The primary characteristic of medium and low-density heat-resistant materials is the addition of light functional fillers, such as glass microspheres and ceramic powders, to the phenolic resin matrix. By varying the formula for the reinforcement and resin matrix, it is possible to produce heat-resistant materials that meet various heat-resistant requirements. The addition of hollow spheres and micropores can drastically lower the material’s heat conductivity while decreasing its density. The material density can be decreased by about 43% compared to classic dense glass/phenolic and quartz/phenolic heat-resistant composite materials, and the thermal conductivity at ambient temperature can be decreased to about 50% of conventional heat-resistant materials. The use of it for lunar orbit return vehicles has been successful for protecting against heat for vital components. In addition, a low-density, heat-resistant integrated composite material with a density range of 0.25-1.3 g/cm3 was created employing porous hybrid phenolic resin as the matrix and varying the reinforcement’s fiber structure. The internal structure of the composite material is typically modified to incorporate the micro-nano pore structure of the airgel material, which dramatically reduces the material's thermal conductivity and enhances its thermal insulation ability. The porous hybrid resin's mechanical, ablation, shear, oxidation, and mechanical characteristics are all improved by the inclusion of nano-functional components, which also further lower the material's thermal conductivity (9). The goal of the development of resin-based ablative heat-resistant materials is to achieve their lightweight, multifunctional compatibility and integration. They will also use the synergy of various thermal protection mechanisms to further enhance their heat-resistant insulation performance and service temperature.

Material with Low Ablative Heat Resistance

In general, aircraft terminals, leading edges, engine combustion chambers, and other elements are made of low-ablation heat-resistant materials. USA developed a variety of low-ablative carbon-based composite materials, such as C/Zr-Si-C, C/ZrC-C, and C/Zr-Hf-C, by breaking through the preparation method for refractory metal-doped C/C composite materials. The engineering-size combustion chamber components repeatedly passed the ignition test at 2,400 ℃/30 s during the 2,691 ℃/125 s condition test (10). The multi-component refractory metal modified material realized the transition from low-ablation carbon-based materials to micro-ablation or zero-ablation materials by achieving no evident ablation assessment on the surface of oxyacetylene at 2,015 ℃/240 s. C/HfC and C/HfB2 shown good temperature resistance and oxidation resistance during the oxyacetylene flame test of materials made using the PIP process (11). In the Horizon2020 initiative, several European research institutions collaborated to conduct studies on ultra-high temperature ceramic matrix composites appropriate for combustion chamber settings (12). Furthermore, ultra-high temperature-resistant HfC and TaC fibers were produced and the expansion of low-ablation material reinforcements from carbon fibers to ablation-resistant fibers was realized (13).

Continuous fiber and chopped fiber reinforced zirconium have been used in research on fabric reinforced ultra-high temperature ceramic matrix composites to further increase the content of ceramic components. A representative sample has completed the ground test and assessment based on the production and structure control of silicon-based composite materials, demonstrating strong temperature resistance and ablation resistance. The components made of low-ablation and heat-resistant materials were developed with the thermal environment of the new engine combustion chamber in mind, and they successfully completed ground and flight tests. Future service needs for harsh settings will call for low-ablation heat-resistant materials that can withstand higher service temperatures.

Material for Heat-Transparent Waves

The majority of airplane radomes are made of heat-transparent materials. Early high-temperature wave-transparent materials were primarily made of ceramics, such as glass-ceramics, quartz ceramics, and alumina, but these materials could not withstand the demands of high reliability in extremely hot environments. This led to the development of a second-generation thermal wave-transparent material with silicon oxide as the matrix and continuous fiber braid as reinforcement. The SiO2f/SiO2 composite material is the most advanced in the United States, whereas quartz fiber reinforced phosphate is mostly used in Russian precision guided missiles (14). The tensile strength of the material can reach 60 MPa, the bending strength can reach 150 MPa, and the short-term service temperature can exceed 2,000 ℃ of the surface temperature (15). The dielectric constant of quartz fiber reinforced silica-based composites is 2.8-3.3, the dielectric loss can be controlled at the order of 10-3, the high temperature dielectric properties are stable, and the bending strength can reach 60 MPa. Quartz fiber reinforced aluminum phosphate, chromium phosphate, and chromium aluminum phosphate composite materials are the primary types of phosphate composite materials, and the matrix has good thermal stability at 1,200, 1,200-1,500, and 1,500-1,800 ℃, respectively. The temperature resistance of the nitride system is greater than that of the quartz system. Utilizing the precursor impregnation pyrolysis technique, SRI in the United States has created a silicon nitride fiber reinforced nitride composite material. The material has a density of 2.85 g/cm3, a bending strength of 184 MPa at room temperature, a modulus of 102 GPa, and a strength of 191 MPa at 1,000 ℃. East Asia Fuel Company in Japan creates a composite material of Si3N4 and SiBN fibers that has a density of 2.36 g/cm3, a bending strength of 618 MPa at room temperature, and a bending strength of 546 MPa at 1,250 ℃. A composite material with a density of 1.85 g/cm3 was created by the American Emery Company using BN fiber, but the pertinent qualities have not been disclosed. Additionally, there has been a fair amount of study done on silicon nitride ceramics in other countries on high-temperature wave-transmitting materials. Israel has created a porous silicon nitride radome that not only has good dielectric qualities but also a high strength. Boeing has created a multi-frequency broadband silicon nitride radome employing reaction sintering technology, with a dielectric constant of 2.24-2.5 and a dielectric loss of 0.005 showing high, positive resistance to rain erosion (16).

A crucial technology of continuous silicon nitride fiber has been made with engineering preparation, achieved silicon nitride fiber mass production, and completed the design and preparation of reinforced ceramic composite materials based on continuous silicon nitride fiber and wave-transmitting performance research in order to meet the demand for high temperature and long-term heat-transparent waves in the future. The creation of heat-transparent materials with improved wave-transmission capabilities, increased resistance to high-temperature ablation, and stability of high-temperature dielectric properties will be crucial in the development of hypersonic vehicles in the future.

Effective Insulating Materials

Heat insulation materials are the most crucial barrier to prevent the passage of aerodynamic heat to the interior of the vehicle since hypersonic vehicles travel at high speed for a prolonged period of time in the thin environment. As a result, lightweight, low thermal conductivity, high temperature resistance, and high efficiency heat insulation materials are becoming more crucial. The first spacecraft to make extensive use of high-efficiency thermal insulation materials was the space shuttle. Specially designed heat insulation tiles and blankets are used on the leeward and windward sides of the structure, respectively. The maximum service temperature for heat insulation tiles from the LI (Lockheed Insulation), FRCI (Fibrous Refractory Composite Insulation), AETB (Alumina Enhanced Thermal Barrier), BRI (Boeing Reusable Insulation), and other series is 1,500 ℃; for thermal insulation blankets from the FRSI (Flexible Reusable Surface Insulation), AFRSI (Advanced Flexible Reusable Surface Insulation), and CRI (Conformal Reusable Insulation). They continue to be a key candidate material for the thermal protection system of numerous hypersonic, reusable, and spacecraft, including the X-37B, Dreamchaser, and Orion spacecraft (2). Study on the HTV-2, X-51A, and X-37B, three near-space vehicles that glide, cruise, and return, has advanced fast globally. This study not only influences the development of heat insulation tiles and blankets but also other technologies. The performance has increased, and as a result, the second generation of high-efficiency thermal insulation materials, represented by nano-thermal insulation materials, has been developed through research, development, and engineering application. SiO2 aerogels have found usage in large-area thermal insulation for hypersonic vehicles and power systems for Mars probes (17). The Parker Solar Probe was successfully launched in the United States in 2018. The maximum service temperature of this heat shield, which is formed of carbon foam reinforced carbon aerogel material, exceeds 2,000 ℃, which is a common application scenario for thermal insulation materials (18).

There are two types of thermal insulation tiles that operate at 1,200 and 1,500 ℃ and have successfully completed a type of flight test that demonstrates the material’s dependability. Launch vehicles and other types frequently employ thermal insulation blankets from the 600 and 1,000 ℃ series. Maximum service temperatures for carbon-based nano-insulation materials approach 2,000 ℃, while those for oxide nano-insulation materials reach 1,400 ℃. An important development path for high-efficiency heat insulation materials is the creation of lightweight, high-efficiency heat insulation materials with higher operating temperatures and integrated anti-heat insulation materials in order to meet future demand.

Composite Structural Materials

A rapid manufacturing cycle, high specific strength, high specific modulus, great design ability, superior seismic performance, and structural composite materials (materials based on resin) are all attributes of these materials. They are a key component in achieving the lightweight design of spacecraft and weapons (19). First, its use has grown to be a crucial gauge of how advanced a structure is. The first generation of structural composite materials uses T300 and T700 carbon fibers as reinforcements, the second generation of structural composite materials uses T800 grade carbon fibers as reinforcements, and the third generation of structural composite materials uses high strength, high modulus, and high toughness as characteristics. These generations are categorized according to the performance level of fiber reinforcements. The third generation of structural composite materials is now being bred and developed, following the development of aerospace structural composite materials for two generations. Launch vehicles including the Saturn 5, Ariane, Falcon 9, and Energy as well as missile armaments like the Trident-2, Tomahawk, Poplar, and Dwarf frequently employ structural composite materials. The degree of material development and engineering application is quite advanced, and materials like IM7, T800H, and other high-strength, medium-modulus carbon fiber reinforced second generation structural composite materials satisfy the requirements of medium and high temperature resistance (20).

In order to overcome the key technological barrier of polyimide structure design and engineering application resistant to 500 ℃, structural composite materials have formed the backbone material system represented by epoxy and Bima resin matrix, realizing the steady application of “large use at low temperature, small use at high temperature.” For the improvement of novel aircraft equipment materials, structural composite materials with high strength, high modulus, and high toughness are the foundation.

Conclusion and Perspective

It is critical to improve the current composite material system before creating a new generation of composite materials that can withstand harsher conditions and repeated use, working hard to create a third generation of resin-based composite materials, and increasing the effectiveness of composite materials as a whole. To achieve high reliability, low cost, and quick manufacturing, as well as to encourage the integration and development of material systems and manufacturing systems, aerospace composite materials’ automated manufacturing capabilities should be improved. Of course, further studies are needed to achieve the development and advancement of aerospace composite materials, coordinate the innovation chain, supply chain, industrial chain, and value chain of aerospace composite materials.■

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