Development status and prospect of aviation materials in China

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Abstract. Aviation materials are closely related to the development of aviation technology, also indirectly affect the air force. With the rapid development of advanced technologies, the achievements in aviation could well represent the strength of a country. In this paper, the characteristics, status and functions of aviation materials are respectively introduced and summarized in this paper, note that the representative aviation materials, i.e., structural materials (e.g., aluminum alloy, titanium alloy and advanced composite materials) and functional materials (e.g., wave-transmitting composite materials, and wave-absorbing stealth composite materials) are described in details with specific cases. Finally, the future development of aviation materials is analyzed and given.

Keywords: Aviation material; Structural material; Functional material; Aluminum alloy; Titanium alloy.

1. Introduction
The 20th century is a period when science technology experienced a rapid boost in development. One of the obvious symbols is the achievements made in aviation. In the 21st century, the aviation industry shows vast potential for future development, high-level or ultra-high-level aerospace activities are more frequent, the role of which will be far beyond the field of science and technology[1], and will have a broader and more profound effect on politics, economy, military, and even human society life.

All the achievements of the aviation industry lie in the development and breakthrough of the aviation material technology. Materials are the foundation of the modern advanced technologies and industries. In most cases, materials are also the pre-requisite for the breakthroughs of modern advanced technologies, e.g., the material breakthrough of high-purity silicon semiconductor in the 1960s leading to the information age[2]. The development of aviation materials plays a substantial role in supporting and guaranteeing aviation technology. In turn, the internal development demands of aviation technology significantly promote the development of aviation materials.

The aviation field had entered a new stage since the 21st century, which will promote aviation materials towards the directions of higher quality, more complete categories, stronger functions, and more economic effectiveness [3].
2. Status and function of aviation materials

Aviation materials are not only the foundation of aviation products, but they are also the basis for the expected technical performance, service life, and working reliability of aviation products. Aerospace and aviation materials generally refer to the materials used to produce the aircraft and the spacecraft[4]. For example, targeting a modern plane, metallic materials, inorganic non-metallic materials, organic polymer materials, and inorganic non-metallic materials are four types of used materials. In addition, materials can be classified into structural materials and functional materials in terms of the applicable performance[5].

The structural materials are mainly used for the structural parts/components of an aircraft, e.g., fuselages, bearing tubes, and engine vessels, which are primarily to withstand various loads, including the static loads caused by its weight and various dynamic loads generated in flight[6]. On the other hand, the functional materials mainly refer to materials with specialized functions in the perspectives of light, sound, electricity, magnetism, and heat, such as, the electronic information materials in the measurement and control systems of an aircraft (i.e., the functional materials of microelectronics, optoelectronics, and sensing devices), wave-transmitting and absorbing materials for modern aircraft stealth, and the thermal protection material on the surface of the spacecraft, etc.

The general development trends of the structural materials are lightweight, high strength, high modulus, high temperature resistance, and low cost. And the functional materials are developing in the direction of high performance, multi-function, vest varieties and vest specifications. Based on the development need of the modern high-performance aircraft, structure-function integration and intelligence give an important direction for material development.

Besides, development and achievement in aviation technologies play a decisive role in aviation materials. Meanwhile, the development of material science and engineering, the emergence of new materials, and the progress on manufacture and testing have provided essential materials and technologies for the development and design of new aviation products. Thus, it effectively promotes the development of the aviation industry[7].

In conclusion, aviation materials and their manufacturing-process technology are one of the three key technologies in the aviation field, an important branch of creativity and pioneering in the material science field, and the basis for aviation modernization and high-tech development. Aviation materials are the basis for technical performance, survivability, life extension, and economic affordability of aviation products, and are critical technologies for prioritized development and crucial breakthroughs. And the level of research, development, and application of aviation materials also reflects the comprehensive strength and technological level of a country.

3. Aviation structural materials

The reasonable selection of materials directly affects the working performance, design progress, production feasibility and reliability for an aircraft, and directly leads to the structural-efficiency improvement, weight reduction, thrust-to-weight ratio increase, maneuverability, and load-capacity improvement for a plane[8]. Currently, the aviation structural materials mainly contain aluminum alloy, titanium alloy, and advanced composite materials.

3.1. Aluminum alloys

The aluminum alloy has outstanding advantages, such as high specific modulus and specific strength, high corrosion resistance, good processing performance, and low cost, which is mainly used in engine compartments, cabin structures, bearing wall panels, beams, instrument installation frames, fuel tanks. Thus, aluminum alloys are considered to play a vital role in the aerospace industry.
Many researches have been carried out on the manufacturing methods, processing techniques, service performance of aluminum alloys for aerospace. As a result, the material products have been serialized, and a series of remarkable results have been achieved in the application. Since the late 1980s, with the gradual formation of aircraft damage tolerance and durability design criteria, high requirements, e.g., the strength, fracture toughness, corrosion resistance, and fatigue resistance, have been put forward for the aluminum alloy[9].

The development direction of aluminum alloys is to develop thick plates with low internal stress to realize the integral structural parts which can replace assembled components. The widely used large-scale integral siding structures made the new generation aircraft to achieve higher structural efficiency, reduce the number of parts, reduce costs, and shorten the development cycle. For example, after Boeing 747 adapted integral ribbed panels, the number of parts is reduced from 129 to 7, and the cost is reduced by 25%, while the crack propagation life and residual strength are both increased by three times. In short, due to the advantages of aluminum alloy[10], e.g., mature technology, low cost, and rich experience in use, the aluminum alloy will remain one of the primary structural materials for subsonic aircraft and low-supersonic aircraft.

### 3.2. Titanium alloys

The titanium alloy is an essential new structural material developed in the 1950s, and it has high strength, good corrosion resistance, excellent fatigue resistance, low thermal conductivity and linear expansion coefficient compared with aluminum, magnesium, and steel. And it can be used in a wide temperature range, from -196°C to 450°C[11]. Note that it is often used in compressor blades, casings, engine compartments, and heat shields of aero engines.

In the 1950s, the United States used titanium alloys for the first time on F-84 bombers as non-load-bearing components, such as rear fuselage heat shields, wind def deflectors, and tail covers. Beginning in the 1960s, the amount of titanium alloy used in military aircraft has increased rapidly, accounting for 20% to 25% of the weight of the whole structure. The scope of the part moved from the rear fuselage to the middle fuselage, and partially replacing important load-bearing components such as bulkheads, beams, and flap slides made of structural steel. Since the 1970s, civil aircraft have also begun to use titanium alloys in large quantities. For instance, the amount of titanium alloy used in Boeing B747 passenger aircraft has reached more than 3640 Kg. For the airplanes with Mach numbers less than 2.5, titanium alloys are used instead of steel, which can reduce structural weight. E.g., the US SR-71 high-altitude and high-speed reconnaissance aircraft (i.e., the Mach number of 3, the flying height of 26212
m), titanium alloy accounts for 93% of the weight of the whole aircraft structure, which is known as the all titanium plane[12].

In the 1970s, titanium alloys were mainly used in the manufacture of compressor parts in aero engines, such as fans, compressor discs and blades, compressor casings, and bearing housings, etc. It weighs about 20%-30% of the whole structure. When the thrust-to-weight ratio of the aero-engine increased from 4-6 to 8-10, and the compressor outlet temperature rises from 200-300°C to 500-600°C, the original low-pressure compressor discs and blades made of aluminum alloy must be replaced by titanium alloy, or the high-pressure compressor disk and blade made of titanium alloy must be replaced by stainless steel to reduce the structural weight. Because of high specific strength, good corrosion resistance, and low-temperature resistance, the titanium alloy is mainly used as pressure vessels, fuel tanks, fasteners, instrument straps, frames, and rocket casings[13]. And it is also applied in earth satellites, lunar modules, manned spacecraft, and aerospace aircraft.

The current development trends for titanium alloys are multi-purpose and multi-variety. To meet the development of high thrust-to-weight ratio engines, the research on high temperature[14], high strength alloys and other functional alloys has been carried out, such as high temperature titanium alloy and titanium-aluminum intermetallic compound (up to 982°C), high-strength titanium alloy (tensile strength more than 1000 MPa), flame retardant titanium alloy utilized to solve the burning titanium issues with engines.

3.3. Advanced composite materials

Now days, with the continues improvement of the working performance of aero-engines, the weight of the aero-engine has been dramatically reduced compared to the past. While relying on new structures, e.g., integral blade disks, integral blade rings, hollow blades, and counter-rotating turbines, advanced materials with high specific strength, low density, high rigidity, and high temperature resistance will attract attention[15]. Although traditional aero-engines material, e.g., nickel alloys and titanium alloys, can still be developed further, it is difficult to achieve the more demanding temperature and weight requirements of future aero-engines.

Note that metal matrix composite materials, ceramic matrix composite materials and C/C composite materials have become candidates for essential parts/components of aerospace products due to their excellent low-temperature performance[16].

(1) Metal matrix composite materials

In recent years, significant progress has been made in composite materials based on aluminum, titanium, and intermetallic compounds, e.g., SiC fiber-reinforced Ti, Ti₃Al, TiAl and MoSi₂-based composite materials. The high melting point intermetallic compound Nb₅Si or Nb₅Si₃ is added to the Nb alloy to form an Nb-Si self-generated composite material. Its working temperature is 200 °C higher than that of a single crystal, and its density is 25% lower than that of the third-generation single crystal. It is also an application prospect of metal matrix composites.

(2) Ceramic matrix composite materials

At present, the main ceramic matrix composite material products are SiC or C fiber reinforced SiC and Si₃N₄ matrix composite materials, which are used to produce static parts, such as afterburner, combustion chamber tiles, nozzles, and flame stabilizers to replace high-temperature alloys. The toughened Si₃N₄, SiCF/ SiC and CF/ SiC composite materials can be resistant to temperatures of 1350 °C, 1450 °C and 1650 ºC, respectively. At present, a variety of all-ceramic simulation parts have been made and are undergoing test evaluation.

(3) C/ C composite materials

C/C composite materials have the advantages of density less than 2g/cm3, temperature resistance higher than 2,000 °C, high strength, high modulus, high thermal conductivity, low expansion rate, excellent creep resistance and thermal shock resistance, and it is successfully used in areas such as rocket engine nozzle throat lining, insulation tiles, and aircraft brake blocks[17]. However, note that the main disadvantage of this type of materials is weak oxidation resistance. Hence, the development of a
new series of coatings will be a key technology for the application of C/C composite materials to high-thrust engines.

In short, since advanced composite materials have a much higher specific strength, specific modulus and fatigue resistance compared to steel, aluminum and titanium, they will play an increasingly important role in high-performance aircraft structural materials in the future, and it is even possible to have an aircraft with a fully composite structure.

4. Aviation functional materials
The Gulf War in the 1990s was a major review of new aviation materials. In particular, the combination of absorbing materials and stealth structure design achieved stealth technology, it greatly improved the aircraft’s penetration capability. In some aspects, modern military aircraft have entered the era of stealth, and aviation materials play a vital role in improving the performance of military fighters[18]. Aviation functional materials mainly include microelectronic and optoelectronic materials for airborne equipment, piezoelectric sensitive element materials, wave-transmitting materials, wave-absorbing materials, infrared-sensitive materials, laser crystals, and low-expansion glass-ceramics. This article will mainly discuss about wave-transmitting composite material and wave-absorbing stealth composite material.

4.1. Transparent composite material
Transparent composite material is a type of material composed of a low dielectric material permeable to electromagnetic waves and a matrix. It is also a type of material that integrates structure and function[19]. The wave-transmitting composite material has high comprehensive properties, including excellent dielectric properties, good heat resistance, environmental adaptability, and high mechanical strength. It is widely used in various types of aircraft radars, missiles, satellite rodomels and antennas windows.

Transmitting composite materials require the resin matrix to have low tangent loss and high strength, modulus, toughness, and environmental resistance. The use of phenolic resins, epoxy resins, and unsaturated resins in early years makes it difficult to make significant progress in the study of reducing losses due to the limitations of the resin molecular structure and formulation. Thermoplastic resin matrix has excellent mechanical properties, wear resistance, dimensional stability, electrical properties, and heat resistance. The disadvantage is that it is difficult to process and is suitable for manufacturing small-sized, large-scale comrades.

In short, the performance of the wave-transmitting composite material is determined by two aspects: the reinforcing fiber and the resin matrix. In general, the mechanical properties and dielectric properties of the reinforced material are better than the resin matrix. Therefore, the properties of resin matrix have more decisive significance in the permeability of composite materials. However, electrical properties are not the only consideration when choosing a resin matrix. Because the resin must also act as an adhesive in the composite material, this also determines the basic function of the composite material in terms of heat resistance. With the high speed development of aerospace flight technology and radio communication technology, composite materials must not only have excellent dielectric properties, sufficient mechanical strength, appropriate elastic modulus and good corrosion resistance, but also must have a certain degree of temperature resistance, which can better meet the current application level for wave-transmitting composite materials in many aspects.

4.2. Absorbing stealth composite material
The absorbing stealth material is the most representative composite material with integrated structure and function now days. The structure shape is special, the degree of integration is high, and the requirements from design to material molding are different from those of general composite materials. Integrating a variety of modern high-tech into one, absorbing stealth composite material represents the current development level of composite materials. Among them, ferrite, metal powder, barium titanate, silicon carbide, graphite, conductive fiber are all traditional absorbing materials, and they usually have disadvantages such as narrow absorption band and high density. New absorbing materials include
nanomaterials, metal fiber materials, chiral materials, conductive polymers, and circuit analog absorbing materials. They have new absorbing mechanisms different from traditional absorbing materials. The shape structure design and the use of stealth materials are two main ways that can achieve stealth for aircrafts[20]. But this paper does not focus on the shape structure design. At present, the remote sensing equipment for detecting aircraft mainly includes radar, infrared, optical and acoustic detection systems. Therefore, stealth technology can also be divided into radar stealth, infrared stealth, visible light stealth, and acoustic stealth. Since radar detection accounts for more than 60%, the focus of aircraft stealth is radar stealth. This function is mainly constructed by using absorbing materials. Therefore, radar absorbing materials can be divided into two categories, one is resonance type and the other is broadband type. Resonant radar absorbing materials are designed for a certain frequency, based on magnetic materials, which can combine destructive interference and attenuation. Broadband radar absorbing materials are usually made by adding carbon-energy-consuming plastic materials to a matrix such as polyurethane foam, which maintains effectiveness in a wide frequency range. The radar absorbing material is combined with a rigid material through which radar energy can pass to form a radar absorbing structural material. It is also one of the confidential absorbing materials. Using the latest materials, the energy reflected by the stealth aircraft on the radar can almost be the same as the reflected energy of a sparrow. It is very difficult to distinguish the stealth aircraft only through radar.

5. Development trend and prospects of aviation material technology

5.1. Development trend of aviation material technology
Develop and apply new types of aircraft and engines with high specific strength, high specific rigidity metals, non-metals, composite materials and materials with excellent comprehensive performance could further improve the stealth performance of the aircraft and the thrust-to-weight ratio of the engine[21]; extend the service life; promote the development and application of new aluminum alloys, titanium alloys, and composite materials; increase its weight ratio; reduce the structural weight coefficient of aircraft, engines, airborne equipment and weaponry.

Develop and apply key materials required for important components such as high thrust-to-weight ratio engine fans, compressors, turbines, and combustion chambers, including high-temperature titanium alloys, powder discs, single crystal blade materials, etc., to improve the temperature and thrust-to-weight ratio of the engine terbinafine-compounds, metal, epoxy, ceramic-based high-temperature composite materials and C/C composite materials, etc.[22], to further increase the turbine inlet temperature; gradually research and develop new materials and preparations that can meet the higher thrust-to-weight ratio engines technology.

Develop and apply new functional materials to improve the performance of airborne equipment and missiles. Focus on the development of infrared materials, laser crystals, functional ceramics, piezoelectric materials, antireflection films and other materials, as well as stealth materials and coating materials for high thrust ratio engines such as heat insulation, oxidation resistance, sealing, and wear resistance[23]. Carry out the research on damping, vibration reduction and noise reduction, bullet-proof armor, sealing, insulation, shape memory, conductive polymer materials, high and low temperature resistant rubber, and tracking the world's advanced level of smart materials and high temperature superconducting materials[24].

Enhance the application of new materials and basic research on application technology; continuously improve the reliability and life of aviation products with special attention to the life research under a comprehensive environment.

5.2. Development prospects of aviation material technology
Titanium alloys are widely used because of their high specific strength, good corrosion resistance, and excellent heat resistance. The usage of titanium alloys in plane and engine indicated the advancement of the technology[25], while the amount of titanium used in aviation in China is very different compared
to foreign countries, so further increasing the dosage and catching up with the international advanced level is one of the main goals of the research on titanium alloys in China.

Aluminum alloy has the characteristics of light weight, easy processing, high durability, and wide application range. It is mainly used as the internal frame, reinforcing ribs, webs, joints and some skins and other structures. Its weight accounts for 50% of the front fuselage, 35% of the middle fuselage, 22% of the rear fuselage, and 23% of the center wing [26]. Therefore, aluminum alloys need to be developed and researched in response to the requirements of the development of aircraft weight.

Ultra-high-strength steel is mainly used in important load-bearing parts, such as landing gear, spars, load-bearing bolts. In order to make the life of the landing gear reach the same lifespan as the body, the need for ultra-high-strength steel with higher strength and better toughness is urgent.

Composite materials can solve the compatibility problem of various material properties, so the amount of composite materials in the body needs to be increased.

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