Research Status and Prospects of Materials for Aero-engines in China

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Abstract. Aero-engine, a highly complex and precise thermal machinery, is the engine that provides the aircraft with the necessary power for flight. As the heart of aircraft, it directly affects the performance, reliability, and economy of the aircraft, and it is also an essential embodiment of a country's scientific, technological, industrial, and national defense strength. Thus, this paper compares the material, structure, and process characteristics of China's aero-engines and the development process and research status of high-temperature alloys in the field of aero-engines. Finally, some prospects are put forward for the development of aero-engine materials.

Key words: Aero-engine; Aircraft; Superalloy material; High-temperature alloy

1. Introduction
The development of aviation industry is mainly reflected in whether the design, manufacturing technology and production technology of aero-engine have reached an advanced level, whether the advanced aero-engine can be produced, which reflects the scientific and technological level of a country, military strength and comprehensive national strength, and that the modern advanced aero-engines must meet the requirements of ultra-high-speed, large lift, long voyage time and long voyage [1]. Thrust is bound to increase, and the temperature of the combustion chamber will increase. The performance and reliability of the aero-engine mainly depend on whether its components can effectively withstand thermal shock, high temperature corrosion and change, as well as complex stress. To achieve the purpose of high working reliability, the components of the aero-engine are most made from high temperature alloys [2]. Thus, this paper mainly introduces the manufacturing materials, internal structure and manufacturing characteristics of the modern advanced aero-engines, and the research development and application status of superalloys in aero-industry. Based on the recent development of domestic aero-engines, some suggestions on the development of advanced materials for aero-engines in China are put forward.

2. Basic configuration and related information of aero-engine

2.1. Basic configuration of the aero-engine
All the aero-engines have the similar basic configuration, which consists of a fan, compressor, combustor, turbine, and a nozzle, as shown in Figure 1. The design of the aero-engine is based on one principle-thrust that is a forward force generating by the aero-engine to push the aircraft forward.
Fundamentally, the engine sucks in the air with a gigantic fan which speeds up the air and splits it into two parts [1]. Then, the compressor made up with numerous blades attached to the center shaft increases the pressure of the air. High speed spinning blades compress and squeeze the air into the combustor where fuel and compressed hot air are mixed up and ignited. Later, the high energy flow from the combustor is sent to the turbine, causing the turbine to rotate. The rotation takes some energy from the high energy flow. At nozzle, the cold and hot mixed air are expelled then produce an exhaust that forms the thrust to push the aircraft forward.

2.2. Characteristics of commonly used materials

Recent material technology has improved the performance and efficiency of the aero-engines. And Figure 2 is shown that the drop in the fuel consumption rate concerning the improvement and advancement of new types of turbo engines. To improve the efficiency of the aero-engines, weight reduction is necessary for the aero-engine with higher efficiency, which could decrease the fuel consumption drastically. To achieve the low weight, the materials of the aero-engine in each section are carefully selected. All the materials on the aero-engines must be durable and lightweight, which means that the properties of those materials will have low density, high heat resistance, high ductility, high strength, and working performance. Thus, this paper will describe the commonly used materials of aero-engines.
2.3. Material processing performance
As known, the high temperature titanium alloy and other superalloy materials have high thermal hardness, thermal strength, and dynamic shear strength, which are widely used in the main high temperature parts/components of the aero-engine. Note that they belong to difficult-cut-materials. Thus, it is easy to cause severe wear and tear between cutting tools and workpieces in the machining process, which lead to significantly reduce the machining quality and integrity of the workpiece surfaces [3, 4]. In order to guarantee the working parts of aero-engine, the performance and safety of components, whose core rotor parts are usually machined by integral forging blanks, lead to the material removal rate of more than 90%. Therefore, the modern aviation industry is committed to improving the machining accuracy and surface integrity of the aero-engine parts/components in the process of machining.

2.4. Internal structure
Due to lightweight constructions are designed and applied in the modern aero-engines to increase its work efficiency, their parts/components are generally designed for complex curved surfaces and high-efficiency structural integrity [5,6]. Therefore, the manufacturing process of aero-engine components requires more advanced manufacturing technologies and manufacturing equipment. The internal structure is particularly complicated, and the machined parts are challenging to achieve the production requirements via the existing manufacturing technologies and equipment. Therefore, for the complicated part construction, the advanced manufacturing techniques should be actively studied on the current basis to address complexity. And the manufacturing level of aviation components and effective control of production costs.

2.5. Machining accuracy
The working performance and operational safety of aero-engines depend on the accuracy of their components. Therefore, the manufacture of aero-engine parts/components requires extremely high machining accuracy. Due to the difficulty in machining materials for aero-engines, the internal structure is complex, and the current machining processes cannot meet its high production requirements. The requirements for precision manufacturing have led to poor consistency of parts/components of domestic aviation engines, low qualification rates, and the backwardness of manufacturing technologies have greatly hindered the development of advanced aviation engines in China.

To ensure the thrust ratio, weight ratio and working reliability of the advanced aero-engines, many high-temperature alloys are commonly adopted in its production process. The internal structure is complex, and the precision of parts processing is very demanding [5]. Therefore, the production of aero-engine requires more advanced manufacturing processes and equipment. To improve the working performance of the new generation aero-engines, the lightweight construction, advanced manufacturing technology and manufacturing materials is a key.

3. Materials of Fan
Most of the intake is the fan section where the air is initially taken into the engine. The large spinning fan will suck into a huge number of airs; then it speeds up the air and separate the air into two parts. Most of the blades are made of light and high-strength materials in case of the distortion and deformation of the blades caused by objects in air. High strength would prevent the blades from being subject to distortion.

3.1. Fan Blades
Usually, fan blades are made of titanium or aluminum because of their properties like light-weight, corrosion resistance, and ductility, etc. For aluminum is a very light metal that its specific weight is only 2.7 g/cm3 [6]. Compared to Aluminum, Titanium has a slightly higher specific weight of 4.5 g/cm3. However, titanium has a higher combination of high strength, stiffness, and toughness. The low density of titanium attributes its light-weight. Properties of high boiling and melting points, high corrosion
resistance, and high tensile strength make it a perfect material for fan blades of aero-engine since fan blades of aero-engine are easily exposed to high heat, moist, and collision.

3.2. Fan Casings

Large fans drawing air into the compressor rapidly in a short time, so it is easy for fan blades to spin off or break, damaging other crucial parts of the aero-engine. In this case, a protector is required to prevent the damage, which is called the fan casings. Therefore, fan casings must be strong enough to contain the blade; also, they need to be tough enough to withstand the punishment of the broke blade projectiles. Weight reduction is still one of the significant factors being considered by researchers [7].

Normally, materials like titanium or titanium alloys are used to make fan casings because of its high strength, light-weight, and high corrosion resistance. Nowadays, researchers from NASA are trying to find the alternative to aluminum and titanium in pursuit of better weight reduction and performance of the aircraft. One company called A&P Technology. Inc now is promoting to use triaxial carbon braided fan containment cases as the fan casings to protect the blades, as shown in Figure 3.

![Triaxial carbon braided material](image)

The advantage of the triaxial carbon braided material is that it is tougher than those aluminum and titanium cases because the efficient distribution of the load makes braided structures impact resistant. Moreover, the braid absorbs a great amount of energy since the fibers in the structure participate the loading event [2]. Furthermore, the manufacturing process for the braided carbon is more low-cost and repeatable.

4. Materials of Compressor

The role of a compressor is to increase the pressure of incoming air before it enters the combustor chamber. Also, the compressor is one of the core sections of aero-engine where the pressure can be raised to 30 times, and the temperature can rise to 1000 °C, which means the materials used to make compressor must have high strength and high heat resistance, e.g., Nickel-, cobalt-, or iron-based alloys. Sometimes aluminum, titanium, and chromium are preferable because of their high strength, light weight, and high corrosion resistance.

One of the alternatives to those traditional materials used to make compressors is titanium alloys. Titanium alloys are preferable because of its high strength-to-density ratio. Titanium alloy can help increase the thermal efficiency of the aero-engine with its high temperature capability, which would help reduce the emission of CO2 and fuel consumption [3]. Titanium matrix composites and titanium aluminides are introduced to future application in high - pressure compressors.
5. Combustor Chamber
The combustor chamber is where air mixed with fuel and ignited, and the mixture of air and fuel are ignited, which provides high temperature, and high energy flow to propel the aircraft. The heat inside the combustor chamber can reach to 2700 °C. Therefore, high heat-resistant materials are required in this section.

6. Development of superalloy in aero-engine field
The research and development of superalloys in China began in 1956. Under the guidance of experts from the former Soviet Union, China produced superalloys GH3030. After 1960, experts from the former Soviet Union withdrew from China. Many new superalloys are needed to be independently developed to meet the working performance requirements for the Chinese aero-engines. Therefore, China has successively established superalloy production plants and research bases. They are equipped with complete production, testing and scientific research instruments and equipment [8].

In 1964, when the WP-7 engine is developed, China produced a low-density, high-strength nickel-base cast superalloy K417 to meet the demand for a 100 °C increase in temperature before the turbine, and in the next 30 years, it used the superalloy to produce a total of 410,000. The hollow cast turbine blades are equipped with WP-6, WP-7 aircraft engines. These engines have not experienced major accidents during their service, which proves the reliability of the K417. From the early 1970s to the early 1990s, in the process of developing new superalloys to equip WS-9, WZ-6, WZ-8 engines. China introduced a series of advanced superalloys and manufacturing technologies from the developed countries and independently produced them according to international technical standards, which greatly improved the comprehensive properties of materials. In this process, China's production technology has made significant progress, and at the same time established and improved the high temperature combination. Gold quality management system, and successfully developed a series of high-performance wrought alloys, casting alloys, directional solidification, and single-crystal alloys [9, 10].

From the early 1990s to the beginning of the 21st century, China's various types of military aircraft engines were facing replacement. The third-generation fighters and a specific type of drone development project were launched, and various advanced aero-engine researches and development projects were put on the agenda. Therefore, China has developed several new high-temperature materials that meet the above aero-engine performance requirements [11]. The oxide dispersion strengthened superalloys MGH4754 and FGH2756 were developed by mechanical alloying process technology. The first- and second-generation single crystal superalloy (e.g., DD3 [12], DD402, DD408 and DD406 [13]), new directionally solidified cylindrical alloy (e.g., DZ4125, DZ4125L, DZ604M, DZ417G), the low expansion coefficient alloy (e.g., GH2907, GH2909 [14]) and the heat corrosion-resistant high chromium alloy (e.g., GH466 ) was developed. At this stage, GH22, GH418, GH411, GH605GH and other superalloys [14-18] were served in the manufacture of turbofan engines. Thus, looking back on the development history of superalloys in China, it can be concluded that the performance-requirement improvement of the aero-engine promotes the development of new superalloys.

7. Application status of high temperature alloys in aero-engine field
Since the beginning of the 21st century, to cope with the complex international environment and strengthen national defense construction [19-21], China's aviation industry has developed a series of new aircraft, including the fourth-generation fighter aircraft project, carrier-based aircraft project, new generation long-range strategic bomber project, general medium helicopter project and large military transport aircraft project, in order to self-produce the aircraft mentioned above and break the restriction of imported engines, China has also developed many advanced aero-engines [22, 23]. To meet the requirements of advanced aero-engines, the temperature of the combustion chamber has further increased, and the components manufactured by existing superalloys cannot meet the performance requirements of advanced aero-engines. Therefore, the development of new superalloys is one of the keys to the advanced aero-engine in China.
8. Conclusion

China's superalloy industry is currently in a stage of rapid development. High-temperature alloys are widely used in military or civilian industrial fields, especially in the aerospace industry. However, there is still a big gap in the working performance of Chinese aero-engines compared with the developed countries. By studying the development trend of aero-engines, the high-temperature alloys must be oriented toward low-cost, high strength, high-heat resistant, low-density development. Thus, the recommendations of the research development can be drawn as follows.

Based on the existing technology, the load-carrying capacity of high-temperature alloys should be continued to improve at various temperatures, and the working life of the alloy should be further extended, and the investment of the scientific research in the field of superalloys should be further increased to develop new excellent superalloys. Critical performances, such as the surface's ability to withstand high temperatures, should be improved so that the superalloy materials can be served more critical industrial fields.

The development of low-density single-crystal superalloys has great centrifugal force when the aero-engines work on the moving blades. Therefore, low-density alloys can help to improve its working performance. Thus, more advanced manufacturing techniques and equipment should be developed and introduced to reduce the production cost and increase the production quality of superalloy materials.

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