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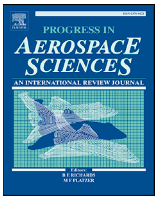

Recent advances in the development of aerospace materials

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ABSTRACT

In recent years, much progress has been made on the development of aerospace materials for structural and engine applications. Alloys, such as Al-based alloys, Mg-based alloys, Ti-based alloys, and Ni-based alloys, are developed for aerospace industry with outstanding advantages. Composite materials, the innovative materials, are taking more and more important roles in aircrafts. However, recent aerospace materials still face some major challenges, such as insufficient mechanical properties, fretting wear, stress corrosion cracking, and corrosion. Consequently, extensive studies have been conducted to develop the next generation aerospace materials with superior mechanical performance and corrosion resistance to achieve improvements in both performance and life cycle cost. This review focuses on the following topics: (1) materials requirements in design of aircraft structures and engines, (2) recent advances in the development of aerospace materials, (3) challenges faced by recent aerospace materials, and (4) future trends in aerospace materials.

1. Introduction

The rapid growth in the aerospace industry gives an impetus for the fast development of new aircraft materials. The main driving force is cost reduction through weight reduction and service life extension of aircraft parts/structures. Light weight design of aircraft frames and engines design with materials of improved mechanical properties can improve fuel efficiency, increase payload, and increase flight range, which directly reduce the aircraft operating cost [1]. Therefore, many researches have been devoted to developing materials with optimized properties to reduce weight, improve damage tolerance, fatigue and corrosion resistance [1].

The development of aircraft materials can be traced back to the first day of flight in the year of 1903 when the airframe was a wooden structure. After the year of 1927, Al-based alloys achieved the dominant position in aircraft materials with the development of cladding and anodizing technologies [2]. Al-based alloys are dominant in aerospace materials over 80 years [1]. However, this situation has been changed in recent few years. Fig. 1 shows the total materials used in Boeing series aircraft. Al-based alloys tend to decrease, and composites have experienced a rapid increase in the total materials in the latest Boeing models.

The attractiveness of light-weight alloys in the manufacturing of high-performance aircraft parts relies on their high specific properties (property/density), damage tolerance, corrosion resistance, and high-temperature resistance. The typical yield strength and elongation of some metal alloys are summarized in Fig. 2. The density of aluminum is one-third that of steel [4], while the yield strength (YS) of Al-based alloys, such as 7075-T6, can reach up to 520 MPa [1]. The density of magnesium is only two-thirds that of aluminum and a quarter of steel, while the tensile strength of Mg-based alloy ($Mg_{97}Zn_1Y_2$) can reach up to 610 MPa [5]. In addition, Mg-based alloys possess exceptional stiffness, and damping capability. Such high specific properties of Mg-based alloys enable aircraft to further reduce weight and increase payload [5,6]. Ti-based alloys, such as Ti-6Al-4V alloy, B120VCA alloy, and Ti-10V-2Fe-3Al, possess lower density, higher strength than high strength steels at high-temperature. The F-22 fighter aircraft employed Ti-10V-2Fe-3Al alloy at 1240 MPa tensile strength for arrestor hook structures [7]. The increasing use of composite materials in the aerospace industry is mainly due to their higher specific strength and better corrosion and fatigue resistance than most metals [1]. For example, the minimum yield strength of carbon fiber reinforced polymer (CFRP) is 550 MPa, while the density of CFRP is only one-fifth that of steel and three-fifths of Al-based alloys [8]. Moreover, composite materials, such as ceramic matrix composites, have been proven to withstand high operating temperature of 1400 °C [9], which can satisfy the increasing demand for aircraft speed. Ni-based superalloys have excellent

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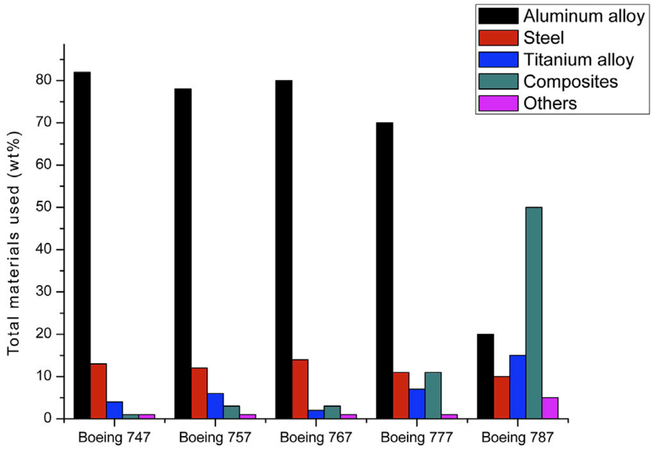

Fig. 1. Total materials used in Boeing series aircraft [1,3].

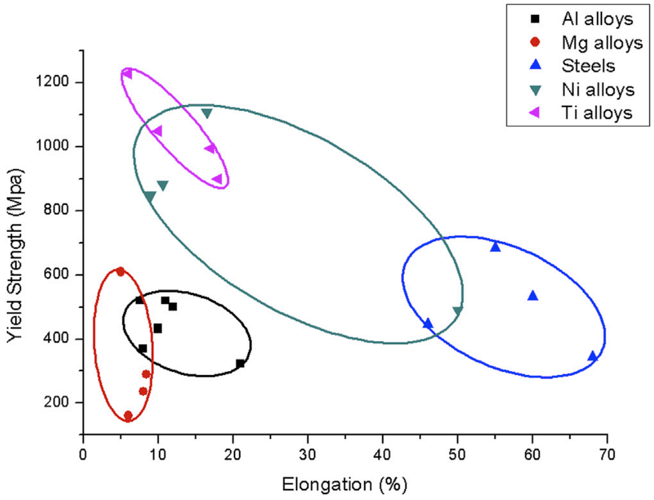

Fig. 2. Typical yield strength and elongation of some metal alloys. Al alloys include 2024-T351, 2324-T39, 7050-T73651, 7075-T651, 7475-T7351, 2099, and 2199 [1]; Mg alloys include $Mg_{97}Zn_1Y_2$, AZ91, Zk60, and WE43 [5]; Ti alloys include Ti-5Al5V5Mo3Cr and Ti-6-4 [12], Ti-10V2Fe3Al [13], and Ti-600 [14]; Ni alloys include Ni-15.6Cr10·6Co5·5W [15], alloy 625 [16], CM-247LC [17], and wrought In718 [18]; Steels include AISI 316L, AISI 321, AISI 304, and AISI 347 [19].

mechanical properties than conventional stainless steel at high temperatures such as 700 °C. For instance, the yield strength of wrought Ni-Cr-W superalloys can reach up to 300 MPa at 700 °C, which is 2–3 times more than the strength of stainless steel at 700 °C [10,11].

Although aerospace materials have made great advancements, they still face major challenges. The applications of aerospace materials are still limited by the insufficient mechanical properties such as strength, which is not high enough to meet the increasing demand. Moreover, fretting wear accelerates the fatigue failure of components to cause crack initiation sites on the material surface. However, the general theory that identifies fretting behavior and the prevention of fretting is still unclear yet [20]. Furthermore, corrosion problems also inhibit the use of aerospace materials and have caused a loss of $276 billion per year in the US, which is much greater than the loss caused by natural disasters [21]. This paper aims to review the recent advances of major aircraft materials, as well as to provide a picture of current challenges and future trends.

2. The design criteria of the aerospace materials

The material property requirements for aerospace materials vary with the particular component under consideration. Materials selection for an aircraft design depend on the design requirements of each component, including loading conditions, manufacturability, geometric limits, environmental aspects, and maintainability [21].

2.1. The design criteria of the airframe materials

Airframe materials are designed to provide long-term (60000 flight hours) support for both the static weight of aircraft and additional load subjected from service [1]. This concept requires airframe materials to possess acceptable densities for the weight reduction and appropriate mechanical properties for the intended use. It also requires materials to provide suitable damage tolerance for the purpose of long-term use in extreme temperature conditions (-30-370 °C), moisture (both extreme humidity and desert environment), and ultra-violet radiation [22]. Different applications have their specific design and selection criteria of airframe materials. For example, the wing is subjected to bending during flight to support the static weight of the aircraft and dynamic loads due to maneuvering or turbulence. It is also subjected to additional loads from the landing gear, the leading edge slats, and the trailing edge flaps during taxiing, take-offs and landings. Therefore, the wing's upper surface is under compression during the flight and tension during the taxing, while the lower surface is under the opposite loads. This requires the materials for the wing to provide both high tensile strength and high compressive strength [1]. The fuselage is exposed to the conditions of high cabin pressure and shear loads, and requires the materials to possess high tensile and shear strength. Al-based alloy is one of the widely used airframe materials. For example, 2024 Al-based alloy has been widely used in fuselages because of its moderate yield strength (324 MPa), good fracture toughness (37 MPa $m^{1/2}$), and high elongation rate (21%). Moreover, the use of polymer matrix composites (PMC), such as CFRP, for aircraft structures has significantly increased in recent years because of their high strength (3450–4830 MPa for standard modulus CFRP) and elastic modulus (224–241 GPa), and high-temperature capability (to withstand temperatures between 290 and 345 °C) [22].

2.2. The design criteria of the aircraft engine's materials

Thrust improvement and weight reduction for aircraft engines have been the driving forces in development of engine materials. The engine materials are required to possess low densities for weight reduction, and good mechanical properties in a high-temperature and corrosive environment. Aircraft turbine engines consist of cold sections (fan, compressor, and casing) and hot sections (combustion chamber and turbine). Different sections of engines have different temperatures, resulting in different selection criteria for aircraft engine materials. Cold section components require high specific strength and corrosion resistant materials. Ti-based alloys, Al-based alloys, and polymer composites are optimum materials choice for this application. The operating temperatures of the compressor are normally in the range of 500–600 °C. The frequently used material for this part is Ti-based alloys (Ti-6Al-2Sn-4Zr-6Mo) because of their high strength (YS = 640 MPa) at high temperature (450 °C) and excellent corrosion resistance. The hot sections of aircraft engines require materials with high specific strength, creep resistance, hot corrosion resistance, and high temperature resistance [21,22]. The operating temperatures of the turbine section are usually in the range of 1400–1500 °C, which greatly exceeds the limit of Ti-based alloys (around 600 °C) [22,23]. Consequently, the widely used materials for this applications are Ni-based superalloys (Ni-14.5Zr-3.2Mo) because of their excellent heat-resistance strength (780 MPa at 950 °C) [24].