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A critical review of recent advances in the aerospace materials

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ABSTRACT

The pursuit for improved performance in the aerospace and aviation industries has inspired the development, investigation, and research of advanced materials. Since the last few years, a lot of research on different alloys, composites and some other advanced materials has been performed to perfectly meet the needs of the aerospace field such as basic frames of aircraft, fuselages, engine parts, wings etc. Various aluminium, magnesium, titanium, and nickel-based alloys have been developed with certain advantages like strength-to-weight ratio, corrosion resistance, wear resistance etc. However, there are major challenges to aerospace materials such as insufficient mechanical and chemical properties, overall weight of aircraft, fretting wear, stress corrosion cracking, incapability at high temperatures, and low oxidation resistance. Therefore, vast studies have been conducted for the development of next-generation aerospace materials. In the present article, attention has been made to study the contemporary materials, current research going on and future trends on advanced materials in the field of aerospace engineering. Aluminium-based alloys are found as the most widely used metal alloys in the aerospace sector for their strong mechanical properties. However, polymer matrix composites and metal matrix composites have gained popularity due to their exceptional strength and stiffness. Titanium-based alloys are favoured for their strength and corrosion resistance, leading to increased adoption.

1. Introduction

In this article, aerospace materials are the structural components used to support the loads applied to the aircraft while it is in flight operation. Structural materials are used as safety–critical airframe components in the wings, fuselage, empennage, landing gear, tail boom, and rotor blades of helicopters, as well as the airframe, skins, and thermal insulation tiles of spaceships like the space shuttle [1]. The momentum for the development of aviation materials has accelerated due to the way the aerospace industry is expanding. The primary motivating factor is cost reduction via lighter construction and longer-lasting aircraft parts/structures. Improved mechanical qualities in the materials used to make lightweight aircraft frames and engines can enhance payload, extend flight range, and improve fuel efficiency i.e., all of which immediately lower aircraft operating costs [2]. A wooden airframe was used on the first day of flight in 1903, marking the beginning of the development of aeroplane materials. Through the advancement of cladding and anodizing processes after 1927, aluminium-based alloys took the lead in aircraft materials [3]. Aluminium alloys have been successfully used for over 80 years as the principal material for the structural components of aeroplanes [4]. Due to their exemplary qualities (i.e., admirable strength with reduced weight, high corrosion resistance, and decent machinability) as well as their benefits in terms of cost compared to steel and titanium alloys, aluminium alloys are frequently used for the fabrication of structural elements used in the defence, automotive, and aerospace sectors [5]. Advanced aluminium alloys for aerospace applications have been required to allow for high fracture toughness, higher fatigue performance, high formability, and superplasticity to meet the demands for reduced structural weight, more damage tolerance, and more durability [6]. Due to its exceptional blend of strength and lightweight, titanium appeals to aircraft designers. Due to its low machinability, it causes significant issues in manufacturing [7]. The aerospace material titanium alloys must be viewed as being far more modern and superior to steel or aluminium alloys. In the USA, At the end of the 1940 s, the first alloys were developed. Among the available alloys, Ti-6Al-4V still dominates the present aerospace industry in terms of applications [8]. In recent decades, the fabrication of titanium alloys with high strength has

Abbreviations: CFRP, Carbon fibre-reinforced polymer; CNT, Carbon nanotube; HCP, Hexagonal close packing; BCC, Body-centred cubic; UTS, Ultimate tensile strength; YS, Yield strength; CMC, Ceramic matrix composite; MMC, Metal matrix composite; PMC, Polymer matrix composite; GNP, Graphene nanoplatelets.

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received a great deal of attention from the titanium community, and both theoretical research and technological exploration have produced several promising results [9]. In recent years, CFRP composites i.e., carbon fiber-reinforced polymer composites have taken centre stage in the manufacturing of aerospace and energy storage equipment due to their benefits of being extremely strong, lighter in weight, and resistant to corrosion [10]. By merging the winding technique with ultrasonic tow-spreading technology, carbon fibre-reinforced epoxy composites with various CNT content were created. A particular CNT content was discovered to improve the mechanical properties of the epoxy resin matrix significantly, resulting in structural–functional integrated ultra-thin CFRP composites, which have applications in energy storage and aerospace [11]. (See Figs. 1 and 2 Table 1).

The purpose of the presented article is to study the recent investigations conducted on aerospace materials and contemporary research going on in view to enhance the properties of materials to have better durability and economy. The article includes cost and weight consideration for material selection, criteria for selection of materials for fuselages and wings, engine and its parts followed by modern progress in aerospace materials. This article also exhibits the timeline of the aerospace industry shift from one to another advanced materials. In the last section of this article, the future scope of the article has been presented.

2. Materials selection criteria in designing the aircraft

Depending on the specific component under consideration, different aircraft materials have different material property requirements. The requirements of design for each component, such as the conditions of loading, ability to be manufactured, geometrical restrictions, surface finish, ecological considerations, and ability to be maintained, influence the material selection for an aeroplane [13].

2.1. Design criteria for fuselages and wings

The aircraft's components are made of materials that are intended to last a long time (around 60,000 working hours). Strength and material weight are two important considerations when constructing wings and fuselages. For this concept to work, the materials used in the airframe must have lower densities for weight reduction and suitable mechanical qualities for the application. Additionally, materials must have adequate damage tolerance for long-term use in environments with high levels of moisture, ultraviolet light, and extreme temperatures (-30 °C to 370 °C) [14].

2.2. Design requirements for engine and engine parts

The material for the aircraft engine and its parts is designed in such a way that it has low density and sufficient strength to sustain mechanical and thermal loadings. Operating temperature in different sections of an aircraft engine ranges between 300 °C and 600 °C. Due to these high operating temperatures and high engine speed, a maximum tangential stress of approximately 600 MPa is induced on the rotor [15].

3. Modern progress in aerospace materials

Alloys based on aluminium from the 2000 and 7000 series as well as Al-Li alloys are the main topics of recent studies. Even while composites appear to substantially replace aluminium-based materials, they still have several benefits, including low cost, simple manufacturing, lighter weight, and high resistance to sustain with mechanical and thermal loadings.

Al-based alloys from the 2000 series are typically alloyed with copper. They are being extensively researched as materials for aeroplane fuselages since they outperform every other series of Al-based alloys in terms of damage tolerance and fatigue resistance [4]. However, due to their relative weakness, they cannot be used in areas with significant levels of stress.

The appropriate fusion of these materials with Sn, In, Cd, and Ag can result in materials with higher mechanical characteristics due to the improvement in microstructure and grain size [17]. Reducing the number of contaminants like Fe and Si can also improve the mechanical qualities.

Al-based alloys from the 7000 range are typically alloyed with zinc. Of all the elements, Zn has the maximum solubility in aluminium (31.6% weight). Al-Zn-based alloys are employed in the skin of the upper wing, longerons, and vertical fins because they have the maximum strength when compared to other Al-based alloys [4]. Unfortunately, the corrosion resistance, fracture toughness, and damage tolerance of these alloys are subpar.

Their optimal fusion with elements such as Zn or Mn can result in

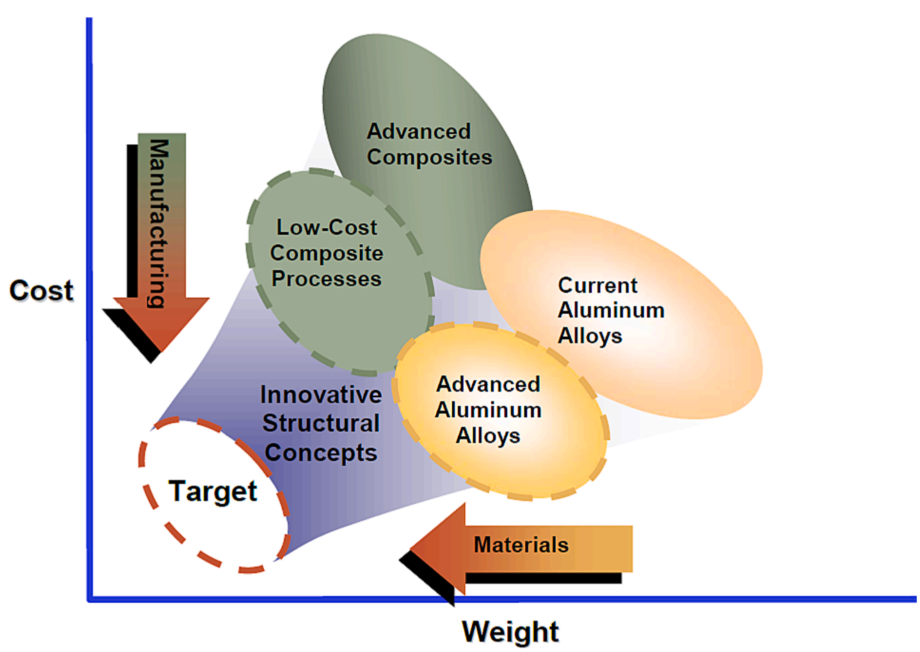

Fig. 1. Schematic view of cost weight considerations for material selection [12].

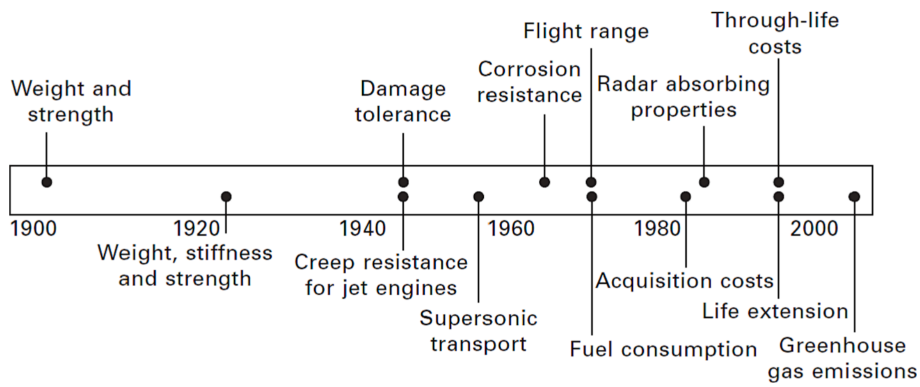

Fig. 2. Timeline in history demonstrating the introduction of important materials selection factors into aeroplane design [1].

Table 1
Different materials used in aerospace application [2].

S. No.	Material		Application
1	Aluminium based alloys	Aluminium-Copper based alloys	Aircraft fuselages
		Aluminium-Zinc based alloys	Upper-wing skin, stringers, and stabilizers
		Aluminium-Lithium based alloys	Fuselage skin and upper wing skin
2	Magnesium based alloys		Gearbox transmissions in the Helicopter industry
3	Titanium-based alloys	Alpha-Titanium alloys	Disc blades of the compressor
		Beta-Titanium alloys	The landing gearbox of aircraft and aircraft spring applications
4	Composite Materials	Ceramic matrix composite materials	Exhaust nozzles, aircraft brakes
		Metal matrix composite Materials	Fuselage skins and wide-body wings
		Polymer Matrix Composites	Fuselages, ailerons, flaps, and landing-gear doors
5	Steels		Gears, bearings, carriages & fasteners
6	Nickel-based superalloys		Combustor and turbine section

improved mechanical characteristics. For instance, adding Mn to 7000 series alloys at 1% weight can increase their fracture toughness by roughly 100%. Better mechanical qualities are also offered by reducing impurities like Fe and Si [18].

The lightest weight among all Al-based alloys are Al-Li-based alloys and, in comparison to alloys from the 2000 and 7000 series, they have a lower density and good mechanical characteristics. Al-Li-based alloys can save weight by about 10% when used in place of the 2000 and 7000 series alloys on the fuselage and upper wings, respectively [4].

The problem of anisotropy, or the fluctuation of characteristics in different directions, can occur with Li-Al alloys. Additionally, they have weak corrosion resistance and low hardness [19].

In addressing these inadequacies of recent studies magnesium (Mg) is the lightest structural metal. Its use in the aerospace industry is very restricted although it can lower the structure's weight by 33% and 77%, respectively in comparison to aluminium and steel of the same volume, [20]. This is because of its inadequate mechanical characteristics and poor corrosion resistance. The mechanical qualities of alloys based on magnesium can be enhanced by adding the right amount of aluminium, zinc, zirconium, or rare earth metals like yttrium. Corrosion resistance will be improved using Al. Additionally, the strength and ductility of the Mg-Al alloy are improved by adding zinc up to a critical level (5% wt). Mixing Mg-Zn with Zr or Y greatly increases the strength in the absence of Al. For instance, the Mg97Zn1Y2 alloy, which is based on magnesium, has the maximum strength (Yield Strength = 610 MPa) [21].

Because of their excellent strength concerning weight, improved resistance to corrosion, and effective performance at elevated temperatures, titanium-based alloys have gradually seen a surge in usage in recent years. They serve as components for engine compressors, helicopter rotor systems, and aircraft springs. α, β and α-β titanium alloys are the three categories of Ti-based alloys.

α-titanium alloys have a crystal structure known as HCP. In comparison to β-titanium alloys, α-titanium alloys are less dense, exhibit higher creep resistance, and exhibit better corrosion resistance. α-titanium alloys, such as commercially pure Ti and Ti-3Al-2.5V, are therefore utilized in the blades of the compressor of an aeroplane engine. However, at high temperatures, their usefulness is severely constrained. Al is frequently employed to enhance their performance at high temperatures [22].

β-titanium alloys have a crystal structure called a BCC. They are simpler to produce and their tensile and fatigue strength are greater in comparison to α-titanium alloys. β-stabilizers such as vanadium, molybdenum, niobium, and chromium can lessen the beta-titanium atomic cluster's binding energy, resulting in stronger bonding between Ti and the alloying atoms and boosting the alloy's strength. A good example is the β-titanium alloy Ti-3Al-8V-6Cr-4Mo-4Zr, which is employed in high-stress areas of aircraft like landing gears and springs and has a UTS of 1240 MPa [23].

α-β titanium alloys combine the qualities of α-titanium and β-titanium alloys, and they have exceptional strength, improved fracture toughness, good ductility, and better corrosion resistance. They account for 70% of the titanium market in the United States and are the most utilized Ti-based alloys. Ti-6Al-4V and other α-β alloys are employed in the fuselage, landing gear, floor support structures, nacelles, and compressor discs, among other applications [24].

Any substance created from two or more constituent materials is referred to as a composite material. These constituent materials are combined to produce a material with characteristics that are distinct from the constituent parts despite having chemical or physical qualities that are noticeably different. According to Fig. 3, Airbus A380 uses more than 25% and Boeing 787 uses more than 50% share of composite materials in its construction, the utilization of these materials in the aircraft industry is expanding. Since composite materials are less dense than most metals, they have an enhanced strength-to-weight ratio and better resistance to corrosion and fatigue.

CMCs are composed of ceramic fibres and a ceramic matrix. Even at 1400 °C, CMCs maintain good high-temperature stability. They also have excellent hardness and robust corrosion resistance. Examples include silicon nitride (Si_3N_4), silicon carbide (SiC), and alumina. They are thus commonly used in hotspots like exhaust nozzles [25].

CMCs, however, have weak fracture toughness. Current research has concentrated on using GNPs and CNTs to increase the fracture toughness of CMCs. According to scientific tests, adding 1.5 vol% of graphene can raise the fracture toughness of Si_3N_4 by 235% [26].

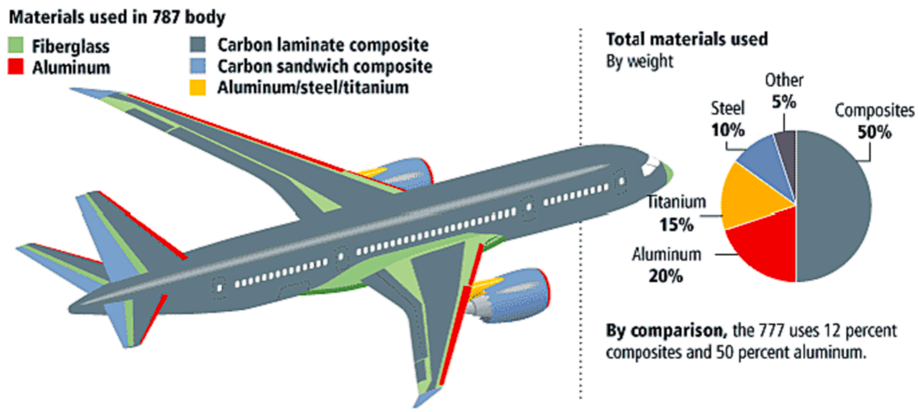

Fig. 3. Material used in Boing 787 [16].

In MMCs, reinforcing elements are spread throughout a metal matrix. MMCs have improved wear resistance, lower thermal expansion, higher yield strength, and fracture toughness. As a matrix, metals such as aluminium, magnesium, titanium, copper, and nickel are employed. Glass and carbon fibres are two types of regularly utilized reinforcement materials. However, these fibres have already provided everything they are capable of. To achieve better mechanical qualities, novel materials including CNTs and graphene nanosheets are under research. The regulated inclusion of CNTs has been reported to enhance the mechanical characteristics (such as UTS, YS and hardness) of aluminium, magnesium, titanium, copper, and nickel matrix composites [27].

PMCs are the type of composite materials made up of several short or continuous fibres joined by an organic polymer matrix. Commonly used fibres include aramid, graphite, and fibreglass. PMCs are divided into two categories: thermoset (which cannot be heat remoulded) and thermoplastic, depending on the properties of the polymer matrix (which can be heat remoulded). Epoxy, polyurethane, polyamide, and other thermoset matrices are frequently used to create PMCs for the aerospace sector, which are employed in ailerons (hinged flight control surface), flaps (a high lift device consisting of a hinged panel or panels mounted on the trailing edge of the wing), and landing gear doors [28].

The greater specific strengths and specific modulus of PMCs are well recognized. For instance, the density of carbon fibre-reinforced alloys in an epoxy matrix binder is half that of alloys based on aluminium, while their modulus of elasticity and tensile strength are two and three times more than that of alloys based on aluminium, respectively. However, since they are fragile, carbon fibres are vulnerable to stress concentration. So, currently, basalt, carbon nanotubes, graphene, and natural fibres are being studied as reinforcing elements for polymer matrices [29].

Low specific strength and resistance to corrosion of steel have drastically reduced their utilization in the aircraft sector in recent years. Due to its higher density, mild steel has a comparatively high UTS (840 MPa), but its unique features make it unsuitable for use in aircraft. However, it continues to be a crucial component of fasteners, carriages, and bearings. For enhanced particular characteristics and corrosion resistance, new low alloy steels and nano steels are now being investigated [30].

Superalloys based on nickel are extremely strong even at high working temperatures. As a result, they are frequently employed in the turbine and combustion chamber of aircraft engines, where the operating temperatures vary from 1100 to 1250 °C [31]. The two most widely used Ni-based superalloys are Inconel and Nimonic. To increase resistance to oxidation of Ni-based superalloys, Al is added [32].

Literature suggests that due to its well-known mechanical properties, Al-based alloys are the primary material in the aerospace industry but the use of PMCs has been amplified in recent years because of their excellent specific strength and stiffness. However, the conventional PMCs and MMCs are known to suffer stress corrosion cracking. Mg-based alloys due to their low ductility and abundance are attractive candidates for various applications but their use by top aircraft manufacturers is very limited due to their poor corrosion resistance. Ti-based alloys are acknowledged for their high specific strength and corrosion resistance. That is why their use has been increased in recent years but the α-phase of these alloys greatly limits its capability at higher temperatures. The metal alloys, super alloys, and composites available in the previous literature have majorly better qualities but lag in some other required qualities. Therefore, further investigations and research are required to be conducted to enhance the properties of materials to a greater extent.

4. Conclusion & future trends

The aircraft sector has undoubtedly advanced significantly over the past century, and a large portion of this development can be attributed to the advancement and innovation of structural and engine materials. The foundation of the present aerospace engineering is high-performance alloys based on aluminium, magnesium, titanium, and nickel, along with composite materials. They still deal with several problems, such as corrosion, stress corrosion cracking, fretting wear, etc. Therefore, to increase the safety, effectiveness, and affordability of air travel, substantial focus should be given to research of new aerospace materials of the next generation with higher mechanical qualities and better corrosion resistance. In the future, for airframe structures, the development of new aerospace alloys and composites of high specific mechanical properties with refined microstructure and thermo-mechanical processing is a major concern. However, for the engine and its parts, improvement of high-temperature resistance, high-temperature oxidation resistance and higher fracture toughness is a primary concern.

CRediT authorship contribution statement

Rahul Soni: . **Rajeev Verma:** . **Rajiv Kumar Garg:** Supervision. **Varun Sharma:** Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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