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A Brief Introduction to the Properties of Aerospace Materials

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Abstract

This article provides a detailed examination of the historical development and areas of use of aviation materials. By investigating the fundamental properties of materials used in aircraft and aerospace vehicle design, such as durability, lightness, heat resistance, and corrosion resistance, the study aims to offer an important perspective from both engineering and industrial viewpoints. Additionally, the role of material selection in factors like flight safety, efficiency, and environmental impact is discussed. The field of aviation materials is a fundamental element of aerospace engineering, encompassing many areas such as aircraft technology design, aerodynamics, flight control systems, avionics, propulsion systems, fuselage structures, and other critical disciplines. Launching a vehicle, whether an aircraft or a spacecraft, requires significant thrust and energy to initiate and sustain flight. Reducing engine weight to improve performance, while maintaining thrust capabilities, is of critical importance. Achieving these advancements requires the use of new materials that offer higher melting points, enhanced durability, and longer lifespans. As a result, materials such as polymer composites and magnesium alloys are in demand. With the advancement of superalloy technology, faster and more powerful aircraft for passenger, cargo, and other aviation applications are expected. This article aims to explore the historical development and applications of aviation materials.

Keywords: Aerospace materials, Alloy, Composite Material, Nano Composite, Material Selection.

1. Introduction

Aviation and space materials technology is advancing rapidly to keep pace with the ongoing changes in the air transport industry. Developments in aircraft, spacecraft, engines, landing gear, and more continue to drive progress in the creation of new materials and manufacturing techniques.

Many of the major breakthroughs in aircraft and rocket propulsion have been achieved through improved materials and their production methods. To enhance the performance and thermodynamic efficiency of jet engines, higher operating temperatures are required. To boost efficiency further, it's essential to reduce engine weight without compromising thrust. All of these advancements depend on the use of new materials with higher melting points, as well as greater strength and durability. Similar advancements are needed for the development of rocket casing and nozzle throat materials. The creation of lighter, more robust materials capable of withstanding higher temperatures leads to substantial improvements in engine thrust, weight, fuel efficiency, and service life [1].

A variety of innovative processing methods have been developed in response to the material demands of the aerospace industry. The focus of materials research and development has shifted from traditional materials processing companies to integrated aerospace organizations. This trend is likely to become even more pronounced in the future, driven by the need for improved quality, safety, and cost efficiency. The transfer of advanced aerospace materials and processing technologies to other sectors is feasible and often beneficial, though it can sometimes present economic challenges.

Since aluminum was first used as a structural material in Zeppelins in the early 1900s, this lightweight metal has been further refined through a range of alloys and properties designed to meet the specific needs of aircraft manufacturers around the world. However, the market for aluminum has started to reach saturation with the rise of carbon fiber reinforced polymer matrix composites. Titanium and nickel-based superalloys are commonly employed in the construction of compressors and turbines for jet engines. In the future, intermetallics and ceramics may replace certain alloys. In brief, this study aims to understand technological advancements, innovations, and changes in engineering, while also exploring how material choices have evolved according to the needs of the aviation industry and the role these materials play in aircraft design, safety, efficiency, and environmental impacts.

1.1. Development Process of Aerospace Materials

The development of new materials and the enhancement of existing ones play a key role in the progress of aerospace engineering. Advances in the structural performance, safety, fuel efficiency, speed, range, and service life of aircraft have been closely tied to improvements in the materials used for fuselages and engines. Since the Wright Brothers' first successful flight in 1903, the materials used in aircraft have evolved significantly in terms of mechanical performance, durability, functionality, and quality. Additionally, the factors considered when choosing materials for aircraft have undergone significant changes over the past century [1]. Fig. 1 illustrates a timeline showing the approximate years when new criteria for selecting aircraft materials were introduced.

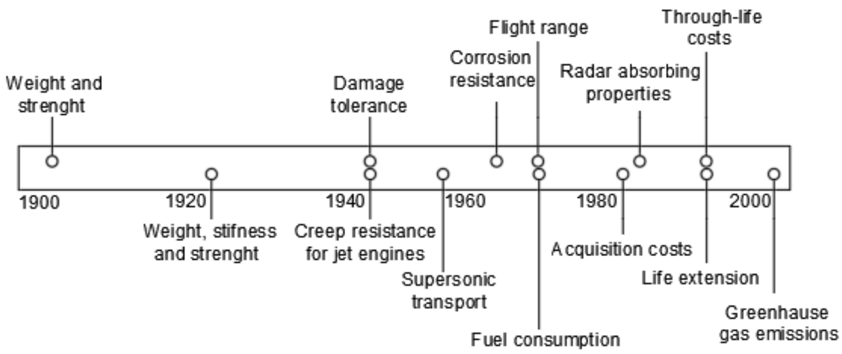

Fig. 1. Historical timeline showing when key criteria for material selection were incorporated into aircraft design [2]

The primary considerations for material selection in the earliest aircraft (c. 1903–1920) were minimal weight and maximum power. The initial airplanes were designed to be light and powerful, with a strong emphasis on achieving the highest strength-to-weight ratio. During this period, less attention was given to other important design factors such as cost, toughness, and durability. Many of the criteria that are crucial in material selection today were overlooked by the first generation of aircraft designers, who focused solely on using high-strength materials to minimize weight. Wood was chosen as the ideal material to meet the strength-to-weight requirements at the time.

In the 1920s and 1930s, the criteria for material selection expanded to include a broader range of factors influencing aircraft performance. While the focus on strength-to-weight ratio remained central, additional factors such as high stiffness and durability gained importance. These new criteria led to the development of not only new materials but also new manufacturing techniques to transform these materials into aircraft components. Aluminum alloys, processed with new heat treatments and metal forming techniques, were introduced to meet the growing number of material selection requirements.

During World War II, aluminum supplies to Japan were disrupted in the late 1930s and early 1940s, forcing military forces to turn to magnesium in the construction of many fighter jets. Another significant development in this period was the introduction of pressurized cabin airplanes designed for high-altitude flights in the 1940s. The increased compressive loads applied to the aircraft's structure led to the creation of tensile leather panels made from high-strength materials. However, the growing need for materials with better fatigue and fracture properties became a critical safety concern, prompting the establishment of damage tolerance criteria. Damage tolerance refers to an aircraft structure's ability to contain sub-critical cracks and other forms of damage without leading to catastrophic failure.

Metal fatigue became a more pressing issue in the mid-1950s when two Comet aircraft, the first civilian jets of the next generation, crashed due to fatigue-induced cracks in the fuselage. This disaster highlighted the importance of fracture toughness and fatigue resistance, which were added to the existing material selection criteria such as weight**,** hardness, and strength.

With the advent of rocket technology and supersonic aircraft in the 1960s, materials capable of withstanding high temperatures became necessary. The aerospace industry made substantial investments in developing new materials for supersonic aircraft like the Concorde**,** high-speed fighter jets**,** surveillance aircraft for the Cold War, and spacecraft and satellites for the Space Race. A key development was titanium alloys that could resist the effects of frictional heating without softening during supersonic flight. This led to the creation of heat-resistant materials such as specialized aluminum alloys. More powerful engines were needed for both aircraft and rockets, which prompted the development of high-temperature materials capable of operating at temperatures above 800 °C. New nickel-based alloys and other heat-resistant materials were created to withstand the extreme conditions in the hottest parts of jet engines.

In the late 1970s, the demand for damage-resistant materials increased following unexpected failures in ultra-high-strength steel components in United States Air Force (USAF) aircraft. These failures were found to be caused by manufacturing defects and fatigue cracks too small to be detected reliably. In response, the USAF established a design philosophy that acknowledged the presence of cracks in aircraft and emphasized damage resistance to ensure reasonable service life. This approach required materials resistant to fatigue cracking and fracture. The aerospace industry took additional steps to minimize weight and maximize structural performance by using higher-strength aluminum alloys and carbon-epoxy fiber composites in secondary structures such as engine hoods and chassis doors.

As the cost of new aircraft increased and low-cost airlines entered the market, competition among airlines grew, making the extension of aircraft life a priority. The need to extend the operational lifespan of older aircraft in the 1980s and 1990s led to a stronger emphasis on improved damage tolerance and corrosion resistance. New aluminum alloys with enhanced corrosion resistance and composite materials that were completely resistant to corrosion began to see widespread use.

In the 1990s, factors like production and maintenance costs became increasingly significant in material selection for aerospace applications. Simultaneously, new structural materials with radar-absorbing properties and low thermal emissions were widely utilized in stealth military aircraft. Although drones with limited stealth capabilities had been in use since the 1970s, the growing need for aircraft to have extremely low radar visibility played a critical role in the development of radar-absorbing materials.

Key material selection factors such as weight, hardness, strength, damage tolerance, fracture toughness, fatigue resistance, corrosion resistance, and heat resistance are all crucial in the material selection process for modern aircraft. In the first decade of the 21st century, the focus shifted toward materials that reduce production costs and lower operating expenses throughout the aircraft's service life. Addressing greenhouse gas emissions by reducing aircraft weight and enhancing engine fuel efficiency has also become a priority in material selection. Additionally, the development of environmentally friendly production processes and the use of sustainable materials that can be easily recycled remain key areas of focus.

As aircraft technology and the factors influencing material selection have evolved, both fuselage and engine materials have continuously changed. The approximate introduction years of major aerospace materials are depicted in Fig.2.

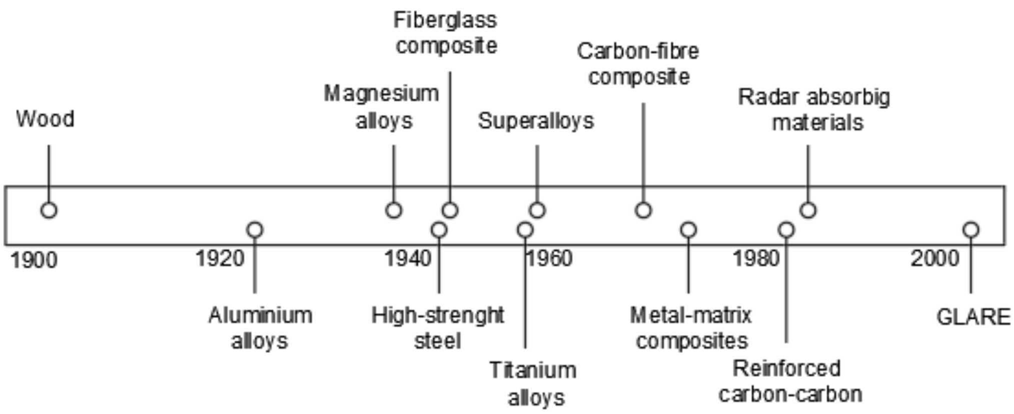

Fig. 2. Historical timeline showing the approximate year that major material types were first used in aircraft [2]

2. Materials Used in the Aerospace Industry

There is a broad range of materials that can be utilized in the construction of aircraft. It is estimated that over 120,000 materials are available for aeronautical engineers to select from when designing the airframe and engine. This includes more than 65,000 varieties of metals, over 15,000 types of plastics, over 10,000 forms of ceramics, composites, and natural materials like wood. The number of available materials is growing swiftly as new substances with enhanced or distinct properties are introduced. Approximately one hundred types of metal alloys, composites, polymers, and ceramics are believed to possess the necessary properties for aerospace applications. Achieving a material that is lightweight, structurally efficient, damage-resistant, cost-effective, and simple to produce seems unattainable [2].

The primary material groups used in aviation structures include aluminum alloys, titanium alloys, steel, and composites. In addition, nickel-based alloys are also regarded as a key structural material for jet engines. When the right materials are chosen for aviation, it is possible to achieve excellent performance and reasonable production costs. Factors such as environmental conditions, ease of processing, and the ability to inspect and repair components influence material selection.

Materials and structures for spacecraft applications present one of the most significant challenges for materials engineers. Although altered high-temperature metal structures may meet some required specifications, fiber-reinforced composites with metal or ceramic matrices are seen as promising materials for next-generation systems [3].

Aircraft, rockets, and other air vehicles are designed to operate under challenging conditions; therefore, the selection of materials is based on numerous factors. The main factors considered in material selection in the aviation field are as follows:

Cost: The selection of aviation materials is crucial for the safety, performance, and cost-effectiveness of aircraft. In the aviation industry, high-quality materials are generally expensive. However, in materials that are critical for safety and performance, cost is often secondary. However, cost-effective alternative materials can be used to minimize production costs.

Mechanical and Thermal Properties: Aviation materials must be able to withstand the high speeds and variable temperature conditions they will encounter during flight. The material's durability, mechanical properties like tensile and fatigue resistance, and its performance in high and low temperatures directly affect flight safety. Especially, engines and structural components require materials that can withstand high temperatures and pressure.

Weight: One of the most effective factors on aircraft performance is weight. Materials used to increase fuel efficiency and extend flight range must be as lightweight as possible. However, lightness must be achieved without compromising the material's strength. Therefore, lightweight yet strong materials such as aluminum alloys and composite materials are preferred.

Availability, Workability and Manufacturability: During material selection, the workability of the material is also an important factor. Manufacturing processes and the shaping and assembly of parts require the material to be suitable. To avoid delays in aircraft production and to prevent large fluctuations in purchase prices, materials must have a continuous and reliable supply chain.

Fatigue Resistance: Materials used in aviation must resist cracking, damage, and failure under fluctuating (fatigue) loads during flight, ensuring long-term structural integrity.

Damage Tolerance: Aerospace materials need to maintain their ability to support the final design load even after sustaining damage from events like bird strikes, lightning strikes, hail, falling objects, and other routine operational hazards. This includes resisting cracks, delaminations, and corrosion after such impacts.

Corrosion Resistance: Aircraft can suffer from corrosion due to humidity, salty air, and other environmental factors in the atmosphere. Therefore, it is essential that the materials used show high resistance to corrosion. Materials with high corrosion resistance, such as aluminum and titanium alloys, are commonly used in aircraft structures.

Electrical Properties: Aerospace materials must be electrically conductive to help distribute the charge during a lightning strike, ensuring safe discharge of electricity.

Electromagnetic Properties: Aviation materials should have low electromagnetic properties to prevent interference with the electronic systems controlling the aircraft.

Radar-Absorbing Properties: Stealth military aircraft require materials for their coatings that can absorb radar waves, making the aircraft harder to detect.

Standards and Regulations: The aviation sector is subject to strict national and international regulations. Therefore, materials must meet safety, environmental impact, and performance requirements. Adhering to relevant regulations and industry standards plays a critical role in material selection. This is necessary for aerospace engineers to certify their designs and ensure the airworthiness of aircraft.

Environmental Impact: The environmental impact of the materials used in the construction of aviation vehicles is becoming increasingly important. Sustainable material usage, recyclability, and carbon footprint are factors that are considered in material selection.

3. Evolution of Materials in the Aerospace Industry

3.1. Wood

The primary consideration for material selection in the first generation of aircraft (1903–1930) was maximum durability while keeping weight to a minimum. The high strength-to-weight ratio was the most important factor among all others, such as hardness, toughness, and overall durability. Given the low power of the early aircraft engines, weight had to be kept as low as possible. The fuselage of the first airplanes was almost entirely constructed from wood because it was the only material that combined both strength and lightness. Although stronger materials like steel and cast iron were available in the early 1900s, they were approximately 10 times denser than wood, which would significantly increase the weight of the airframe. For this reason, wood was favored over these heavier materials. Guided by the studies of German engineer Otto Lilienthal, the Wright Brothers developed the Wright 1 aircraft shown in Fig. 3, thus achieving the first successful powered and controllable flight, marking a historic milestone [4-7].

Following the successful flight of the Wright 1, the Wright brothers developed the Wright 2 and Wright 3 aircrafts, achieving successful flights in succession [4,8]. Wood was also cost-effective, and its properties were well-known, as it had been widely used in other structural applications such as buildings and bridges. Additionally, wood was easy to work with, and the craftsmen who built the first planes by hand could readily process it into lightweight frames, beams, and other structural components. However, despite these advantages, wood had its drawbacks. Its mechanical properties were inconsistent and anisotropic, meaning the aircraft had to be carefully designed to avoid structural failures. Because wood had weak or "soft" spots, many aircraft suffered from structural breakdowns due to its unstable strength characteristics. Furthermore, aircraft made from wood required constant maintenance due to issues like moisture absorption, warping, and rot over time.

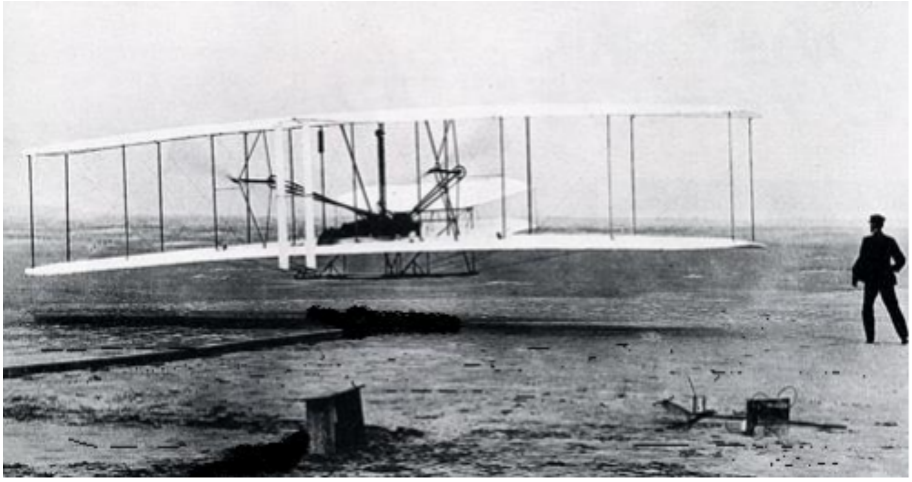

Fig. 3. Appearance of the Wright 1 Aircraft Designed by the Wright Brothers [5]

The aviation industry eventually found that laminated plywood construction offered greater strength, durability, and a lighter weight than solid wood. Laminated plywood is made from wood layers oriented at different angles and glued together into thin sheets. This method quickly gained popularity, particularly in the period between the two world wars. Even some warplanes and light bombers were constructed using wood and plywood during World War II. One of the most famous wooden aircraft of the war was the de Havilland Mosquito, a highly advanced fighter/bomber that could reach speeds of 650 km/h for its time [2].

However, with the mass production of fighters, bombers, and heavy-duty transport aircraft during World War II, wood became less favored as a structural material. The shortage of high-quality timber in many countries during the war led to the increased use of alternative materials like aluminum. Additionally, wood lacked the necessary hardness and strength for many military aircraft, especially bombers, cargo aircraft, and other lift-intensive aircraft that required strong wings and fuselages. After the war, the development of pressurized cabins for high-altitude flights further diminished the use of wood in aircraft design. Today, wood is mainly used in certain gliders, ultralight aircraft, and piston-powered planes, as newer, lighter, and more structurally efficient materials have become available [9].

3.2. Aluminum

Aluminium alloys have been successfully used for over 80 years as the principal material for the structural components of aeroplanes [10]. Aluminum has been utilized by aircraft manufacturers since the early 1900s, although it wasn't initially tough enough for widespread use. During World War I, aluminum was first employed in the hulls of Zeppelin airships. Due to the heaviness of steel, the aircraft industry turned to aluminum alloys in the 1920s, making it a preferred material over wood. Aluminum is one of the lightest metals, approximately 2.5 times lighter than steel, and it is harder, stronger, and more durable than wood. Additionally, aluminum can be easily molded into thin-coated panels and easily machined into components like posts, supports, and beams for the fuselage and wings. To this day, aluminum remains widely used due to its low cost, light weight, and excellent properties such as rigidity, strength, and fracture toughness.

Despite the many advantages of aluminum, it does have some drawbacks. At high temperatures, its mechanical properties decrease, and it is prone to stress corrosion cracking. Additionally, aluminum can corrode when in contact with carbon fiber composites. Aging-hardenable alloys also have the disadvantage of being difficult to weld.

At the turn of the twentieth century, metallurgists began adding alloying elements and heat treating aluminum to enhance its strength properties. Various alloying elements were experimented with to improve the strength and hardness of aluminum. Additionally, heat treatments and metal coatings were tested to further refine its mechanical properties. Since the 1950s, aluminum alloys have been commonly used in satellites and space launch vehicles. However, with the recent rise of fiber-polymer composite materials, the use of aluminum has declined in some areas. Despite this, aluminum will continue to be a vital material in aerospace, as there are many types of aluminum alloys, each controlled by heat treatment to serve specific functions. For example, in aircraft, high-strength aluminum alloys are used in the upper wing fins to withstand high bending loads during flight, while other types are used in lower wing claddings to enhance fatigue strength [11]. The most elements that are alloyed with aluminum are copper (Cu), Zinc (Zn), Lithium (Li), Silicone, Magnesium (Mg), Nickel (Ni), Titanium (Ti), etc. [12]. Examples of aluminum alloys in use include the Boeing 747 and the F/A-18 Hornet military aircraft. In the Boeing 747, the majority of the fuselage is constructed from high-strength aluminum alloys, with only a small percentage of other metals and composites used. Aluminum is employed in the main structural components of the B747, including the wings, fuselage, and tail. The only □ürbi parts not predominantly made of aluminum are the landing gear and □ürbine engines [2]. As seen in Fig. 4, all modern spacecraft are made of 50% to 90% aluminum alloy.

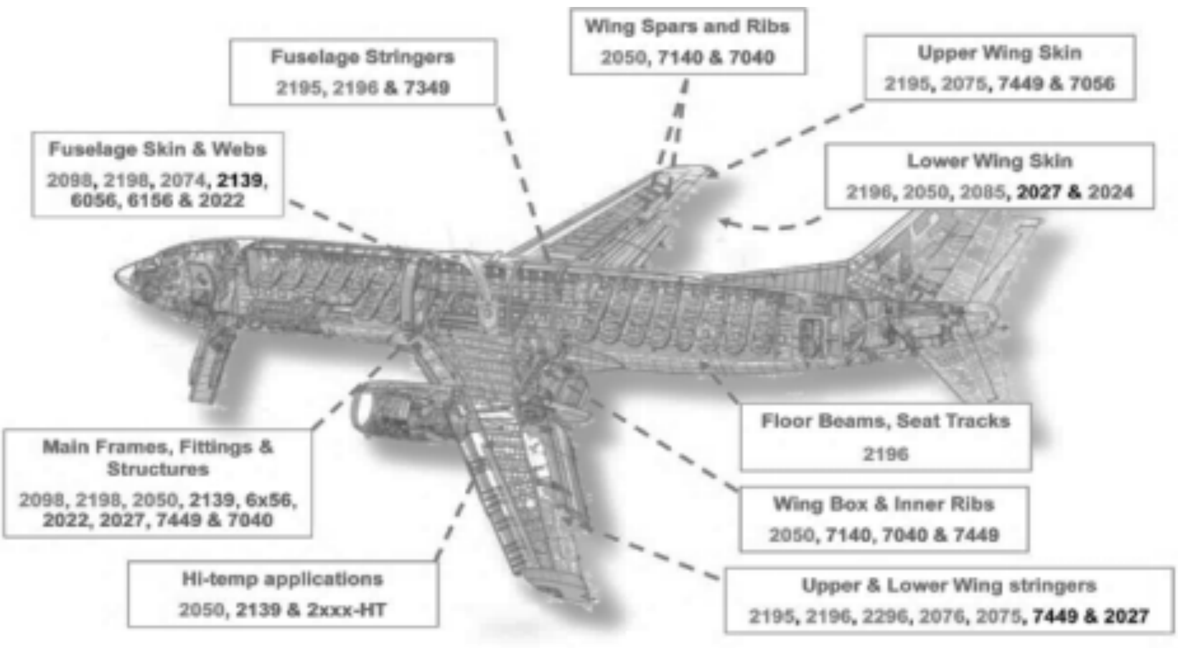

Fig. 4. Alloys used in different parts of the Aircraft structure [13]

3.3. Titanium

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 [14]. In recent decades, the fabrication of titanium alloys with high strength has received a great deal of attention from the titanium community, and both theoretical research and technological exploration have produced several promising results [15]. Common titanium alloys include alpha alloys, (alpha + beta) alloys, and beta 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 [16]. 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. A good example is the β-titanium alloy Ti-3Al-8V-6Cr-4Mo-4Zr, which is employed in highstress areas of aircraft like landing gears and springs and has a UTS of 1240 MPa [17].

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 [18]. Titanium alloys are high-strength materials used in airframe applications for critical components such as wings, engines, pylons, fuselage frames, hydraulic line pipes, fasteners, rivets, springs, beams, and various undercarriage elements, including wing and batten rails [19].

In gas turbine engines, titanium is used in components that must endure temperatures ranging from 450–500°C. It is particularly suitable for jet engines due to its superior resistance to high-temperature corrosion. Titanium alloys contribute to 25-30% of the total weight in many modern jet engines [20].

Titanium is also used in a variety of structural elements in commercial aircraft, such as wings, wing boxes, and undercarriage parts. While heavier than aluminum, titanium has higher strength and density, enabling smaller structural parts to bear the same load. The other Ti-6-4 parts shown in Fig. 5, machined from forgings, are used because of the alloy's excellent corrosion resistance with the added benefit of reduced weight. These components are fabricated using low alloy steel for other airplane models, which eventually develops corrosion pits, as the wheel well can be a very corrosive environment. These pits are initiation sites for stress corrosion or fatigue cracks, which means down-time for the airlines, and part replacement. Titanium eliminates this issue. It has a higher initial cost, but lower life cycle costs.

Examples of titanium use in military aircraft include the F/A-18 Hornet and the F-15 Eagle, where around 26% of the fuselage, cladding, wing torque boxes, wing pillars, bulkheads, engine compartment frames, and firewalls separating engines from the fuselage are constructed from titanium.

In helicopters, titanium is similarly essential, being used in components such as main and tail rotor hubs, grippers, shafts, and blade tips, all of which require high strength and resistance to fractures.[2]

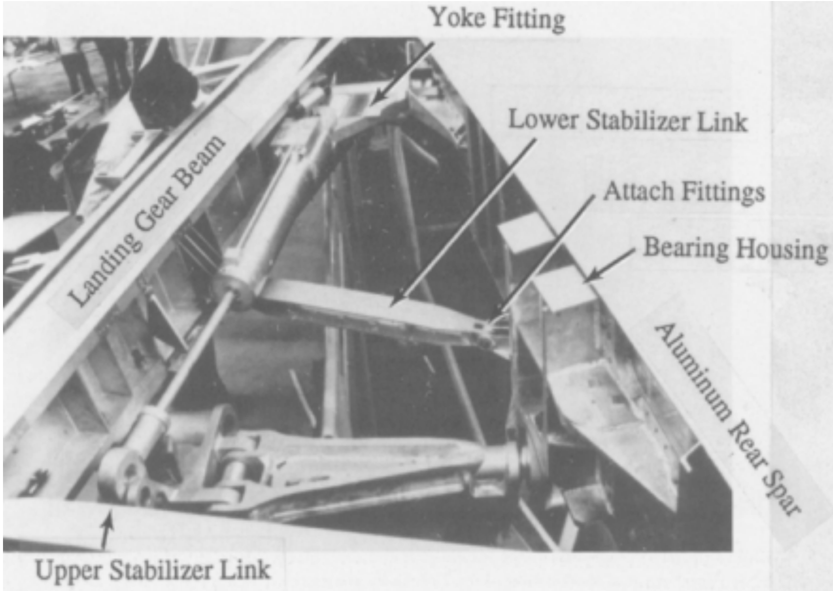

Fig. 5. Titanium forgings used in 757 landing gear support structure (from the 757 mock-up). All of the indicated parts are annealed Ti-6AI-4V except the bearing housing which is Ti-10V-2Fe-3A1 [21]

3.4. Magnesium

Magnesium is recognized for its light weight, exceptional vibration damping properties, electromagnetic shielding capabilities, high recyclability, and ease of processing. Being a lightweight material similar to aluminum, it has been employed in aircraft construction for many years. Magnesium is roughly 40% lighter than aluminum but has never been as widely preferred as aluminum due to its higher cost and weaker structural characteristics. The main drawback of magnesium is its susceptibility to corrosion. It is highly prone to various types of corrosion and, when utilized in aircraft, requires anti-corrosion coatings and routine inspections for any corrosion damage. Today, the use of magnesium in modern aircraft and helicopters typically makes up less than 2% of the total structural weight.

A significant amount of magnesium alloys were employed in the primary structures of aircraft built during World War II and the 1950s. For instance, the Lockheed F-80C Shooting Star was predominantly constructed with magnesium alloys, and the Convair B-36 featured approximately 8,600 kg of magnesium components. Figure 6 shows the magnesium components of the Convair B-36. More contemporary commercial aircraft, such as the Boeing 727, incorporate magnesium alloy components in parts like trailing edge flaps, control surfaces, door frames, wheels, engine gearboxes, accessory drives, thrust reversers, actuators, and power generation systems [22].

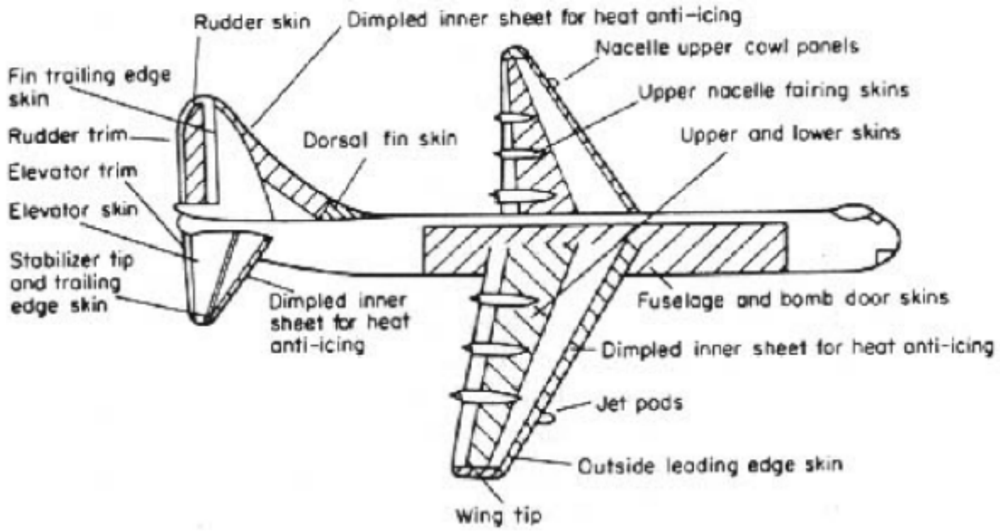

Fig. 6. B36 Bomber (Shaded Magnesium Elements) [23]

Although magnesium is less favored compared to other materials in aircraft construction, it remains a valuable material in both airplanes and helicopters, and it seems unlikely that its use in aviation will be entirely phased out [2].

3.5. Steel

While steel is the most widely used metal in structural engineering, its application as a construction material in aircraft is relatively minimal, typically making up less than 5-10% of the total weight. One of the primary reasons steel is commonly chosen is its ability to offer a broad range of mechanical benefits through heat treatment. For instance, a part may need to be initially soft and malleable during manufacturing but must exhibit high strength throughout its operational lifespan. Both ductility and strength can be achieved within the same material. All steels can be made more malleable through the annealing process, depending on the chemical composition of the specific steel. Annealing involves heating the steel to an optimal temperature, maintaining it for a period, and then cooling it at a controlled rate. In a similar manner, steels can be hardened or enhanced through cold working, heat treatment, or a combination of both.

Steels used in aircraft are often alloyed and heat-treated to reach very high strength levels, making them approximately three times stronger than aluminum and twice as strong as titanium. Additionally, steels possess a high modulus of elasticity, fracture toughness, and resistance to fatigue. However, the strength of steel is temperature-dependent—its strength diminishes as temperature rises. Furthermore, steel exhibits strain rate sensitivity, especially when exposed to temperatures above 600 to 800°F, where creep can occur. At lower strain rates, both yield and ultimate strengths are reduced. Due to these attributes, steel is often the material of choice for safety-critical components that require exceptional strength but are constrained by limited space, such as landing gear and wing box parts. However, steel is not used extensively in aircraft construction, mainly due to its higher density. Additionally, some high-strength steels are prone to embrittlement, which can result in corrosion and cracking [24].

Although the usage of steel in aviation has declined over time, it is still employed in both fixed-wing and rotary-wing aircraft. Steel remains essential in certain critical applications, as the failure of vital components made from steel could jeopardize the aircraft's safety. Common steel components in aircraft include gears, bearings, and undercarriage parts.

3.6. Ceramic

Ceramic materials offer several advantageous properties that make them valuable in a variety of aerospace applications. One of the key benefits of ceramics is their ability to withstand higher temperatures than metals. This makes them suitable for use in gas turbines, where they can handle elevated temperatures and reduce the need for cooling, as well as in high-speed aerodynamic surfaces of missiles and aircraft. Additionally, ceramics have greater hardness and durability compared to metals, providing enhanced wear resistance for components like bearings and seals. Moreover, ceramics are transparent to radar, infrared, and other electromagnetic wavelengths.

These properties arise from strong interatomic bonds, typically achieved through a combination of lighter elements capable of forming covalent bonds. Most ceramics contain at least one such element, contributing to their superior strength and durability.

Ceramics, particularly monolithic ceramics, are actively being developed and evaluated for their substantial potential benefits. The concept of using high-performance ceramics in gas turbine engines emerged in the late 1960s with the development of hot-pressed silicon nitride in England, leading to extensive research into their use in aerospace applications. In the late 1970s and early 1980s, significant advancements were made in the USA with programs like CATE, AGT 100, and AGT 101, demonstrating the feasibility of using ceramics in engines. However, several challenges have emerged, such as low levels of reliability and repeatability, which have hindered their widespread adoption in aircraft engines.[9]

As a result, current research efforts are focused on developing a new generation of monolithic and hardened ceramic components with enhanced reliability. Additionally, significant strides are being made in the development of fiber-reinforced composite ceramics for use in aerospace and other industries.

3.7. Superalloys

"Superalloys" refers to alloys that exhibit exceptional heat and corrosion resistance and maintain their superior properties even at elevated temperatures. Due to these qualities, they are often called "high-temperature alloys." Superalloys are primarily classified into three categories based on their main elements: iron-based, nickel-based, and cobalt-based superalloys. In a broader sense, superalloys are any alloys that can sustain their mechanical, physical, and chemical stability under high temperatures and in harsh corrosive environments. The advancement of aircraft design heavily relies on the development of materials for gas turbine and rocket engines that can retain their hardness over extended periods at high temperatures without deteriorating. Superalloys possess outstanding heat resistance and retain their strength, toughness, hardness, and dimensional stability at temperatures much higher than other aerospace materials. These alloys are also highly resistant to oxidation and corrosion, making them ideal for use in jet engines operating at extreme temperatures.

The most significant type of superalloy is the nickel-based superalloy, which contains substantial amounts of chromium, iron, titanium, cobalt, and other alloying elements. Nickel superalloys are particularly useful in the highest temperature regions of gas turbine engines, where they can endure temperatures ranging from 800 to 1000°C. Superalloys are commonly used in critical engine components such as high-pressure turbine blades, discs, combustion chambers, afterburners, and reverse thrusters [2].

3.8. Composite Materials

Composite materials are unique combinations formed by volume from two or more distinct elements, where each element maintains the attributes of an individual material, taking advantage of the strengths of each. These materials are typically categorized based on the material utilized as the matrix, including metal matrix, ceramic matrix, and polymer matrix. Beyond these three categories, there are various other types of composites, such as a particular form known as fiber-metal laminate, sandwich composite type, and nano composite type. Composites employed in aircraft manufacturing are predominantly made of polymer matrix substances. Metal matrix composites, ceramic matrix composites, and fiber-metal laminates are used in significantly smaller proportions [25]. 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 [26]. Fig.7 shows some ceramic matrix applications addressed in the aircraft engine gas turbine industry.

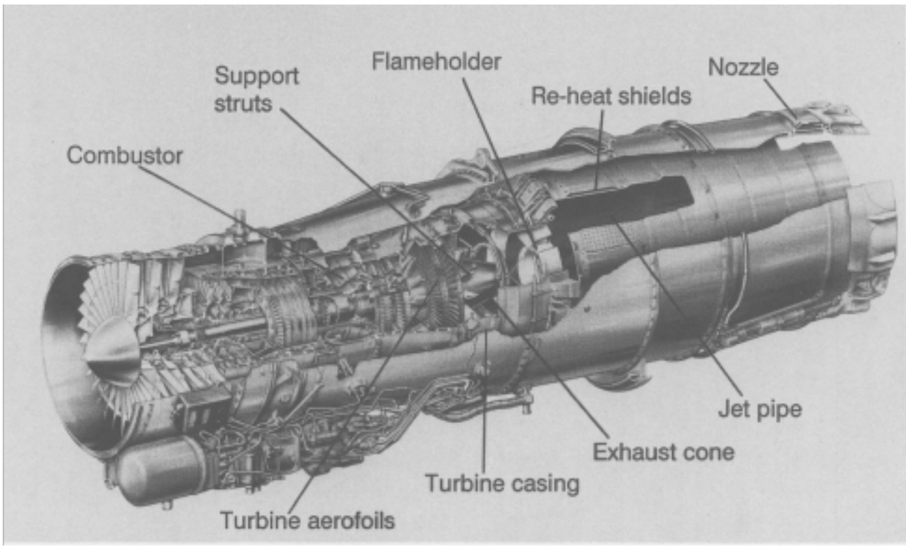

Fig. 7. Potential applications for ceramic matrix composites in military engines [27].

Fiber-reinforced polymer composites have a long-standing history of application. These composites were initially selected in the 1940s for their resistance to corrosion and their high strength-to-weight ratio. The first composite material created consisted of glass fibers embedded in a low-strength polymer matrix. This material was utilized in several prototype aircraft components and filament-wound rocket engine casings during the late 1940s and 1950s. Initially, composites were not widely adopted due to the high production costs of the original fiberglass materials. Due to insufficient processing techniques, their mechanical characteristics were inconsistent and variable, making them difficult to produce. At the same time, delamination cracking was more likely when exposed to events such as bird strikes. Moreover, due to the low modulus of elasticity of glass fiber composites, they were not employed in structural applications requiring high rigidity. Over time, composites were gradually integrated into semi-structural aircraft components like engine fairings and landing gear doors during the 1950s and 1960s to decrease weight and combat corrosion.[2]

With the industrial manufacturing of carbon fiber in the 1960s, the use of composite materials surged significantly. Carbon fiber composites are lightweight, resilient, strong, and resistant to fatigue and corrosion, which has made them broadly accepted for potential uses in airframes and engines. Initially, carbon fibers saw limited application due to the poor understanding of the design principles, structural properties, high costs, and technical challenges in certification. Until the 1970s, carbon fiber composites used in aircraft constituted less than 5% of the structural weight. However, following the OPEC energy crisis of the 1970s and aluminum's poor resistance to corrosion, the use of carbon fiber composites in both military and commercial aircraft grew. In the 1980s and 1990s, with advancements in design methodologies and manufacturing processes, along with a rise in the cost of carbon fiber, the adoption of composite materials in aircraft increased.[2] 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 ultrathin CFRP composites, which have applications in energy storage and aerospace [28].As shown in Fig.3.6, almost all aerospace programs use a significant amount of composites.

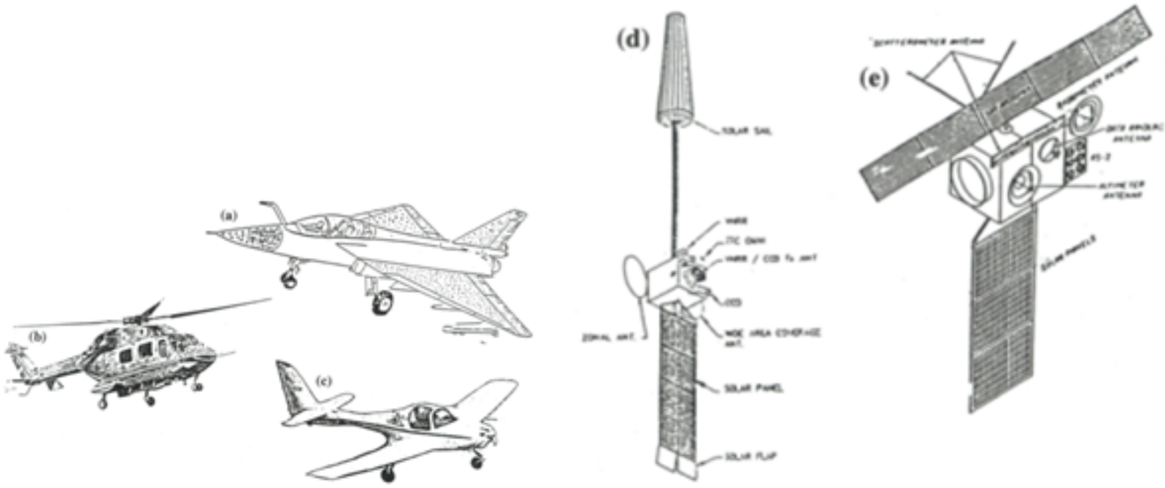

Fig. 8. Use of composites in various aerospace programmes: (a) A military aircraft with wings, fin, control surfaces, and fuselage panels made in carbon-epoxy, radome in aramidpolyester. (b) An advanced helicopter using aramid, glass and carbon composites in all structural parts. (c) An all composite 2-seater transport aircraft using glass-epoxy supplemented with carbon. (d) and (e) satellites using carbon composites for solar panels, antennae, etc. [29]

4. Conclusions

Advancements in material technology can be categorized into two groups: evolutionary and revolutionary developments. Evolutionary advancements refer to the discovery of new alloys with different compositions or modest enhancements in existing materials, such as through heat treatment or machining techniques. Almost every new material faces some initial challenges, so the evolutionary approach, which focuses on refining existing materials, is typically favored. For the aerospace industry, gradual improvements in traditional materials are the more straightforward and preferred approach, as there is extensive knowledge regarding their design, manufacturing, maintenance, and repair. 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 [30] Revolutionary advancements in aerospace involve the adoption of entirely new materials that differ significantly from those previously used in aircraft construction or engine components. One example of such a breakthrough is the introduction of carbon fiber composites in the production of the tail section of the B777 commercial jet in the mid-1990s. Another notable case is the first application of GLARE, a fiber-metal laminate, in the airframe of the A380 in 2005 [2].

The direct application of revolutionary materials in aircraft has been limited due to the high costs involved in production, qualification, and certification. The expenses and time required to develop a new material, test it, and validate its suitability for safety-critical components are substantial. Introducing new materials may also necessitate significant modifications to the manufacturing infrastructure of aircraft production plants and maintenance and repair facilities. For instance, incorporating new radar-absorbing materials into stealth aircraft or dealing with challenges such as bird strikes, hail, and lightning strikes calls for the development of novel repair techniques. Despite these challenges, revolutionary materials are integrated into new aircraft when the advantages outweigh the potential risks and obstacles.

A broad range of both evolutionary and revolutionary developments continues to shape the next generation of aircraft material technologies. Some of these advancements include: the development of high-temperature polymers for composites that can operate at temperatures exceeding 400°C; novel polymer composites reinforced and hardened by the addition of carbon nanotubes or nano-sized clay particles; composites strengthened through thickness by methods such as stitching, orthogonal weaving, or z-needling; multifunctional materials that fulfill various roles such as thermal regulation, load-bearing strength, self-assessment, health monitoring, and self-healing; bio-inspired polymer materials with self-repairing abilities; sandwich materials with trusses or periodic open-cell cores, and high-performance metal foam cores; newly developed hard ceramic materials; easily solidifying amorphous metals with enhanced mechanical properties and resistance to corrosion; and innovative welding and joining techniques for different materials. Ongoing advancements in structural and engine materials are essential for the progress of aerospace engineering. Material research continues to meet the objectives of higher performance, reduced operating costs, and more environmentally sustainable propulsion systems.

As aircraft technology has advanced, the materials used in aircraft structures and engines have greatly improved over the past century. As airplanes grew faster, larger, and more sophisticated, the demands on materials also increased. While strength and weight remain the primary factors in material selection, as aircraft technology progresses, choices are increasingly influenced by various factors such as structural performance, durability, damage tolerance, economic considerations, environmental impact, and others. This has made improvements in aerospace material properties essential over the last 100 years, and these advancements are expected to persist as research and development in new materials and processing techniques continue.

Author Contribution

Ayşe Ece Aşık Yılmaz: Conducted a literature review, Conceived and designed the analysis, Wrote the paper, Prepared the paper for publication.

Ömer Civalek: Conducted a literature review, Designed and directed the paper, Verified the theories and methods, Prepared the paper for publication.

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