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Journal of Scientific Reports-A

journal homepage: *https://dergipark.org.tr/tr/pub/jsr-a*

E-ISSN: 2687-6167 ***Number 58, September 2024***

REVIEW ARTICLE

Receive Date: 09.05.2024 *Accepted Date: 28.06.2024*

Evolving trends and advanced applications of engineering materials in contemporary aircraft: a review

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Abstract

This review article discusses the engineering materials used in aircraft, with a focus on aluminum alloys, titanium alloys and composite materials, including where and why they are most used in aircraft. There are many research papers that deal in detail with materials such as aluminum alloys, titanium alloys and composites used in an aircraft, including theoretical and experimental results. However, the author felt that a review of aircraft materials was necessary, both for himself and to help others interested in similar topics. In addition, the author felt the need of thinking back to the past on what materials used to be prevalent and what materials have superseded them. One such example written in this study is the case of Aluminum that used to be the predominant material in aircraft structural components, has been increasingly supplanted by polymer composites in recent years due to their advantageous properties. It is hoped that from this review article the reader will be able to understand the general trend of recent developments in aeronautical engineering materials and be able to choose which path to follow and which area to focus on in their future research.

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Keywords: Aircraft materials; aluminum alloy; titanium alloy; polymer matrix composite; metal matrix composite; ceramic matrix composite.

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1. Introduction

In the past decades a focus on developing better aircraft materials and a trend to use more composite materials are seen in Aerospace Industry and this leads to the need of aircraft material review for both researchers and industrial manufacturers alike [1–4]. Prime example for this is the Boeing 787 that uses 50% composite materials compared to its predecessor Boeing 777 that only uses 11% [5]. Boeing 787 only uses about 20% aluminum alloys compared to 70% in Boeing 777 [6]. The reason for using composite materials instead of metal alloys such as aluminum alloys is because the driving force in many airline companies is cost reduction for aircraft purchase and operation [7-9]. This cost reduction is derived from reducing weight of the aircraft by using composites instead of aluminum alloys [10]. The reduction of weight means less fuel needed for aircraft operation which in turn means less operating cost [11,12]. It should be noted that the material selected should not increase the cost of production by more than the cost reduction resulting from the reduction in weight [13,14]. Another way to reduce total cost is to build a more durable aircraft with very high tensile strength, elastic modulus, and/or damage tolerance [15]. This way less maintenance is needed and less cost will be incurred [16,17]. Several design trials have been made and the result shows that reducing the weight is 3-5 times more effective than increasing the durability [18].

Following the consideration that aircraft materials need to be lightweight while not compromising its strength, polymer matrix composites came to a rise [19,20]. Polymer Matrix Composites or commonly known as PMC have better mechanical properties such as higher specific modulus, normalized-by-density specific strength, fatigue, and corrosion resistance than aluminum alloys [21,22]. Nevertheless, there are instances where the PMC is unable to provide protection due to its relatively low resistance to impact and inability to withstand extremely high temperatures like the turbine blades inside the engine [23]. Engine pylon also requires high-strength material capable of supporting the engine weight and thrust and thus, steel and titanium are chosen [24]. Figure 1 shows the materials used in the Boing 787 aircraft and the distribution of these materials in the aircraft components conforming to the fact that not all aircraft parts can be made out of PMC. Certain parts like the leading edge (colored red in Figure 1), the joining between wings and fuselage (colored green in Figure 1) and engine pylon (colored yellow in Figure 1) are using aluminum, fiberglass, and steel/titanium respectively.

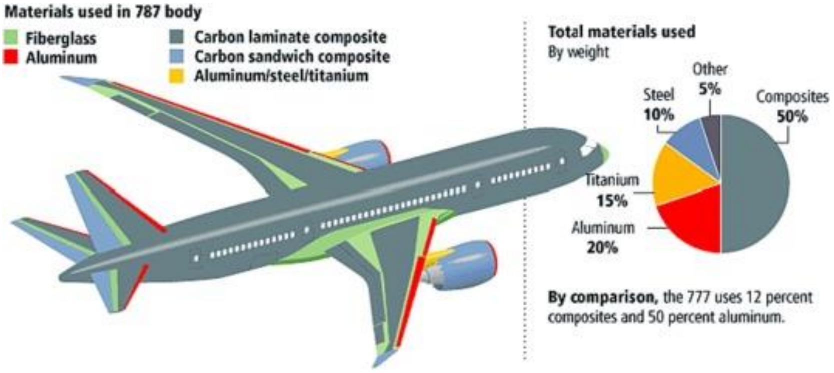

Fig. 1. Boeing 787 materials. It was adapted and reprinted by B. Parveez et al. in MDPI in 2022 [25].

When an aircraft is flying, various parts of the aircraft are affected by different types and amounts of loads [26]. The atmospheric pressure above sea level will be lower than that on the sea level (when aircraft is on ground) [27]. Human would prefer a stable and not too low atmospheric pressure otherwise some medical complications could happen such as difficulty in breathing and in extreme case, the bubbling of blood due to very low atmospheric pressure [28]. For this reason, typical commercial aircraft that flies high will have a pressurized cabin for both aircraft crew and passengers [29]. The cabin is inside the fuselage, and thus fuselage will be like a pressurized vessel [30]. Fuselage is being held by the wing during flight, this in turn causes the fuselage to experience bending load too [31]. To summarize this part, the fuselage of an aircraft will experience bending compression and tension loads and shear stress due to pressure difference [32]. These loads will mostly be loaded to the skin of the fuselage and to alleviate some of them, stringers and frames are added to the fuselage [33]. Stringer help holding the compression and tension loads transferred from skin [34]. In addition, frames help give the fuselage shape and maintain it [34]. Also, for the fuselage, the front of the cockpit will be more exposed to pressure from airflow than the sides of the fuselage [35].

The same situation cannot be mentioned on the wings. The wing of an aircraft can be thought of as a cantilever beam extending from the fuselage, subject to bending and torsion during flight due to the lift force acting on the wings [36]. Think of it like a wide beam hanging from a building that is given an upward force to lift said building but the force is not distributed evenly hence the torsion of the beam [37]. Additional wing loads may also occur during taxiing, take-off, and landing due to the position of the landing gear and due to the use of flaps and slats on the trailing edges [38]. Aircraft on ground will put most of its weight on the landing gear hence there will be force concentration around it [39]. Think of it like the wide beam from before is now getting supported by pillars and the building is floating because the pillars lifted the building up [40]. The wing of an aircraft has weight too, so in the absence of lifting force this cantilever beam will instead feel the downward force from its own weight [41]. This means the wing will experience bending in both up and down direction, and thus the upper and lower wing will also experience compression and tension due to the different bending alternatingly [42].

Also, landing gear strut and wheels will mostly deal with the impact during landing and to hold the aircraft on ground [43]. The more an aircraft weight the higher requirement the landing gear will have [44]. It is apparent that although a soft landing is preferred for passenger safety and comfort, a hard landing will occur due to environmental reasons or some unforeseen emergency situations [45]. Therefore, landing gear must be able to withstand severe impact loads to ensure that the integrity of the aircraft is not compromised [46]. Evidently, the plane is also expected to have a braking system so that it can stop after landing. The aircraft braking system is also important to ensure that the aircraft can land safely [47]. The disc brake will need to be designed in a way that it can withstand high pressure and high temperature during this braking [48].

The engine of an aircraft is an intricate and delicate system of propulsion, air circulation, and electric power generation [49]. Different parts of this engine will experience different loads in different temperature and requires different materials [50]. Generally, when discussing about the aircraft engine materials, the turbine and compressor blades, combustion chamber, and the nozzle are the three most discussed components [51]. The turbine and compressor blades are rotating in high speeds and experience high temperature. This requires materials that have high specific strength even when subjected to high temperature. As for the combustion chamber, the main concern will be the very high pressure and very high temperature produced from the combustion of fuel and air in a contained space. The materials used in this section must not melt and still maintain their shape integrity [52].

This review article will discuss the types of materials commonly used as aircraft materials and why they are used in the part of the aircraft. Table 1 provides information about the materials used in aircraft.

Table 1. Materials used in an aircraft [53].

No	Material		Application
1	Aluminum Alloys	Aluminum-Copper (Al-Cu) alloys	Fuselage skin and lower-wing skin
		Aluminum-Zinc (Al-Zn) alloys	Upper-wing skin, stringers, stabilizers
		Aluminum-Lithium (Al-Li) alloys	Fuselage skin and upper-wing skin
2	Titanium Alloys	Alpha-Titanium (α-Ti) alloys	Fan blade

		Beta-Titanium (β-Ti) alloys	Landing gear, springs
		Alpha-Beta Titanium alloys	Disc blade of the compressor
3	Composite	Polymer Matrix Composite (PMC)	Fuselage, ailerons, flaps, landing gear door
		Metal Matrix Composite (MMC)	Fuselage skin and wide-body wing
		Ceramic Matrix Composite (CMC)	Exhaust nozzle, aircraft brakes

2. Aluminum alloys

Aluminum alloys have been used as aircraft materials for many years due to its mechanical behavior, ease of design, well-developed manufacturing process and material inspection techniques [54]. Material properties such as density, strength, Young’s modulus, fatigue resistance, fracture toughness and corrosion resistance are the important parameters that need to be tailored according to the particular component of the aircraft [55]. For this reason, different types of aluminum alloys are introduced. Aircraft fuselage’s main design criterion is damage tolerance, thus aluminum-copper alloy is used for fuselage [56]. While the upper-wings main design criterion is compressive strength and fatigue resistance, thus aluminum-zinc alloy is used for upper-wings [57]. Aluminum-lithium alloys are specially made to reduce weight without reducing strength and replaced the conventional Al-Cu and Al-Zn alloys in their respective application areas [58].

2.1. Aluminum-Copper (Al-Cu) alloys

The most well-known among aluminum alloys are aluminum-copper (Al-Cu) alloy. Al-Cu alloys, commonly referred to as the Aluminum 2000 (Al-2XXX) series, are designated by a four-digit code starting with '2' to indicate their series, followed by three additional digits to indicate other alloying elements and properties [59]. Certain alloys in this series undergo specialized tempering processes, which is reflected in their names with an appended ‘-Txx’ [60]. A notable feature of these alloys, as indicated in the Table 2, is their substantial magnesium content [61]. This is of particular importance because the inclusion of magnesium in the 2000 series alloys enhances their resistance to fatigue crack propagation, a property that aligns with the critical design requirement of damage tolerance in aircraft fuselage structures [62].

Table 2. Chemical composition of two 2000-series aerospace aluminum alloys [63].

Components (wt. %)	Al 2024	Al 2524
Al	remainder	remainder
Cr	⩽0.1	⩽0.05
Cu	3.8 – 4.4	4.0 – 5.5
Fe	⩽0.5	⩽0.12
Mg	1.2 – 1.8	1.2 – 1.6
Mn	0.3 – 0.9	0.45 – 0.7
Si	⩽0.5	⩽0.06
Ti	⩽0.15	⩽0.1
Zn	⩽0.25	⩽0.15

Of these alloys, the oldest historically aluminum alloy, Al 2024-T351, was the material of choice for the construction of aircraft fuselages due to its robust yield strength, superior resistance to fatigue crack growth, and impressive fracture toughness [57]. However, this type had limited use in high-stress areas of aircraft due to its low yield stress [64]. By reducing contaminants such as iron and silicon, significant improvements in fracture toughness and resistance to fatigue crack initiation and growth have been achieved as shown in Table 3 when comparing the number of impurities (Fe, Si, Cr, Ti) [65].

Table 3. Mechanical properties of two 2000-series aerospace aluminum alloys [63].

Mechanical Properties	Al 2024-T351	Al 2524-T3
Ultimate Tensile Strength	428 MPa	434 MPa
Yield Strength	324 MPa	306 MPa
Fracture Toughness	37 MPam$^{1/2}$	40 MPam$^{1/2}$
Elongation	21 %	24 %

The Al 2524-T3 alloy, known for its high damage tolerance and outstanding fatigue characteristics, has shown a 15-20% increase in fracture toughness and a 30-40% extension in lifespan before failure compared to the Al 2024-T351 alloy, all while maintaining strength and corrosion resistance [66]. These advancements have contributed to weight reductions and an extended service life for the Boeing 777, leading to the replacement of Al 2024-T351 with Al 2524-T3 [67].

Further studies involving observation and microstructural analysis have been conducted to investigate the fatigue crack behavior of the Al 2524-T3 alloy [68–71]. The microstructure, which encompasses inclusions and grain orientations, revealed that inclusions significantly influence fatigue crack progression, forming large voids that act as conduits for accelerated crack propagation [66].

In the aircraft industry, protective coatings are commonly applied to surfaces to mitigate corrosion damage, however, such coatings can diminish mechanical performance and incur high production and maintenance costs [72]. Nickel fluoride sealed anodic films on aluminum alloys offer stable passivity and robust resistance in neutral and basic NaCl solutions. Yet, their effectiveness is compromised in acidic NaCl environments, where passivity and resistance are notably weaker [73].

2.2. Aluminum-Zinc (Al-Zn) alloys

Aluminum-Zinc alloys, categorized under the Aluminum 7000 series, exhibit greater strength compared to the 2000 series [74]. Consequently, they are the preferred choice for critical aircraft structures such as the upper-wing skin, stringers, and stabilizers [75]. These components primarily handle the stresses of compression and tension due to bending forces [76]. Stringers serve as structural reinforcements that fortify the aircraft’s skin [77]. The empennage, or tail section of a conventional aircraft, comprises horizontal and vertical stabilizers, which are primarily influenced by aerodynamic lift forces, leading to bending [78]. Table 4 gives information on the chemical composition of aluminum alloys for the two 7000 series of aircraft.

Table 4. Chemical composition of two 7000 series aerospace aluminum alloys [63].

Components (wt. %)	Al 7075	Al 7475
Al	remainder	remainder
Cr	0.18 – 0.28	0.18 – 0.25
Cu	1.2 - 2	1.2 – 1.9
Fe	⩽0.5	⩽0.12
Mg	2.1 – 2.9	1.9 – 2.6
Mn	⩽0.3	⩽0.06

Si	⩽0.4	⩽0.1
Ti	⩽0.2	⩽0.06
Zn	5.1 – 6.1	5.2 – 6.2

The Al 7075 alloy boasts greater strength compared to Al 2024 [79]; however, its fatigue resistance is compromised by its susceptibility to corrosion [80]. The onset of corrosion markedly diminishes the ultimate strength of the aluminum alloy [81,82]. Following the initiation of corrosion, there is a consistent decline in strength coupled with an escalation in mass loss [83,84]. As the mass loss progresses, the fatigue life of the alloy decreases exponentially [85]. Al 7075 was used extensively in the past before the problem with corrosion induced fatigue crack was unveiled, and were either replaced or treated with anti-corrosion protection [86].

The Al 7475 alloy, an advancement over the earlier Al 7075, exhibits enhanced strength, fracture toughness, and fatigue crack propagation resistance [87,88]. This progress stems from the reduction of iron and silicon impurities as shown in Table 4. Characterized by a fine grain structure and optimal dispersion, the Al 7475 alloy achieves the highest levels of toughness [89]. Moreover, Al 7475 T7351 plates maintain strength comparable to Al 7075 while offering fracture toughness values that are up to 40% higher [80].

2.3. Aluminum-Lithium (Al-Li) alloys

Weight reduction is a primary objective in optimizing materials for aircraft construction [90]. At this point, another Al alloy; Al containing lithium (Li), come into play. Li stands out as one of the rare elements that has low density as well as good solubility in Al [91]. The incorporation of each 1% increment of Lithium leads to a 3% reduction in the alloy’s density [92]. While Lithium is effective for density reduction, it has been noted that adding merely 1% can significantly diminish the alloy’s specific strength [93]. On the other hand, enriching the alloy with 2%-3% Lithium can enhance the specific strength by 60%-80% [93].

The first and second generations of Al-Li alloys primarily aimed at density reduction, offering benefits such as decreased density, higher modulus of elasticity, and prolonged fatigue life [94]. However, they suffered from lower fracture toughness in short-transverse and plane stress conditions due to increased tensile property anisotropy [95]. The third-generation alloys are crafted with refined composition and tempering to balance density, strength, and toughness, while also enhancing fatigue crack growth resistance, corrosion resistance, thermal stability, and ease of manufacturing [96].

Al 2198 alloy, developed to supersede Al 2024 and Al 2524 where damage tolerance is critical, contains 2.9%-3.3% Cu and 0.9%-1.1% Li [97]. Stress rates for these structures are also evaluated. With a stress ratio (R=0.1), the fatigue endurance limit is only 8% below the yield stress compared to the 40% below the limit of Al 2024 and also has a reduced density [98]. Under equivalent normalized stresses, Al 2198-T351 can absorb 2-3 times more energy before fracturing than Al 2024, showcasing enhanced damage tolerance [99].

The Al 2060 alloy, belonging to the latest third-generation Al-Li alloys, consists of 3.95% Cu, 0.75% Li, and 0.85% Mg [100]. This generation’s application to fuselage skin can lead to a 7% weight saving, and a 14% saving for upper-wing skin, relative to the conventional Al 2524 and Al 2024 alloys [101]. Test results (III generation) have shown that incorporating advanced structural designs not only enhances material properties and damage tolerance in critical areas but also supports fusion welding [102]. The standardized tooling, established assembly techniques, and streamlined repair and maintenance procedures, coupled with the recyclability of Al-Li alloys, enable them to rival polymer composites in the aerospace industry [103].

3. Titanium alloys

Between the 1960s and the 2010s, the application of titanium-based alloys in aircraft manufacturing has surged from 1% to 19% [104]. These alloys are utilized in both the structural framework and engines of aircraft, owing to their high specific strength, exceptional corrosion resistance, and superior performance at elevated temperatures [105]. Titanium alloys are classified into three types: alpha, beta, and alpha-beta [106]. The distinct properties of each type are determined by their microstructure, which in turn is influenced by their chemical makeup and the thermomechanical processes they undergo [107].

3.1. Alpha-titanium alloys

One of the most well-known structures among Ti alloys is Alpha titanium alloys. Alpha titanium (α-Ti) alloys are predominantly composed of the α phase, supplemented by neutral elements or α stabilizers [108,109]. These alloys are typically employed in aircraft components that encounter severe corrosive environments but are not exposed to intense mechanical or thermal stress, such as support structures [109]. For instance, CP-Ti is utilized in support structures and environmental control systems functioning around 230 °C, whereas Ti-6-2-4-2S is applied in gas turbine engine components operating at temperatures up to 540 °C [110]. Incorporating aluminum into alpha titanium alloys not only enhances their strength but also contributes to a lighter alloy composition [111].

3.2. Beta-titanium alloys

Another one in this structure is Beta Titanium (β-Ti) alloys. B- Ti alloys, which are primarily made up of the β phase and contain β stabilizers, are integral to the manufacture of high-stress aircraft components like landing gear and springs [112]. For instance, the Ti-13-11-3 alloy has been extensively utilized in the SR-71 aircraft, while the Ti-10-2-3 alloy is predominantly employed in the Boeing 777’s landing gear, offering a significant weight saving of 270 kg over traditional steel [110,113].

3.3. Alpha beta-titanium alloys

The most preferred alloy among Ti alloys is Alpha beta Ti alloy. This is the most widely used Ti-based alloy because of the excellent combination of strength, fracture toughness, and ductility [114]. In alpha-beta Ti-based alloys, the flow stress escalates as the strain rate rises at a constant temperature, and conversely, it diminishes as the temperature increases at a steady strain rate, leading to a more pronounced flow softening effect in the stress-strain curves of alpha-beta Ti-based alloys compared to those composed solely of alpha or beta phases [115]. The alloy that is sold and used extensively in the United States is Ti-6Al-4V which is most used in high-temperature compressor part of the engine and most other aircraft parts that requires high strength-to-weight ratio material [110,116].

Table 5. Mechanical properties of three alpha, beta, and alpha-beta aerospace titanium alloys [110].

Mechanical Properties	Ti-6-2-4-2S	Ti-10-2-3	Ti-6Al-4V
Ultimate Tensile Strength	1010 MPa	1000-1400 MPa	900-1200 MPa
Tensile Modulus	114 GPa	110 GPa	110-140 GPa
Yield Strength	990 MPa	1000-1200 MPa	800-1100 MPa
Hardness	340 HV	300-470 HV	300-400 HV

Several mechanical properties for all three titanium alloys are shown in Table 5 above. Ti-6-2-4-2S is the example for alpha titanium alloy, Ti-10-2-3 is the example for beta titanium alloy. Meanwhile Ti-6Al-4V is the example for alpha-beta titanium alloy. It can be inferred that beta titanium alloys are the strongest among the three types.

4. Composites

Another structure most used in aircraft is composites. A composite is a material structure that consists of at least two macroscopically identifiable materials that work together to achieve a better result [117,118]. The matrix of composite determines the major characteristics while the other material(s) reinforces it [118]. The purpose of having matrix with reinforcements is to get the best properties and to reduce the negatives [119]. An example of composite material engineering is when a strong, yet brittle substance is combined with a ductile and lightweight matrix resulting in a material that retains toughness while being less brittle and still maintaining its lightweight characteristic [120]. Based on the material of the matrix, we can categorize composite into three types: polymer matrix, metal matrix, and ceramic matrix composites [121]. We can infer from Fig. 2 that Polymer Matrix Composite (PMC) has the highest specific strength (strength divided by density) among other materials but has the lowest temperature. For this reason, composites capable of higher temperature like Metal Matrix Composite (MMC) and Ceramic Matrix Composite (CMC) are also developed despite having lower specific strength than PMC [122].

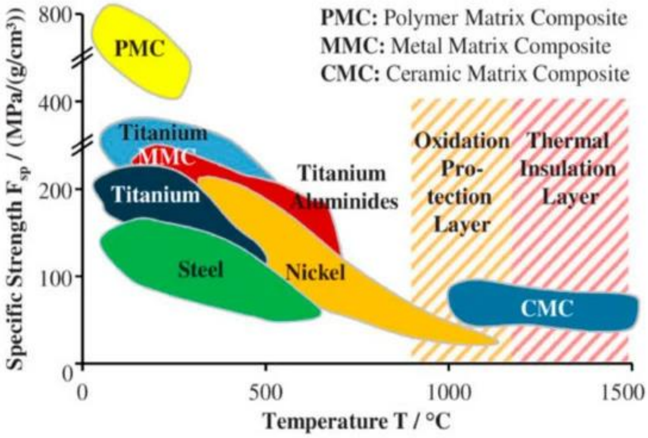

Fig. 2. Specific strength and temperature potential of PMC, MMC, CMC. It was adapted and reprinted by B. Parveez et al. in MDPI in 2022 [25].

Composite materials came to a rise in recent years due to the advancement in health monitoring of composite structures by having a good understanding of the aerodynamic forces-induced wave propagation through the materials [123]. This numerical analysis allows aircraft engineers to implement more composite structures [124].

4.1. Polymer Matrix Composite (PMC)

In composite materials with a polymer matrix, fibers are embedded within a polymer, referred to as the ‘matrix’ [125]. This integration slightly diminishes the inherent strength and stiffness of the fibers due to their combination with the polymer, thus production methods generally aim to minimize the polymer content to retain the fibers’ robust characteristics [126]. The primary purpose of the polymer matrix is to serve as a binder, securing the fibers in place, which then make them capable of withstanding greater compressive forces and distributing loads more effectively from one fiber to another via shear stresses [127]. This results in a more efficient spread of external loads across the fibers in the composite, as opposed to a mere aggregation of dry fibers [117]. Research has corroborated that the matrix plays a crucial role in load transfer between fibers, significantly enhancing the material's overall strength [128].

Moreover, the polymer in a composite material plays a pivotal role in defining its responsiveness to external factors like moisture, chemicals, and ultraviolet radiation [129,130]. It frequently influences attributes such as color, surface finish, opacity, and fire resistance [131,132,133]. Polymers utilized in composites fall into two main groups: thermoplastics, which can be reshaped with heat, and thermosets, which solidify permanently after being heated [134].

Thermoplastics are polymers that melt when heated and thus can be remolded. Thermosets are polymers that disintegrate when heated, cannot be remolded. Most commonly used polymers are thermoplastics, but the drawback of using thermoplastic is its viscosity that makes it hard to penetrate evenly throughout the fibers [134]. Some special manufacturing techniques is thus required to make sure the fibers are wetted properly [135]. In the end, the distinction between thermosets and thermoplastics is not clear as some polymers such as polyesters, usually behave like a thermoset but can also be thermoplastic [136]. While some other polymer like phenolic resins behave thermoplastics up to a certain temperature where it behaves like a thermoset [117].

The production techniques for composites significantly influence the final product's quality. Fibers that are not adequately saturated can become points of stress concentration, diminishing the composite's overall ultimate tensile strength [137]. These areas may also serve as origins for crack formation, while regions with dry fibers — those not encapsulated by the polymer matrix due to manufacturing flaws — can hasten and direct the path of crack propagation [138].

The sustainability and recyclability of materials are pressing issues in today's material industry [139,140]. Plastics are notorious for their environmental impact due to prolonged decomposition times [140]. Nevertheless, advanced recycling and re-manufacturing techniques for composites have been developed, with many processes maintaining a high level of mechanical properties, and several commercial-scale facilities are now operational [141].

Polymer Matrix Composites (PMCs) are commonly utilized in various aircraft components such as fuselage skin, wing skin, ailerons, flaps, and landing gear doors [142,143]. The advantage of PMCs lies in their density, which is roughly half that of aluminum alloys, coupled with a modulus of elasticity and tensile strength that are two to three times greater [144]. These properties enable significant weight reductions in aircraft and lessen the reliance on aluminum alloys. However, PMCs have their limitations, particularly regarding the service temperature constrained by the polymer matrix. Ongoing research aims to identify alternative matrix materials that can achieve further weight savings while meeting design requirements [25].

Table 6. Mechanical properties of two Carbon Fiber Reinforced Polymer (CFRP) composites [145].

Mechanical Properties	CFRP 50%	CFRP 60%
Ultimate Tensile Strength	443 MPa	512 MPa
Tensile Modulus	39.0 GPa	51.1 GPa
Compressive Strength	352 MPa	391 MPa
Density	1.36 g/cm^3	1.39 g/cm^3

PMC manufacturing methods affect the mechanical properties heavily. One such empirically-determined material properties for tensile test is shown in Table 6 above. CFRP 50% meant that there are 50% v/v carbon fiber / polymer fraction in the composite. It can be inferred that having more carbon fiber means more strength at the cost of weight.

4.2. Metal Matrix Composite (MMC)

Metals such as steel, titanium, and nickel alloys are considered for matrix materials due to their ability to withstand temperatures significantly higher than those tolerated by Polymer Matrix Composites (PMC) [146]. Metal Matrix Composites (MMC) are created by embedding ceramic materials within a metal matrix, enhancing the composite's yield strength, fracture toughness, thermal expansion coefficient, creep resistance, and wear resistance [147]. Consequently, MMCs are emerging as alternatives to traditional aluminum alloys [148].

Research on MMCs has particularly focused on aluminum matrices reinforced with silicon-carbide (Si-C) ceramics [149,150]. A major challenge has been the welding of these materials, which previously limited MMCs' application in aircraft [151]. However, recent studies have demonstrated that employing harder tools can significantly improve the wear resistance of the welds, thus overcoming this obstacle [152].

Some other recent studies have revealed that metal composites reinforced with nanoparticles outperform those with microscale reinforcements, leading to the development of nanocomposites [153,154]. It is apparent that nanoparticles are used in sensors, pharmaceutical research, fuel cells, etc. [155–161]. It is used in many areas as well as in aircraft materials. Among these nanostructures, carbon structures are encountered due to their abundance and superior properties. Graphene, graphite, carbon nanotubes and fullerenes can be given as examples. Also, research indicates that the inclusion of nanotubes and graphene nanosheets significantly bolsters the stiffness and strength of these materials [162]. Despite the challenges in achieving optimal integration of the reinforcements within the metal matrix, progress is being made. Achieving a uniform distribution of nanoparticles is crucial for balancing the rigidity of ceramic reinforcements with their spacing, thus optimizing yield strength and creep resistance while preserving ductility [154].

Metal Matrix Composites (MMCs) are employed in areas of aircraft such as fuselage and wing skins, where high temperatures due to air friction and pressure are prevalent, replacing Al 7000 series alloys [163]. Advanced aluminum alloy composites include Al A356 with 4 wt.% nano Al2O3, produced via stir casting, which boasts a compressive strength of 630.5 MPa, and Al 2009 reinforced with 1 wt.% and 3 wt.% carbon nanotubes through friction stir processing, yielding a strength of 385 MPa and an ultimate tensile strength of 477 MPa [164]. Additionally, there are MMCs based on aircraft aluminum alloys such as Al 2024 and Al 7075; for example, Al 2024 combined with 5 wt.% graphite and 20 wt.% SiC via powder metallurgy has a density of 2.94 g/cm^3 and a hardness of 63 BHN (approximately 68 Hv), while Al 7075 with 7 wt.% SiC and 3 wt.% graphite, created through stir casting, has a density of 2.784 g/cm^3 and a hardness of 219 Hv [164].

4.3. Ceramic Matrix Composite (CMC)

Ceramics are highly regarded for their application in components that endure extreme stress and temperatures [165]. Yet, their widespread adoption is limited due to their inherent brittleness, which leads to low fracture toughness, and a susceptibility to vibration-induced damage, culminating in a reduced ability to withstand fatigue from such vibrations [166]. To enhance their performance and mitigate brittleness, ceramics are being reinforced with nanoparticles. The most prevalent nanocomposite materials used in Ceramic Matrix Composites (CMCs) are Graphene Nanoparticles (GNPs) and Carbon Nanotubes (CNTs) [167,168]. This in turn produces a good strength to weight ratio at really high temperature where no metal alloys can manage [169]. Most polymer matrix composites and aluminum alloys cannot manage more than 350-400 °C while Titanium alloys and Nickel-based superalloys cannot manage more than 700 °C and 1000 °C respectively [170].

Recent studies have shown that GNPs exhibit better nanocomposites than CNTs due to the difficulty in ceramic matrix dispersion in CNT reinforced composites. GNPs are well dispersed in ceramic matrix microstructure. Exact measurement of GNPs fraction is a must to ensure porosity is not too much and fracture toughness is not compromised [166,171].

Extensive testing and analysis on carbon fiber-reinforced ceramic matrix composites for nozzle applications have demonstrated that the C/SiC material endures temperatures up to approximately 2300 K (around 2022 °C) while preserving its structural integrity without any deformation and when compared to traditional metal alloy nozzles, this composite material offers a substantial 60% reduction in weight, attributable to its exceptional thermophysical and mechanical properties [169,172,173].

Ceramic Matrix Composites (CMCs) are employed in areas of aircraft that are exposed to extremely high temperatures, such as the engine nozzle and the disc brakes of the landing gear [174]. Key components include combustion lines, ducts, nozzle flaps, acoustic liners, turbine vanes, blades, and discs, among others. However, the application of Ceramic Matrix Composites (CMCs) faces challenges such as insufficient manufacturing and processing technologies, a need for standardized design methodologies, and advanced maintenance evaluation techniques [175].

Machining plays a crucial role in the manufacturing of products and influences the operational performance of components. Given the harsh conditions that Ceramic Matrix Composites (CMCs) are subjected to, any production flaws could significantly shorten their expected service duration [176]. The conventional machining process of carbon fiber reinforced ceramic matrix composites includes matrix crushing, interfacial debonding, and fiber fracture that concludes in brittle fractures [177]. There is a need to develop better machining tools suitable for ceramic matrix composites to ensure quality and performance of said material [178].

Traditionally, ceramics are recognized for their brittleness, especially when contrasted with metals, and this characteristic persists in ceramic matrix composites. To mitigate this, the composites are reinforced with fibers engineered to distribute loads uniformly and effectively. This is achieved by fine-tuning the fiber-matrix interaction to prevent microcracks within the matrix itself. Instead, these microcracks are allowed to develop in the interphase, the boundary layer between the fibers and the matrix. This strategic design results in a composite that exhibits greater ductility than its ceramic counterpart [179].

5. Conclusions

The progress of aircraft material development has been tremendous these last few years and it cannot be denied that composites are becoming more prevalent and are replacing the conventional metal alloys. Aluminum alloy used to be the bread-and-butter material for an aircraft until composites were developed. This is because, at first, composites were very costly to produce. In addition, the limitation in design capacity prevented the widespread use of composite materials in the aircraft industry. However, developments in the fields of material production and development have produced important results in overcoming these limitations. After the R&D studies carried out in these composite materials in recent years, cheaper and easier production of polymer matrix composites has become widespread, and they are taking on the role of Al alloys in aircraft structures. In addition, polymer matrix composites that have an impressive strength-to-weight ratio in a low-temperature environment, as well as ductility that provides sufficient flexibility, can be used for aircraft skins and structural supports. Meanwhile, ceramic matrix composites have become a better option for engine components formerly dominated by titanium and nickel-based superalloys. Because these ceramic matrix composites have a higher temperature threshold and are also lighter than their metal alloy counterparts.

The author believes that the future of aircraft materials will be determined predominantly by composites, and therefore research and development should focus on making non-destructive testing on composites more accessible to make composites cheaper and easier, while also ensuring a good service life. In addition, it is evident that there is a significant increase in the popularity of Nanocomposites. In the light of these findings, it can be inferred that composite materials should be developed and taken further. Magnesium alloys, superalloys, smart materials and light weight steels are also gaining importance in response to the rise of composite materials. One research heading recommended by the author is to focus the research on composites and nanocomposites.

Acknowledgements

None

Author Contribution

M.H.I., and F.S.; Conceptualization, Methodology. M.H.I., M.A., M.B.; Data curation, Writing- Original draft preparation. G.K.; Visualization, Investigation. M.H.I., M.A., M.B., G.K., and F.S.; Writing- Reviewing and Editing.

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