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Recent advances in the development of aerospace materials

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ABSTRACT

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

1. Introduction

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

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

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

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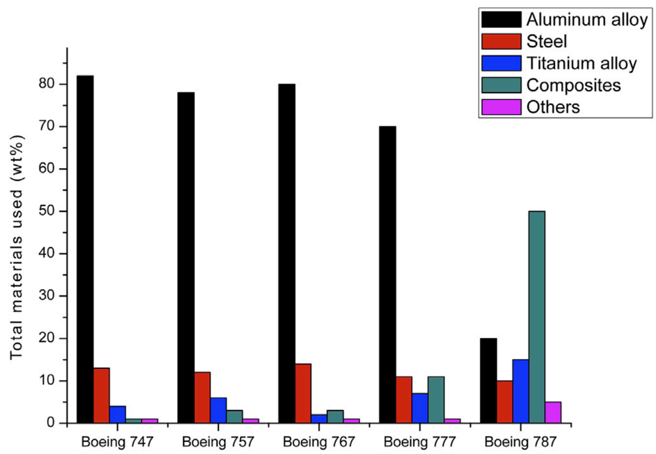

Fig. 1. Total materials used in Boeing series aircraft [1,3].

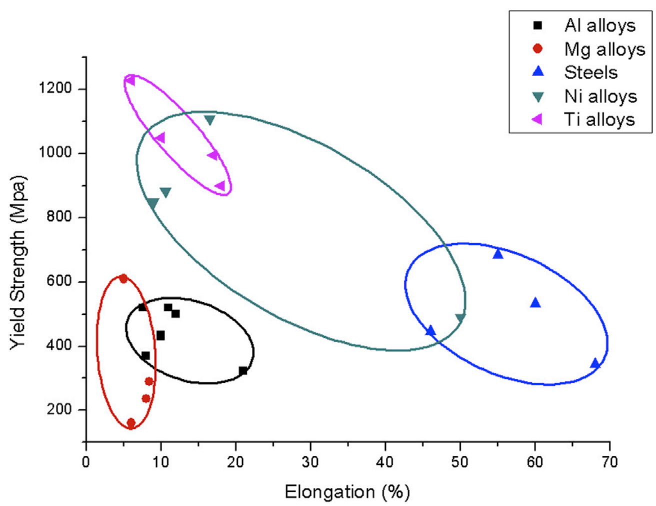

Fig. 2. Typical yield strength and elongation of some metal alloys. Al alloys include 2024-T351, 2324-T39, 7050-T73651, 7075-T651, 7475-T7351, 2099, and 2199 [1]; Mg alloys include $Mg_{97}Zn_1Y_2$, AZ91, Zk60, and WE43 [5]; Ti alloys include Ti-5Al5V5Mo3Cr and Ti-6-4 [12], Ti-10V2Fe3Al [13], and Ti-600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

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

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

2. The design criteria of the aerospace materials

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

2.1. The design criteria of the airframe materials

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

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

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

3. Recent advances in aircraft materials

3.1. Al-based alloys

Al-based alloys have been the primary materials for the aircraft structures before the increased use of composites. Al-based alloys still remain as important airframe structure materials because of their several advantages such as low cost, easy to manufacture, and light weight. Al-based alloys can be heated treated and loaded to relatively high level of stresses. The recent researches on the development of 2000, 7000 series Al-based alloys and Al-Li alloys for aircraft applications are reviewed.

3.1.1. 2000 series Al-Cu based alloys

2000 series Al-based alloys are mainly alloyed with copper and they are heat treatable to strength comparable to steel. Copper has a solubility in Al at the amount of 5.65 wt%. Cu dissolved in the Al matrix forms Al_2Cu phase, and Magnesium is often used in combination with copper to form Al_2CuMg phase. The precipitation of these two phases results in higher strength [1]. In addition, 2000 series Al-based alloys possess superior damage tolerance, and better fatigue resistance than other series Al-based alloys. The properties of some 2000 series alloys, 7000 series alloys, and Al-Li based alloys are shown in Table 1. One of the typical example of 2000 series alloys is 2024 alloy, which has been widely studied as aircraft fuselage material where the damage tolerance is first consideration. However, the relative low yield strength limits the use of 2024 alloy in high stress region. In addition, the intermetallic phase resulted by Cu and Mg can act as anodic site to reduce corrosion resistance of 2024 alloy [1]. To overcome these shortcomings, some elements such as Sn, In, Cd, and Ag have been studied to improve the mechanical properties of Al-Cu based alloys by refining microstructure and grain size. For example, the yield strength (YS), ultimate tensile strength (UTS), and hardness value of Al-Cu-Mg based alloy increase with the content of Sn up to 0.06 wt%, but then decrease with the further increase of Sn content [25]. Further improvement of mechanical properties of Al-Cu based alloys can be achieved by controlling the impurities, such as iron and silicon. For example, 2224-T39 Al-Cu based alloy has higher tensile strength (UTS = 476 MPa) than conventional 2024 Al-Cu based alloy (UTS = 428 MPa) because of the lower contents of iron (0.12 wt%) and silicon (0.10 wt%) than 2024 alloy (0.5 wt% for both impurities) [1].

3.1.2. 7000 series Al-Zn based alloys

7000 series Al-based alloys are mainly alloyed with zinc and they are heat treatable to the highest strength than any other series Al-based alloys. Zinc has the largest solubility (31.6 wt%) in aluminum than any other element, and the increase of Zn content can improve the strength [27]. Mg and Cu often used in combination with Zn to form $MgZn_2$ phase, Al_2CuMg phase, and AlCuMgZn phase in aluminum, resulting in remarkable solid-solute strengthening. The maximum tensile strength of Al-Zn based alloy is achieved at 2.9 wt% Mg content [27]. Some Al-Zn based alloys also contain copper at 2 wt% to improve tensile strength [1]. Al-Zn based alloys exhibit the highest strength of any Al-based alloys, such as 7075 alloy (YS = 510 MPa) Therefore, 7075 alloy is used in building upper wing skin, stringers and stabilizers where strength is the top consideration [1,28]. However, the low fracture toughness and damage tolerance, and poor corrosion resistance limit the use of 7075 alloy in aerospace industry. Recent works focus on the development of Al-Zn based alloys with balanced properties. Dursun et al. reported the modification of Zn/Mg/Cu ratio can improve the damage tolerance of high-strength Al-Zn based alloys [1]. Research has shown that the optimized properties of 7000 series Al-based alloys can be obtained when the Zn/Mg ratio is around three, and Zn/Cu ratio is around four [29]. For example, the recent developed 7085 Al-based alloy is an alternative for 7075 Al-based alloy in aerospace applications due to the high properties (YS = 504 MPa, Elongation = 14%), and better damage tolerance ($44\ MPa\ m^{1/2}$) [30,31]. Zr and Mn have been reported to improve the mechanical properties of Al-Zn based alloys [32,33]. The addition of Zr decreases average grain size (approximately 20%), forms rosette-like microstructure and introduces proper distribution of the second phases [32]. Mn can combine with Fe to form secondary phase in Al-Zn based alloys, which can increase fracture toughness of Al-Zn based alloy by decreasing the adverse effect of Fe on fracture toughness. The optimum Mn content at 1.0 wt% can increase the fracture toughness of 7000 series alloys to $47\ MPa\ m^{1/2}$ [33]. Impurities such as iron and silicon control can also improve mechanical properties of Al-Zn based alloys. The typical example is 7475 alloy, which has higher fracture toughness ($52\ MPa\ m^{1/2}$) and finer grain size than conventional 7075 alloy because of the lower content of iron and silicon (total 0.22 wt%) of 7475 alloy than 7075 alloy (total 0.9 wt%).

Table 1
Mechanical properties of some representative aluminum alloys [1,26].

Alloy	UTS (Mpa)	Yield strength (Mpa)	Fracture toughness, K_{IC} ($Mpa\ m^{0.5}$)	Elongation (%)
2025-T351	428	324	37	21
2026-T3511	496	365	NA	11
2224-T39	476	345	53	10
2324-T39	475	370	38.5–44.0	8
2524-T3	434	306	40(TL)	24
7150X-T6	808.9	776.5	12.7	14.1
7075-T6	656	590	25.5 ± 4.6	11
7475-T651	552	496	42.9	12
2050-T84	540	500	43	NA
2090-T83	531	483	43.9	3
2098-T82	503	476	NA	6
2099-T83	543	520	30(LT)	7.6
2199-T8	400	345	53	10
8090-T851	500	455	33(LT)	12

3.1.3. Al-Li based alloys

The maximum solubility of Li in Al reaches up to 14% at a temperature of 600 °C [34]. The major effect of Li in Al is to reduce the density of Al-based alloys. When 1 wt% Li is added, the density of Al-based alloy is reduced by 3%, while Young's modulus increases by 6% [35]. Therefore, Al-Li based alloys are lightest Al-based alloys [36]. In addition, the addition of Cu is often used in combination with Li to form Al_2CuLi phase to improve the mechanical properties of Al alloys [37]. Consequently, the Al-Li based alloys possess low density and high specific mechanical properties than 2000 and 7000 series alloys. For example, the use of 2060-T8 Al-Li based alloy for fuselage skin and upper wing skin applications can save 7% weight and 14% weight, respectively, compared with that of conventional 2524 alloy and 2014 alloy, respectively [1]. However, high content (>1.8 wt%) of Li in aluminum has been proved to cause an anisotropy problem in Al-based alloys [1,38]. For example, the yield strength of AA2198 Al-Li based alloy in the longitude direction is 90 MPa higher than that in the transverse direction [39]. The anisotropy of mechanical properties results from the crystallographic texture, grain shape and size, and the precipitates in the aging process. In addition, earlier Al-Li based alloys possess low toughness and poor corrosion resistance. Recent studies focus on composition optimization to overcome these shortcomings. The anisotropy problem of Al-Li based alloys can be reduced by introducing recrystallization through optimization of composites and thermal-mechanical processing [40]. For example, the 2198 Al-Li based alloy containing 40 wt% Mn can be recrystallized by 40% in 3 min under the condition of 535 °C [41]. In addition, the yield strength of an Al-Li-Cu-Mg alloy at the rolling direction is 80 MPa higher than it is at 60° from the rolling direction in the condition of under-aged. However, the yield strength of this alloy can be isotropy in over-aged condition [42]. In addition, the low fracture toughness of Al-Li based alloys can be improved by reducing the insoluble second-phase particles such as Al_7Cu_2Fe [4]. For example, the recent advanced 2199 Al-Li based alloy has 20 MPa $m^{1/2}$ higher fracture toughness than earlier 8090 Al-Li based alloy, which is obtained from optimization of composition, thermal-mechanical processing and precipitate microstructure control [1].

3.2. Mg-based alloys

Mg is considered the lightest structural metal [43] and can decrease the weight of structure by approximately 33% when compared to the same volume of aluminum used and by 77% when compared to the same volume of steel used [44]. In addition to low density, the abundance, castability, and recyclability also contribute to the attractiveness of Mg-based alloys [45]. Commercial Mg-based alloys can be divided into two categories: wrought Mg-based alloys and casting Mg-based alloys. Generally, wrought Mg-based alloys have better tensile properties than casting Mg-based alloys but have a higher asymmetry of yield behavior [46]. Admittedly, the use of Mg-based alloys by the top aircraft manufacturers (Airbus, Boeing, and Lockheed Martin) is very limited. Mg-based alloys AZ91, ZE41, WE43A, and ZE41 are used in the helicopter industry to make cast gear box transmissions such as for Sikorsky helicopter S-92® and UH60® helicopters [6,43,47]. The drawbacks of Mg-based alloys for the aerospace industry are their insufficient mechanical properties, poor corrosion resistance, and stress corrosion cracking issue.

To improve the poor corrosion resistance and insufficient mechanical properties, some elements such as Al, Zn, Zr, and rare-earth (RE) elements such as Y are being employed to improve the properties of Mg-based alloys by refining or modifying the microstructure. The most widely studied is Al element. The low-density Al element has a maximum solubility 12.7 wt% in Mg and can merge into Mg to form the phases of γ-$Mg_{17}Al_{12}$ and α-Mg, which is beneficial to solid-solution strengthening. Mg-Al based alloys have moderate mechanical properties and the corrosion resistance, which can be significantly improved by increasing Al content [5,48]. In addition to Al, Zn element can improve the strength and ductility of Mg-Al based alloys at room temperature [5]. The solubility of Zn into Mg is 6.2 wt%, and can form α-Mg and γ-MgZn phases, which are beneficial to improve the strengths of Mg-based alloy. With the increase of the Zn element from 1 wt% to 5 wt%, the yield strength of Mg-Zn based alloys rises. Moreover, the UTS increases to 216.8 MPa and elongation increases to 15.8% when the content of Zn reached up to 4 wt %, and then decreases with additional Zn content added [5,49]. However, the corrosion resistance of Mg-Zn based alloy decreases with the rising Zn content, which is mainly because of the increasing volume fractions of the second phase Mg_xZn_y [50]. In Mg-Zn based alloys, Zr and Y are often used in combination with Zn to improve mechanical properties. Zr is considered the best refiner for Mg-based alloys without Al element due to the reaction of Zr and Al [51]. The benefit of Zr in Mg-Zn based alloy is to refine the grain size and disperse the $MgZn_2$ phase [52]. Homma et al. [52] reported that the UTS and YS of an Al-Zn based alloy increased from 275 MPa and 148 MPa to 357 MPa and 310 MPa, respectively, when the content of Zr increased from 0 wt% to 0.84 wt%. In addition to Zr, the rare-earth element Y can also improve the mechanical properties of Mg-Zn based alloys. The $Mg_{97}Zn_1Y_2$ alloy has the highest strength (YS = 610 MPa) among Mg-based alloys, which is caused by adding Y and the rapid powder metallurgy processing [5]. However, the strengths of Mg-Zn based alloys can be reduced when Y element exceeds the critical amount. For example, Xu et al. reported that the UTS of a Mg-Zn-Zr alloy was increased to 230 MPa by adding 1.08 wt % amount of Y, and then decreased to 180 MPa when the amount of Y was increased to 3.08 wt%. Similar situations occurred on YS. In addition, Xu and co-workers studied the effect of Y on elongation rate of Mg-Zn based alloy, and the results showed that the elongation was decreased to 3.6% when the content of Y increased to 1.08 wt%, and then increased slightly with additional Y content added [53].

3.3. Ti-based alloy

The use of Ti-based alloys has been increased in recent years. As shown in Fig. 3, the operating empty weight (OEW) which is the weight of all operator items, equipment required for flight, and all fluid necessary for operation, has witnessed an increasing use of Ti-based alloys from 1% to 19%. Ti-based alloys have been used for both structure and engine applications, such as aircraft spring, helicopter rotor systems and engine compressor parts, see Fig. 4. The attractiveness of Ti-based alloys is mainly due to their high specific strength, excellent corrosion resistance, and well high-temperature performance. Generally, Ti-based alloys can be divided into three categories based on the type of crystal structure: alpha titanium alloys, beta titanium alloys, and alpha-beta alloys. The recent researches on the development of Ti-based alloys for aircraft applications are reviewed.

3.3.1. Alpha titanium alloys

Alpha titanium alloys can be divided into Alpha and near-alpha alloys, which entirely or mostly consist of α phase with neutral alloy elements or α stabilizers [23]. In general, alpha titanium alloy has a lower density, higher creep resistance and better corrosion resistance than beta titanium alloy [23]. Because of these properties, alpha titanium alloys such as Cp-Ti, Ti-3Al-2.5V, Ti-5-2.5, Ti-8-1-1, Ti-6-2-4-2S, IMI829, IMI834, and Timetal-II00 have been used to manufacture compressor disc blades in aircraft engines [23,56]. Despite the attractiveness of alphas titanium alloy, some research [14,57] has shown that alpha phase can greatly limit the high-temperature capability of titanium alloys. Fortunately, the alpha stabilizing additions enable these alloys to serve in aircraft jet engines in which the temperature can reach up to 600 °C. Al, Sn, Zr, and Si have been investigated to improve the heat-resistance of alpha or near alpha titanium alloys. Al is the most widely used to improve the strengths of alpha titanium alloys at high temperatures [58]. An experiment, conducted by Jiang et al. [59] showed that the tensile strength of a Ti-25Zr titanium alloy increased from 931 MPa to 1319 MPa with the increasing of Al content from 0% to 15%. The yield strength was increased by 47% by raising the addition of Al to 15%. However, the elongation decreased from 14.79% to 5.55% with the increase of Al content. The strength efficiency of Al in Ti-Zr based alloys is mainly due to the size and modulus misfits between Al and Zr.

3.3.2. Beta titanium alloys

Beta titanium alloys are entirely or mostly consist of β phase with β stabilizers. Beta and near-beta alloys have higher tensile and fatigue strength than alpha titanium alloys, and easier fabrication into some semiproducts [60]. The high strength of beta titanium alloys is resulted

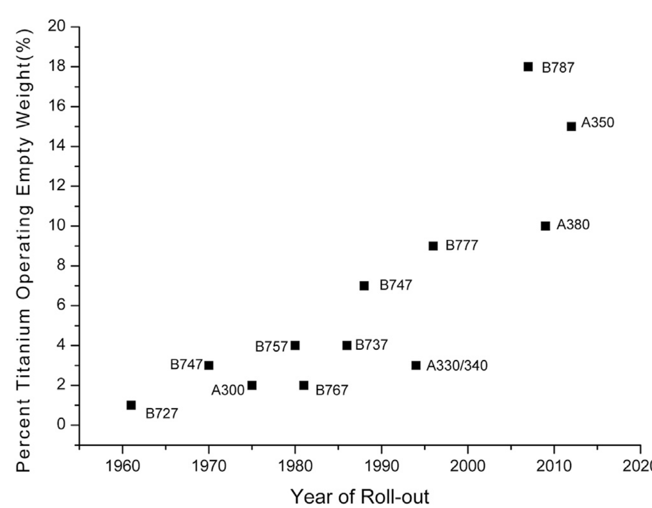

Fig. 3. Titanium usage in some aircrafts [54].

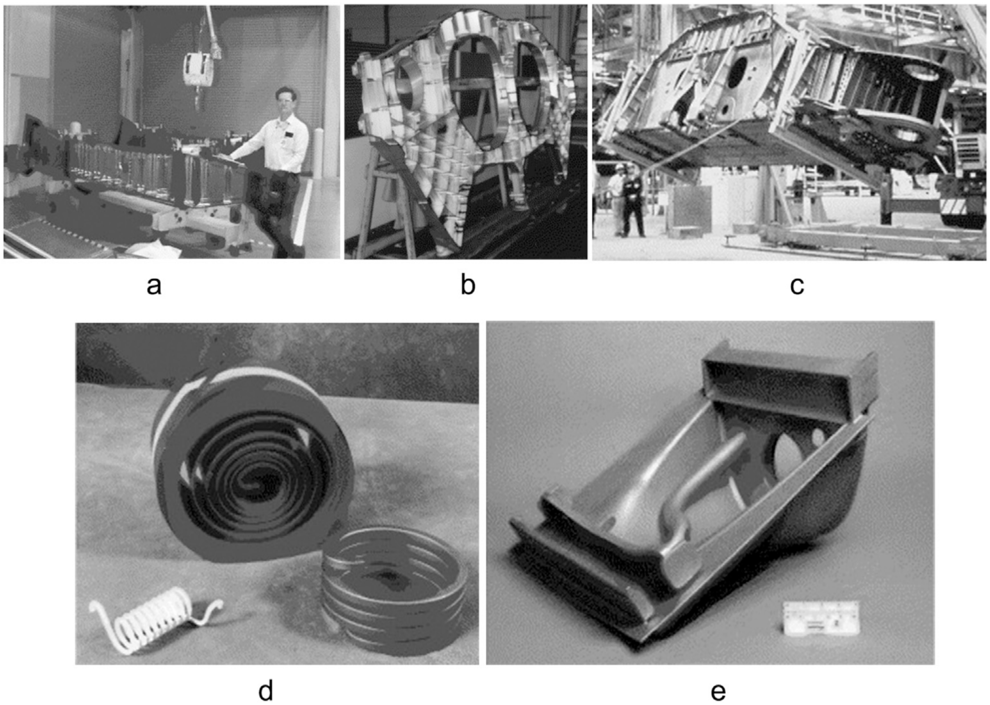

Fig. 4. Some components made from Ti-based alloy; a) landing gear beam for Boeing 747, b) Bulkhead for a fighter aircraft, c) wing box of the B1-B bomber aircraft, d) springs used in Boeing aircraft, e) a casting used in a military transport aircraft [55].

from the beta-stabilizers, such as V, Mo, Nb, and Cr. These alloying atoms can reduce the binding energy of the beta-Ti atomic cluster, resulting in stronger bonds between alloying atoms and titanium atoms than those of Ti-Ti atoms, and the binding energy decreases with the increasing content of alloying element [61]. In addition, the occurrence of ω phase during cold rolling also has a significant effect on mechanical properties of beta titanium alloys [62]. For example, the Ti-3Al-8V-6Cr-4Mo-4Zr alloy has a minimum UTS at 1240 MPa, and Ti-15V-3Cr-3Al-3Sn has a minimum UTS at 1034 MPa. Consequently, these two alloys are widely used in high-stress region such as aircraft landing gear and aircraft spring applications [60]. In addition to Ti-3Al-8V-6Cr-4Mo-4Zr and Ti-15V-3Cr-3Al-3Sn alloys, four beta titanium alloys are in steady production: Ti-10V-2Fe-3Al, Ti-15Mo-2.7Nb-3Al-0.2Si, Ti-5Al5V5Mo3Cr0·5Fe, and Ti-35V-35Cr [63]. However, beta titanium alloys are reported to possess low tensile ductility [55]. Fortunately, this shortcoming can be overcome by optimization of composition and thermal-mechanical processing. For example, the recent developed Ti-5Al3Zr4Mo4V4Cr (UTS = 1370 MPa, elongation = 17%) containing 3 wt% Zr under aging condition has a higher values in both elongation and UTS than Ti-5Al5V5Mo3Cr (UTS = 1200 MPa, elongation = 10%) [64]. The increased ductility in mainly due to the growth of sphericity primary α phase.

3.3.3. Alpha-beta titanium alloys

Because of the excellent combinations of strength, fracture toughness, and ductility, the alpha-beta alloy is the most widely used Ti-based alloy, which accounts for a 70% share of the U.S. titanium market. The widely used and studied alpha-beta alloys are Ti-6Al-4V, Ti-6-22-22S (Ti–6Al–2Sn–2Zr–2Cr–2Mo–Si) [65], ATI 425 (Ti–4Al–2.5V–1.5Fe–0.25O) [66], and TC21 (Ti–6A1–2Zr–2Sn–3Mo–1Cr–2Nb) [67]. These alloys have been applied to both aircraft structures and engine parts, including the fuselage, landing gear, floor support structure, nacelles, and compressor discs [23]. Among these alloys, the most widely used is Ti-6Al-4V, which has accounted for half of U.S. titanium consumption [68]. The Ti-6Al-4V alloy has a yield strength and an ultimate tensile strength of 1180 MPa and 1300 MPa under submicrocrystalline (SMC) condition, respectively [69]. However, Ti-6Al-4V alloy has a low hardness value (28.4 HRC) [70]. Some elements such as Zr has been reported to improve hardness and strength of Ti-6Al-4V alloy due to the effect of solid solution strengthening, in which the α phase platelets are replaced fine acicular α' phases, resulting close lamellar spacings to hinder dislocation movement [71]. The microhardness of Ti-6Al-4V alloy can be increased to 420 HV by adding 20 wt% Zr. In addition, the tensile strength can be increased from 996 MPa to 1317 MPa by increasing Zr content from 0 wt% to 20 wt %. However, the elongation ratio dropped to 8.08%.

3.4. Composite materials

The use of composite materials has significantly increased and composites now constitute more than 25% of the Airbus A380 and 50% of the Boeing 787 aircrafts, see Fig. 5. Composite materials show a great potential in not only structural applications but also some engine parts. The rising use of composite materials in the aerospace industry is mainly due to their higher specific strength and better corrosion and fatigue resistance than most metals. The recent researches on the development of ceramic, metal, and polymer matrix composite materials are reviewed.

3.4.1. Ceramic matrix composite material

Ceramic matrix composites (CMC), such as silicon carbide (SiC), silicon nitride (Si_3N_4), alumina (Al_2O_3), zirconia, aluminum titanate (Al_2TiO_5), and aluminum nitride (AlN) matrix composite, have been widely studied in recent years because of their attractive properties, such as high-temperature stability (to withstand operating temperature at 1400 °C), high hardness (22.9 GPa for an Al_2O_3 based composite), high corrosion resistance, and good versatility [9,74]. Ceramic matrix composites are normally used in high-temperature sections in aircraft such as exhaust nozzle. Carbon fiber reinforced silicon carbide has been investigated as a candidate for aircraft brakes where the temperature could reach up to 1200 °C under emergency brake conditions [75]. Despite the merits, MMCs are reported to suffer from the poor fracture toughness [76]. To overcome this shortcoming, various works [74,77] have focused on the addition of nanomaterials such as the carbon nanotubes and graphene to improve the fracture toughness of ceramic matrix composites. However, Ahmad et al. [74] reported the effects of carbon nanotubes (CNTs) on the fracture toughness of CMC are inconsistent. Ahmad et al.

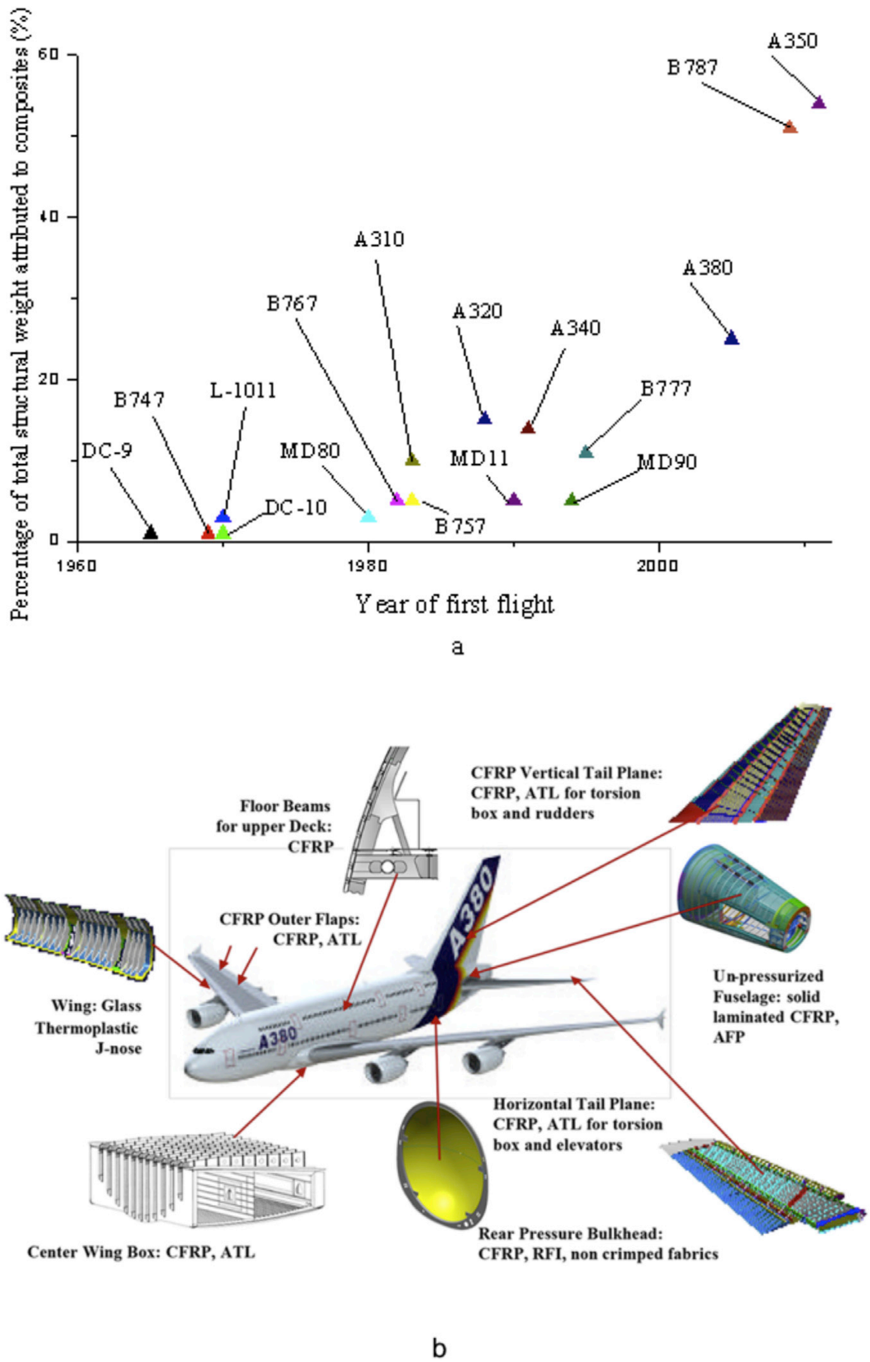

Fig. 5. The percentage of total structural weight attributed to composites and the use of composites in Airbus A380, a) the percentage of total structural weight attributed to composites, b) the use of composites in Airbus A380 [72,73].

believe that graphene nanoplatelets (GNPs) are an efficient alternative for CNTs in ceramic composite because of the similar mechanical properties and better dispersibility to CNTs. An experiment by Walker et al. [76] demonstrated an increase of 235% in fracture toughness of a Si_3N_4 ceramic composite by adding 1.5 vol% of graphene. However, the content of graphene platelet should be limited at critical value. For example, Liu et al. [77] reported the fracture toughness of alumina ceramic composite increased to 4.49 MPa $m^{1/2}$ when graphene content rose from 0 to 0.38 vol%, and then dropped to 3.53 MPa $m^{1/2}$ when the content of graphene reached up to 1.33 vol%.

3.4.2. Metal matrix composite materials

Metal matrix composites (MMCs) hold promise for the aerospace industry because of their reinforced higher yield strength, fracture toughness, low thermal expansion, and suitable wear resistance [78]. The Al based MMC reinforced by 30% SiC has a similar density, 60% higher elastic modulus, 15% higher tensile strength, and 70% higher specific modulus than 2219 Al-based alloys [79]. Recently, some metals and alloys were studied as the matrices such as aluminum, magnesium, titanium, copper, and nickel [80]. The properties of some matrices are shown in Table 2. Some fibers such as ceramic reinforcement and conventional carbon fiber were investigated for their potential to improve the properties of MMC. However, these fibers cannot meet the requirements for further improvement of mechanical properties of MMC. The carbon nanotubes (CNTs) and graphene nanosheets have recently shown attractiveness because of the demands of fibers with a higher strength, lower coefficient of thermal expansion, better self-lubricant ability, and higher damping capacity [81]. The effects of carbon nanotubes on MMC have been studied by Liao et al. [81,82]. They reported that different amounts of multi-walled nanotube (MWNT) have different

Table 2
Properties of some metal matrices of composites [87,88].

Matrices	Density g/cm^3	CTE 10^{-6} K^{-2}	Thermal conductivity W/mK	Yield strength MPa	UTS MPa	Young's modulus GPa	Elongation %
Al 2024	2.78	22.7	120	345	425	70	5
Al 6061/T6	2.71	23.2	160	193	227	69	10
AlBeMet	2.1	13.9	240	282	338	199	10
Ti6Al4V	2.43	8.8	7.2	827	896	110	10
MgAl6Mn	1.78	26	62	130	220	45	8
Mg	1.74	26.1	159	30	115	44	6
Mg + Ni5%	–	–	–	58	146	–	3

effects on Al matrix composites, and the optimal content occurs at 0.5 wt %. In addition, carbon nanotubes influence the properties of Mg matrix composite as well. For example, Zheng et al. [83] reported that the tensile properties of AZ31 Mg matrix composite can be greatly improved by introducing 1 wt% MWNT. Moreover, the effects of CNTs on mechanical properties of Ti matrix composite also have been studied by Kondoh [84]. For instance, as shown in Fig. 6, the addition of MWNT from 0.18 wt% to 0.35 wt% can continuously increase the tensile strength, yield strength, and hardness of Ti and its nanocomposites. Moreover, the addition of MWNT does not reduce the elongation of Ti and its composites, which is in the range of 34–38%. Furthermore, the mechanical properties of CNT reinforced copper matrix nanocomposite were studied by Daoush and coworkers [85]. The results showed that CNT can greatly improve the yield strength, with the highest yield strength achieved at the point when 15 vol% CNT was added into copper matrix. Daoush also found that the Young's modulus of Cu matrix composite was gradually increased by increasing CNT content. In addition to the matrices of Al, Mg, Ti, and Cu, Hwang et al. studied the effects of MWNT on the properties of Ni matrix composite [86]. Specifically, the Young's modulus and yield strength of Ni composite were increased by 21 GPa and 521 MPa with the increase of

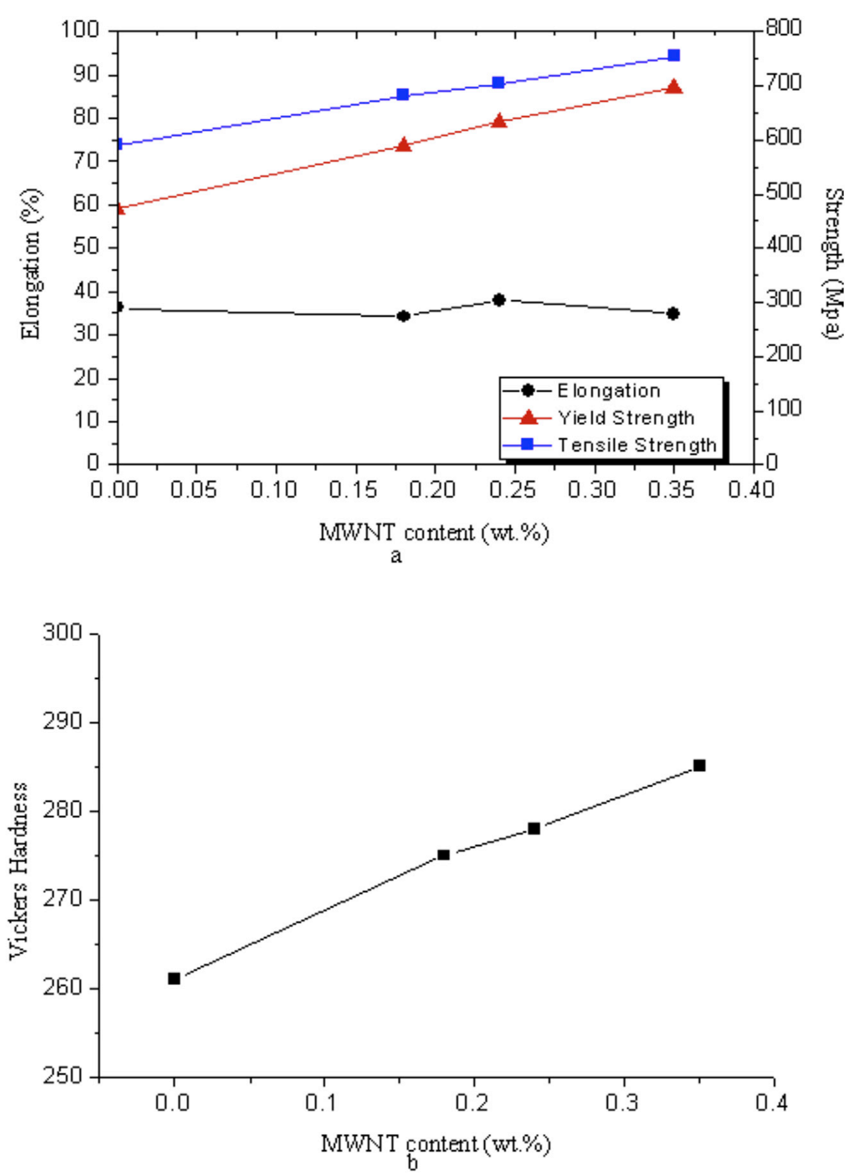

Fig. 6. The mechanical properties of the extruded Ti and its nanocomposites, a) yield strength, ultimate tensile strengths, and elongation, b) vickers hardness [81].

MWNT from 0 to 6 vol%, respectively.

3.4.3. Polymer matrix composites

Polymer matrix composites (PMCs) can be grouped into two categories (thermoplastic and thermoset) based on the differences in matrix characteristics. The prominent advantages of polymer matrix composites are their well-known high specific strength and specific modulus. For example, the density of carbon fiber (CF) reinforced epoxy composite is only half that of Al-based alloys while, the tensile strength and elastic modulus are three times and two times higher, respectively, than those of Al-based alloy [89]. The excellent properties of fibers contribute to advances in PMCs, and the properties of some fibers are shown in Table 3. Both thermoset and thermoplastic PMCs have been used for aerospace structure applications such as ailerons, flaps, landing-gear doors. Boeing 777 and 787 airplanes have up to 50% of their weight in CFRP [90]. Although the conventional CF can improve the strength of PMCs, the CF reinforced composites are more likely to suffer stress concentration because of the brittleness of CF [91]. Therefore, recent investigations of fibers for PMC have focused on the natural fibers [92], carbon nanotubes [93], graphene [94], and basalt [95]. Natural fibers, such as flax, hemp, banana, bamboo, and recycled cellulose fiber (RCF) are being used in the polymer system to improve the mechanical properties of PMC [96]. Li and coworkers [97] reported the tensile strength of high-density polyethylene (HDPE) with 20% flax fiber is twice that of HDPE without any flax content. However, the main disadvantage of natural fibers/polymer composites is the incompatibility between the hydrophilic natural fibers and the hydrophobic thermoplastic matrix [98]. In addition to natural fibers reinforced PMCs, carbon nanotube reinforced PMCs have been widely used in military aircraft such as in structure components and conductive coatings for fighter jets [99]. According to earlier works by Qian et al. [100] and Biercuk et al. [101], carbon nanotubes can significantly improve the elastic modulus, break strength, and hardness of polymer composites. However, according to the review paper by Mittal and coworkers [93], various investigations [102] reported that when the content of CNT exceeded a critical point, the mechanical properties decreased with increasing the content of CNT. Compared to CNT reinforced PMCs, graphene-based polymer composites have much better mechanical properties [103]. For example, Wan et al. [104] reported that the tensile strength of epoxy composite increased from 52.98 MPa to 71.54 MPa by adding only 0.1 wt% graphene oxide (GO). Furthermore, basalt is another effective reinforcement in PMCs. A recent test conducted by Zhang et al. [105] showed that the tensile strength, tensile modulus, flexural strength, and flexural modulus of polybutylene succinate continuously increased when basalt fiber content was increased from 0 to 15 vol%.

3.5. Steels

Steel has been used in the aerospace industry ever since the first aircraft was built by the Wright Brothers. With the development of new technologies, the composition of steel has changed from carbon and iron into a complex alloy combined with the element of Fe and an abundance of additional alloy elements. Although, steel still plays an important role in the aerospace industry, especially for gears, bearings, carriages, and fasteners, steel as a conventional aerospace and industry alloy has experienced a rapid decrease in recent years due to the lower specific strength and corrosion resistance than new materials such as light alloys and composites [106].

To overcome these shortcomings, recent studies focus on the development of new low alloy steels and nanosteels. When compared to conventional carbon steels, low alloy steels show better performance on hardenability, tempering and softening capacity, wear and corrosion resistance. In recent studies, the most attractive type of low alloy steel was shown to be ultrahigh-strength steel (UHSS). UHSS has a yield strength above 1380 MPa due to the finer grain size and precipitation strengthening [107]. Some typical UTSS are: 4130, 4140, 4340, 6150, 9260, 300M and D6ac [106,108]. The compositions, yield strengths, and applications of these typical ultra-high strength low alloy steels are demonstrated in Table 4. However, UHSS are prone to degradation by hydrogen (H), because hydrogen atoms at crack tip can weaken interatomic bonds and facilitate crack growth by slip and microvoid, and the distribution of hydrogen is highly nonuniform under an applied stress, which can cause localized deformation and localized failure [109]. In addition to UHSS, the recent developed nanostructure steels or nanosteels with ultra-fine grains, nanosize particles, and nanosize phases have been studied. The nanosteels have a higher strength and better corrosion resistance due to the prevention of dislocation movement by nanoparticles and fewer defects on the surface of steel [110]. A typical example of nanostructure steels is 9Cr oxide dispersion strengthened (ODS) steel. The strengths of 9Cr ODS steel (YS = 845 MPa, UTS = 915 MPa) are higher than the conventional SAE 2330 steel (YS = 689 MPa, UTS = 841 MPa) [111].

3.6. Ni-based superalloy

Recent advanced Ni-based superalloys are containing γ'-Ni_3(Al,Ti) phase with high volume fractions, resulting the high strength of Ni-based superalloys at high temperature [113]. For example, the tensile strength of a wrought Ni-Cr-W superalloy can reach up to 550 MPa at 800 °C [11]. Due to their high strength at high temperature, superalloys are widely used in some aeroengine parts such as the combustor and turbine section where operating temperatures range between 1100 and 1250 °C [114]. The applications of Ni-based superalloy in the PW4000 engine are shown in Fig. 7. Ni-based superalloys have shown little inherent resistance to high-temperature oxidation [113]. Chiou and coworkers [115] reported that the addition of Al improved the oxidation resistance. The oxide layer thickness of CM-247LC Ni-based superalloy at oxidation time of 100 h can be reduced from 20 μm to 6 μm by adding 1 wt% Al, because the formation of Al_2O_3 can prevent the outward diffusion of cation and inward diffusion of oxygen ions. In addition, some researchers have reported that the addition of chromium in Ni-based superalloy improves the hot corrosion and oxidation resistance. However, the high content of Cr is reported detrimental to the microstructural stability [116]. For example, Chen et al. [116] reported that the stress-rupture life of

Table 3
Properties of some reinforcements of composites [87].

Fiber	Density g/cm^3	Thermal conductivity W/m·°C	Young's modulus GPa	Tensile strength MPa	Strain to failure %	Fracture toughness MPa·m$^{0.5}$	Hardness Vickers HV	Maximum Service Temperature °C
Al fiber	3.5	22.5	305	2200	0.9	1.75	650	1000
Al whisker	3.96	22.5	455	1550	0.225	4.5	2350	1000
Borsic	2.75	38	400	3000	0.75	3	900	550
Gr	1.95	140	700	2200	0.75	1.5	700	600
Sic whisker	3.17	80	460	7000	0.225	2.75	950	1150
Sic	3.18	80	465	2750	0.225	2.75	3250	1050
Boron carbide	2.5	19	400	2400	0.75	3	900	550
Be	1.86	185	307	965	3.5	13	260	300
Ti diboride	4.6	73	525	320	0.15	5.5	2750	1450

Table 4
The compositions, yield strength, and applications of the ultra-high strength low alloy steels [106,108,112].

	C	Mn	Si	Ni	Cr	Mo	V	Co	Maximum Yield strength MPa	Applications
Aermet100	0.23	0.01	0.01	11.14	3.00	1.18	–	13.44	1700	Shaft fittings, landing gears axles, turbine components, airframes
4130	0.31	0.50	0.28	–	0.95	0.20	–	–	1110	Axles, rotors, gears, fuselages, snap springs, crankshafts
4140	0.41	0.88	0.28	–	0.95	0.20	–	–	1110	
4340	0.41	0.70	0.28	1.83	0.80	0.25	–	–	2020	
6150	0.51	0.80	0.28	–	0.95	0.20	–	–	1225	Snap springs, propeller cones, gear, shaft, pins and bolts
9260	0.60	0.88	2.00	–	–	–	–	–	1149	Springs
300M	0.83	0.77	1.63	1.83	0.83	0.40	0.05	–	1689	Landing gears, airframes, fasteners
D6ac	0.45	0.75	0.28	0.55	1.05	1.00	0.08	–	1379	Landing gears, springs, shafts

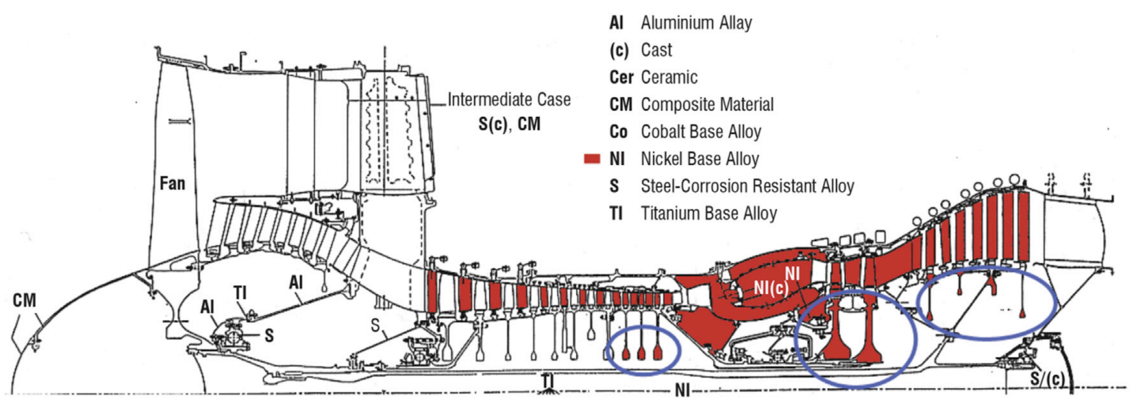

Fig. 7. The use of Ni-base superalloy in PW4000 engine [117].

Ni-based superalloy with 5.7 wt% of Cr was 3.7 times longer than that of the Ni-based alloy without Cr content. However, the high ratio of Cr content results in the formation of the topologically close-packed phase, which is brittle and depleted potent solid solution strengthening elements from the γ' matrix.

4. New materials potential for aircraft

Self-reliant materials such as self-cleaning polymerics and self-repairing materials have potential for high use in flight vehicles. The self-cleaning materials can be found in the natural environment. One example is lotus leaves. When water is poured over these leaves, it rolls off as beads and takes away dirt on the leaves [118]. The mechanisms of self-cleaning materials can be divided into two categories. The first is based on the wettability of the surface, and the second one is the photocatalytic feature [119,120]. On the hydrophobic surface of self-cleaning materials, the material interface is protected from polar molecules absorption as water rolls off the surface with the dirt [5]. Light can be captured by a photoactive surface, and this process produces oxidative radicals which can mineralize and absorb organic molecules [119]. Based on these properties, the material can be applied to the fabric of seats and carpets in future aircraft.

In addition to self-cleaning materials, self-repairing or self-healing materials have been widely studied and researched in last several decades. The self-healing materials can be polymer, ceramic or metal matrix composites [121]. Self-repairing materials can protect the integrity of structures and maintain the function of materials after mechanical damage and corrosion. The self-healing materials can be divided into two categories, which are extrinsic self-healing and intrinsic self-healing. The extrinsic self-healing relies on the healing agent, which is stored in materials in advance by two types of containers: pipelines and microcapsules. The cracks can be re-bound by the releasing of healing agent to crack planes because of the capillary effect. Zhang et al. [122] noted that the cracks healing process is more efficient by mixing epoxy monomer and solvent. It is because the epoxy monomer can be cured on the matrix interface by the effect of residual amine. Intrinsic self-healing is mostly under the condition of manual intervention. Kausch et al. [123] investigated the crack healing behavior of some thermoplastic materials and found that the strength can be restored by heating these materials over the glass transition temperature because of the interdiffusion of molecular and entanglement of glassy polymer. Wu et al. [124] reviewed self-healing behavior for both thermoset and thermoplastic materials and reported that intrinsic self-healing can be achieved by some other methods such as photo-induced healing, reversible bond formation healing, and chain ends recombination. Self-healing materials can be potentially used in the aerospace industry. The self-healing materials containing boron (B) can be used for aircraft engine parts through the formation of B_2O_3, which can seal matrix cracks at high temperatures [121]. In addition, some self-healing materials such as self-healing hollow glass fiber-epoxy composites with excellent fatigue resistance can be potentially used in aircraft structural applications because of the ability to heal microcracks before crack growth to failure [121]. Furthermore, self-healing materials such as self-healing epoxy composite can protect aircraft structures from corrosion by coating, because they can recover their protect ability after damages [121].

5. Challenges faced in the development of recently advanced materials

5.1. Fretting wear

Fretting wear is caused by small-amplitude (less than about 100 μm) oscillatory movement between two contact bodies [20,125]. Fretting wear can create initiate cracks on the damaged surface and reduce fatigue life of components [126]. Fretting wear occurs in both aircraft structural components and engine parts such as the bearing shaft, bolted connection, and blade-disc assemblies [127]. Ti-based alloys mostly are used to connect with other components and often under the fretting loads, which easily suffer fretting damage. Consequently, recent studies of fretting behaviors focus on Ti-based alloys [128]. A few researchers have conducted tests seeking to eliminate the fretting wear behavior of aerospace materials. Fu and coworkers [129] investigated three methods used for fretting damage prevention: new design, surface modification, and the use of lubricants. The most widely studied method is surface modification such as modification of surface hardness and adhesion [126]. The difference in hardness between two mating pairs can greatly influence fretting wear. Lemm et al. [130] reported that the total net wear volumes of a range of equal-hardness steel pairs (hardness from 250 kgf mm^{-2} to 850 kgf mm^{-2}) are similar, around 0.45 mm^3. However, the total net wear volume experienced a small reduction to 0.35 mm^3 by increasing the hardness difference to 600 kgf mm^{-2}. Lemm and co-worker [130] also reported that the wear volume of the harder part can reach up to 95% of total wear volume because of the protection of the softer part by oxide-based fretting wear debris. Sarhan et al. [131] studied the relation of hardness and fatigue life on a hard anodized Al7075-T6 aerospace alloy. The results showed that fatigue life of this alloy was optimized by improving surface hardness to 393 HV in low-stress regions. However, the hard anodized coating has no or negative effect on fatigue life in high-stress regions (over 200 MPa). Zalnezhad and coworkers [132] reported that the improvement of surface hardness can greatly improve the fatigue life of a TiN coated Al7075-T6 alloy in low-cyclic fatigue, and the improvement of adhesion can significantly improve the fatigue life in high-cyclic fatigue. Other properties such as toughness, friction factor, and bonding strength also have been investigated to prevent fretting damage. Du et al. [133] reported that bonding strength and toughness have a greater effect than the friction factor on fretting wear resistance of diamond-like and graphite-like carbon coated Ti-based alloys. Although researchers have studied fretting behavior on some materials, the general theory describing fretting behavior and prevention is still not mature [20]. Further works should concentrate on the mechanism of fretting and develop more effective methods to improve fretting resistance.

5.2. Corrosion

Corrosion involves the chemical degradation of materials when the materials react to their environment [134]. Corrosion, such as uniform corrosion, pitting corrosion, crevice corrosion, or galvanic corrosion, can cause failure of components when the remaining materials after cannot support the applied loads. Moreover, corrosion can compromise components that are prone to fail by other modes [135]. Metal corrosion can cause a loss of $276 billion per year in the US, much greater than the loss caused by natural disasters [21]. Based on the prediction, only up to 30% of the corrosion loss can be avoided by corrosion prevention methods [21]. Various studies have investigated corrosion behaviors in different materials, therefore enabling the straightforward selection of materials for use in different environments. However, some suitable materials for corrosion resistance may not support other requirements. For example, high corrosion resistance materials cannot always be used in aircraft structures because of the strength/weight ratio. Therefore, methods have been developed to prevent corrosion of structure materials, and the most widely investigated is coating [21]. The functions of the coating are (1) to provide a local corrosion barrier, (2) act as a sacrificial anode, and (3) supply solute ions [136]. However, conventional corrosion coating has difficulty providing active corrosion inhibitors. Therefore, the defects cannot be protected by the transport of inhibitor through the liquid corrosive phase [136]. Chromium [137] has been studied as providing efficient corrosion inhibitors. However, chromium has been reported to cause health problems and environment disasters in its hexavalent form [138]. Although some other elements, such as graphene [139], cerium sulphate [140], and oxides of rare-earth elements [141] have been studied to improve the protective performance, the mechanism of corrosion behavior and prevention need to be further study.

5.3. Stress corrosion cracking (SCC) and hydrogen embrittlement (HE)

Stress corrosion cracking is considered as one of the most dangerous failure mechanisms because SCC can cause slow crack growth under a safe loading condition. When the crack size reached the critical value, the crack by SCC with the safe loading can cause the sudden failure of materials. SCC is resulted from three-way interaction, which are mechanical stress, susceptible alloy, and corrosive environment [142]. The mechanisms of HE and SCC are relevant because hydrogen initially occurs at the tips of cracks in an aqueous environment [143]. SCC and HE behaviors in some susceptible metallic materials such as steels [144], Al-based alloys [145], and Mg-based alloys [146] have been widely investigated. Mg has a high intrinsic dissolution tendency, and the impurities and the second phase can act as the local cathodes to accelerate corrosion by local galvanic, which contributes to the Mg-based alloys' susceptibility to SCC. In addition to Mg-based alloys, the Al-based alloys with 3.5 wt% or higher content of Mg are also susceptible to SCC. It is known that the segregation of Mg along grain boundaries can facilitate the hydrogen entry, accelerate the transport of hydrogen, and provide sites for grain boundary embrittlement by hydrogen chemisorption [147]. Mg dissolving into Al forms the highly anodic β phase of Al_3Mg_2, which can increase the susceptibility of Al-based alloys to SCC [142,148]. In order to prevent SCC and HE, some elements have been studied in recent years to improve cracking resistance [144]. Guo [149] studied some alloying elements in Mg-based alloys and reported the Mn element has a positive effect on the improvement of SCC resistance. Peng et al. [150] reported that SCC resistance was increased with the increase of size and spacing of grain boundary precipitates (GBP) by reducing the propagation rate and the concentration of atomic hydrogen. Relatedly, methods such as theoretical and quantum mechanical models, recent nano-research, and atomistic investigations have been developed to study the mechanism of HE and SCC. However, the applicable prediction approach remains nonexistent because the mechanisms of HE and SCC are not affected by one parameter but by multiple factors including ambient medium, mechanical properties, and manufacturing processes [151,152].

6. Conclusion and future trends

The present review shows that significant progress has been made in the development of both aircraft structural materials and engine materials. The design criteria for the aircraft structural materials require the materials to possess appropriate mechanical properties with suitable damage tolerance under different conditions. Al-based alloys are the primary material in this field for many years because of their well-known mechanical behavior. The use of polymer matrix composites has increased in recent years due to superior mechanical properties such as higher specific strength and stiffness when compared to Al-based alloys. However, the conventional carbon fiber reinforced polymer matrix composites are more likely to suffer from stress concentration. In addition, the use of Mg-based alloys, steels and Ti-based alloys in some aerospace applications is restricted by some challenges. The criteria for aircraft engines require the materials to provide suitable mechanical properties, densities, and corrosion resistance at high-temperatures. In the compressor section where the temperature is in a range of 500–600 °C, Ti-based alloys are the primary materials. Ni-based superalloys are the primary materials for the high temperature (1400–1500 °C) turbine section.

In the future, specific mechanical properties and challenges such as fretting wear, corrosion, and SCC will be the main drivers in the development and selection of next-generation structure materials. The airframe materials will be dominated by various materials such as Al-based alloys, Ti-based alloys, steels, and composites. Further work of airframe materials should focus on the following three topics: (i) develop new metal alloys with higher specific mechanical properties by various strategies, including microstructure refinement, impurities control, and thermal-mechanical processing; (ii) develop new methods such as composition modification, coating, and microstructure control to overcome the challenges of metal alloys, including more efficient prevention method for fretting wear of Ti-based alloys, more efficient prediction and prevention methods for corrosion, SCC, and HE of Al-based alloys, Mg-based alloys and steels; (iii) develop new composite materials such as MMC and PMC with more balanced properties by fiber selection. The future trends of aircraft engine's materials focus on how to withstand the rising engine temperature and maintain the proper mechanical properties. The future work should focus on the following topics: (i) further improve the high-temperature resistance of Ti-based alloys by controlling phases through alloying and thermal-mechanical processing; (ii) develop advanced Ni-based superalloys by alloying with elements to prevent high-temperature oxidation, such as Al and Zr; (iii) develop the advanced CMC with higher fracture toughness by revealing the optimized content of fibers, such as graphene platelet.

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