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Review

Recent developments in advanced aircraft aluminium alloys

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ABSTRACT

Aluminium alloys have been the primary material for the structural parts of aircraft for more than 80 years because of their well known performance, well established design methods, manufacturing and reliable inspection techniques. Nearly for a decade composites have started to be used more widely in large commercial jet airliners for the fuselage, wing as well as other structural components in place of aluminium alloys due their high specific properties, reduced weight, fatigue performance and corrosion resistance. Although the increased use of composite materials reduced the role of aluminium up to some extent, high strength aluminium alloys remain important in airframe construction. Aluminium is a relatively low cost, light weight metal that can be heat treated and loaded to relatively high level of stresses, and it is one of the most easily produced of the high performance materials, which results in lower manufacturing and maintenance costs. There have been important recent advances in aluminium aircraft alloys that can effectively compete with modern composite materials. This study covers latest developments in enhanced mechanical properties of aluminium alloys, and high performance joining techniques. The mechanical properties on newly developed 2000, 7000 series aluminium alloys and new generation Al–Li alloys are compared with the traditional aluminium alloys. The advantages and disadvantages of the joining methods, laser beam welding and friction stir welding, are also discussed.

1. Introduction

The cost reduction for aircraft purchase and operation has become a driving force in many airline companies. Cost reduction can be achieved by decreasing the fuel consumption, maintenance cost, operational costs, frequency of periodical controls and increasing the service life and carrying more passengers at a time. Therefore aircraft manufacturers are competing to meet the requirements of their airline customers. Weight reduction can improve fuel consumption, increase payload and increase range. Additionally, improved and optimised mechanical properties of the materials can result in increased period between maintenance and reduce repair costs. Since the material has a great impact on cost reduction, airframe manufacturers and material producers focus on the development of new materials to meet customer requirements. Hence, a current challenge is to develop materials that can be used in fuselage and wing construction with improvements in both structural performance and life cycle cost. According to the design trials it is seen that an effective way of reducing the aircraft weight is by reducing the material density. It is found that the decrease in density is about 3–5 times more effective than increasing tensile strength, elastic modulus or damage tolerance [1]. Airframe durability is another parameter that directly affects costs. The cost of service and maintenance over the 30-year life of the aircraft are estimated to exceed the original purchase price by a factor of two [1]. Therefore, both material producers and aircraft designers are working in harmony to reduce weight, improve damage tolerance, fatigue and corrosion resistance of the new metallic alloys. As a result, near future primary aircraft structures will show an extended service life and require reduced frequency of inspections.

Composite materials are increasingly being used in aircraft primary structures (B787, Airbus A380, F35, and Typhoon). Fig. 1 shows the increased usage of composites in several types of Boeing aircraft. The attractiveness of composites in the manufacturing of high performance structures relies on their superior mechanical properties when compared to metals, such as higher specific stiffness, specific strength (normalised by density), fatigue and corrosion resistance. Although composites are thought to be the preferable material for wing and fuselage structures, their higher certification and production costs, relatively low resistance to impact and complicated mechanical behaviour due to change in environmental conditions (moisture absorption, getting soft/brittle when exposed to hot/cold environments) make designers to explore alternative material systems. Fibre metal laminates such as GLARE which combines aluminium layers with glass fibre epoxy

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plies to improve tensile strength and more importantly damage tolerance are finding great use in aerospace applications [3–12]. Impact resistance, effect of damage on stiffness/strength especially when loaded in compression and damage identification and detection, in addition to joints, repair and recycling remain big challenges for composites with the need of further research [13–18].

Aluminium alloys have been the primary structural material for commercial and military aircraft for almost 80 years due to their well known mechanical behaviour, easiness with design, mature manufacturing processes and inspection techniques, and will remain so for some time to come. However, the non-metallic materials, despite the issues mentioned earlier, due to their superior specific strength properties provide a very competitive alternative, so aluminium producers need to keep investing and put great effort in improving the thermo-mechanical properties of the aluminium alloys they produce.

Density, strength, Young's modulus, fatigue resistance, fracture toughness and corrosion resistance are all important parameters that need to be improved. Depending on the particular component under consideration, material properties have to outperform those offered by polymer composites. Chemical composition and processing control the microstructural features such as precipitates, dispersoids, degree of recrystallization, grain size and shape, crystallographic texture and intermetallic constituent particles. These properties affect the physical, mechanical and corrosion characteristics of aluminium alloys. Therefore material producers working closely with aircraft designers could design different types of metallic alloys where the physical and mechanical properties have been tailored to the specified needs. For instance, the upper side of the wing is mainly subjected to compression loading during flight, but also exposed to tension during static weight and taxiing, while the opposite happens to the lower part of the wing, hence careful optimisation of tensile and compressive strength properties is required. Damage tolerance, fatigue and corrosion resistance are also needed making the selection and optimisation more challenging.

During the design of Boeing 777, aluminium manufacturers were asked for improvements in upper-wing structure and fuselage. Higher compressive yield strength was needed for the upper wing structure. Improved corrosion resistance was also desirable. For the case of fuselage, higher damage tolerance and durability than the incumbent 2024-T3 was needed. Aluminium manufacturers accounting for the designer's needs developed the 7055-T7751 plate and 7055-T77511 extrusions for the upper wing structure, and Alclad 2524-T3 sheet and 2524-T351 plate for the fuselage skin. They also developed 7150-T7751 extrusions for the supporting members of the fuselage structure. The application of these materials saved thousands of pounds of weight for the Boeing 777 [19].

The aircraft manufacturers are also working to decrease the number of parts in new aircraft. These needs could be met by applying several approaches. The first method is producing large and thick plates having fatigue and fracture characteristics equivalent to those of a thin plate. The second method is implementation of joining technologies such as friction stir welding that allows the manufacture of large integrally stiffened panels that can be used for wing and fuselage skins [20].

This review article covers the latest developments related to aluminium alloys used as aircraft primary structures and highlights performance improvements in the 2000, 7000 series aluminium alloys as well as the new generation of Al–Li alloys. Currently the 7000 series Al–Zn alloys are used where the main limiting design parameter is strength; 2000 series Al–Cu alloys are used for fatigue critical applications since these alloys are more damage tolerant, while Al–Li alloys are chosen where high stiffness and lower density are required. The advantages and disadvantages of the joining techniques, laser beam welding and friction stir welding, are also discussed.

2. Developments in 2000 series Al–Cu aluminium alloys

The aluminium–copper (2000 series) alloys are the primary alloys used in airframe structural applications where the main design criterion is damage tolerance. The 2000 series alloys containing magnesium have higher strength resulting from the precipitation of Al_2Cu and Al_2CuMg phases and superior damage tolerance and good resistance to fatigue crack growth compared to other series of aluminium alloys. 2024 and 2014 are well known examples for Al–Cu–Mg alloys. It is well known that due to different loading conditions each component of the airframe requires different material properties for optimum and reliable design. The fuselage is subject to cabin pressure (tension) and shear loads, longitudinal stringers are exposed to the longitudinal tension and compression loads due to bending, circumferential frames have to sustain the fuselage shape and redistribute loads into the skin. Strength, stiffness, fatigue crack initiation resistance, fatigue crack growth rate, fracture toughness and corrosion resistance all are important, but fracture toughness (resistance to crack growth) is

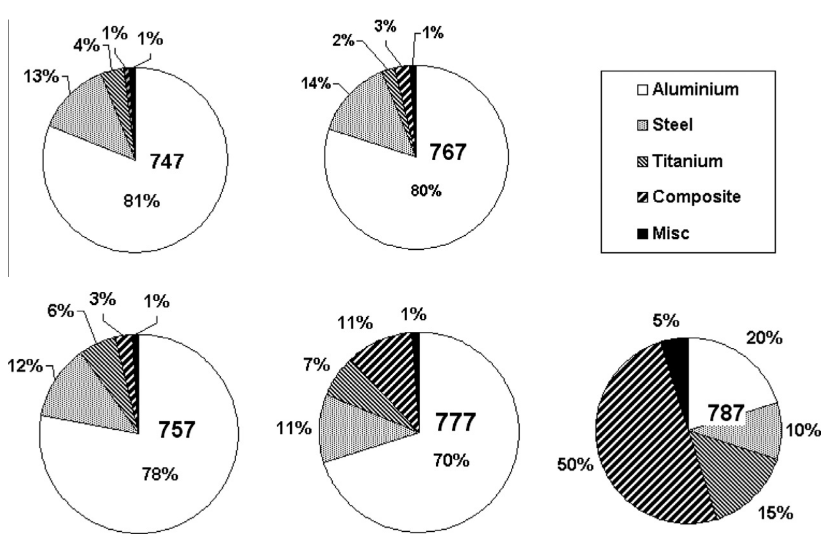

Fig. 1. Combination of materials used in Boeing Aircrafts. The figure is based on [2].

often the limiting design parameter [21]. The wing can be considered as a cantilever type of beam that is loaded in bending during flight but also torsion. The wing supports both the static weight of the aircraft and any additional loads subjected in service. Additional wing loads also come from the landing gear during taxiing, take-off and landing and from the leading and trailing edge the flaps and slats that are deployed during take-off and landing to create additional low speed lift. The upper surface of the wing is primarily loaded in compression because of the upward bending moment during flight but can be loaded in tension while taxiing [21]. Chemical compositions and mechanical properties of some of 2000 series aluminium alloys widely used in airframe design are given in Tables 1 and 2 respectively.

The 2024-T3 has been one of the most widely used alloys in fuselage construction. It has moderate yield strength, very good resistance to fatigue crack growth and good fracture toughness. The 2024 aluminium alloy remains as an important aircraft structural material due to its extremely good damage tolerance and high resistance to fatigue crack propagation in T3 aged condition. The low yield stress level and relatively low fracture toughness, limit the application of this alloy in the highly stressed regions [23]. Microstructural effects on the fatigue properties of aluminium alloys are being investigated intensively. Improvements in compositional control and processing have continually produced new alloys. It is known that inclusions have substantial effects on the fatigue crack propagation. Higher fracture toughness values and better resistance to fatigue crack initiation and crack growth were achieved by reducing impurities, especially iron and silicon. It has been announced that for the fuselage applications the alloy 2524-T3 has a 15–20% improvement in fracture toughness and twice fatigue crack growth resistance of 2024-T3 [24]. This improvement leads to weight savings and 30–40% longer service life [25]. The 2524 aluminium alloy has replaced the 2024 as fuselage skin in the Boeing 777 aircraft. Fatigue tests on the 2524 alloy showed that fatigue strength of this alloy is 70% of the yield strength whereas for 2024-T351 fatigue strength is about 45% of the yield strength [26]. For the lower wing skin applications [27] the 2224-T351 and 2324-T39 alloys offer higher strength values compared to incumbent 2024-T351 with similar fracture toughness and corrosion resistance. Compared to 2024, both compositional and processing changes for 2224-T351 and 2324-T39 alloys resulted in improved properties. A lower volume fraction of intermetallic compounds improved fracture toughness. For instance the maximum iron content is 0.12% and silicon is 0.10% in 2224-T351 whereas in 2024 0.50% for both impurities. A newly developed aluminium alloy 2026 is based on 2024 but it contains fewer impurities such as iron and silicon. Additionally, 2026 contains a small amount of zirconium which inhibits recrystallization [28]. 2026 has higher damage tolerance, higher tensile strength, higher fatigue performance and acceptable fracture toughness compared to 2024 and 2224 [29].

Although the contribution of Cu and Mg in intermetallic phases results in high strength however, due to the intermetallic phase particles the corrosion resistance of the alloy significantly drops. Several investigations have been done in order to increase both corrosion and fatigue resistance of 2000 series alloys [30–32].

3. Developments in 7000 series Al–Zn aluminium alloys

The 7000 series of aluminium alloys show higher strength when compared to other classes of aluminium alloys and are selected in the fabrication of upper wing skins, stringers and horizontal/vertical stabilizers. The compressive strength and the fatigue resistance are the critical parameters in the design of upper wing structural components. The tail of the airplane, also called the empennage, consists of a horizontal stabilizer, a vertical stabilizer or fin, and control surfaces e.g. elevators and rudder. Structural design of both the horizontal and vertical stabilizers is essentially the same as for the wing. Both the upper and lower surfaces of the horizontal stabilizer are often critical in compression loading due to bending [21].

High strength aluminium alloys such as the 7075-T6 are widely used in aircraft structures due to their high strength-to-weight ratio, machinability and relatively low cost. However, due to their compositions, these alloys are susceptible to corrosion. It is well known that corrosion reduces the life of aircraft structures considerably. During normal operation aircraft are subjected to natural corrosive environments due to humidity, rain, temperature, oil, hydraulic fluids and salt water. Among the issues facing ageing aircraft, corrosion in combination with fatigue is extremely undesirable [27] .

The 7000 series alloys are also heat treatable, and the Al–Zn–Mg–Cu versions provide the highest strengths of all aluminium alloys. Some of the 7000 series alloys contain about 2% copper in combination with magnesium and zinc to improve their strength. These alloys although are the strongest they are the least corrosion resistant of the 7000 series. However, newer 7000 series alloys introduced have higher fatigue and corrosion resistance which may result in weight savings. Newer alloys such as the 7055-T77, have higher strength and damage tolerance than the 7075-T6 [1]. The 7475 (Al–Zn–Mg–Cu) aluminium alloy is a modified version of 7075 alloy. The 7475 alloy is developed for applications that require a combination of higher strength, fracture toughness and resistance to fatigue crack propagation both in air and corrosive environment. Both strength and fracture toughness properties of 7075 alloy are improved by decreasing its contents of iron and silicon, and changing both quenching and ageing conditions. The total iron and silicon content in 7075 is 0.90% whereas in 7475 the total content is limited to 0.22%. These changes in the 7075 alloy resulted in the development of the 7475 alloy which is having a fine grain size, optimum dispersion and highest toughness value among the aluminium alloys available at high strength level. It is also reported that the corrosion resistance and corrosion fatigue behaviour of the 7475 alloy are excellent. In general, its performance is better than that of much commercially available high strength aerospace aluminium alloys such as 7050 and 7075 alloys [23]. Yield strength, % elongation, and K_{IC} properties of widely used 2024 and 7075 alloys are compared with 7050 and 7475 in Fig. 2.

It may be seen in Fig. 2 that the 2024-T351 alloy has high ductility and good fracture toughness (both in TL and LT orientations) but has relatively low yield strength. On the other hand, the 7075 alloy under T651 temper condition has yield strength of over 500 MPa. The reported fracture toughness of this alloy (7075-T651) in TL and LT orientations is nearly 24 MPa$\sqrt{m}$ and

Table 1
Chemical composition of some 2000 series aerospace aluminium alloys [22].

2000 Series	Cu	Zn	Mg	Mn	Fe	Si	Cr	Zr	Ti	Al
2024	4.4	–	1.5	0.6	⩽0.5	⩽0.5	0.1	–	0.15	Remainder
2026	3.6–4.3	0.1	1.0–1.6	0.3–0.8	0.07	0.05	–	0.05–0.25	0.06	Remainder
2224	4.1	–	1.5	0.6	⩽0.15	⩽0.12	–	–	–	Remainder
2324	3.8–4.4	0.25	1.2–1.8	0.3–0.9	0.12	0.1	0.1	–	0.15	Remainder
2524	4.0–4.5	0.15	1.2–1.6	0.45–0.7	0.12	0.06	0.05	–	0.1	Remainder

Table 2
Mechanical properties of some 2000 series aerospace aluminium alloys [22].

2000 Series	UTS (MPa)	Yield Strength (MPa)	Fracture Toughness, K_{IC} (MPa m$^{1/2}$)	Elongation (%)
2024-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

27 MPa$\sqrt{}$m, respectively which corresponds to low level of ductility. The 7475-T7351 alloy has higher fracture toughness (42 MPa$\sqrt{}$m and 52 MPa$\sqrt{}$m in TL and LT orientations, respectively) whereas, in comparison to the 7075-T651 alloy, the 7475-T7351 alloy has marginally inferior yield strength but slightly superior ductility. In view of these facts, the use of appropriately treated 7475 alloy is expected to safely reduce the overall weight of aerospace structure, an important criterion for such applications [23].

In Fig. 3 fatigue crack growth rates for different aluminium alloys are compared. It is shown that the 7475 has higher fatigue resistance compared to the 2024, while the 7075-T6 has the lowest fatigue resistance.

Corrosion resistance and fatigue behaviour of alloy 7475 are equal to/or better than many of the high strength aluminium alloys such as the 7075, 7050 and 2024. Alloy 7475 plate and sheet are currently being selected for fracture critical components of high performance aircraft applications [33].

Alloy 7050 is another important alloy having the good balance of strength, stress corrosion cracking (SCC) resistance and toughness. It is particularly suited for plate applications in the 76–152 mm thickness range. Alloy 7050 exhibits better toughness/corrosion resistance characteristics than alloy 7075 because it is less quench sensitive than most aerospace aluminium alloys. The 7050 retains its strength properties in thicker sections while maintaining good stress corrosion cracking resistance and fracture toughness levels. Typical applications for alloy 7050 plates include fuselage frames and bulkheads where section thicknesses are 50–152 mm. On the other hand alloy 7050 sheets are used in wing skins applications. Long-term controlled and in-service evaluations have shown that alloy 7050 plate and sheet products remain equal exfoliation and stress corrosion resistance at higher stress levels compared with other high strength aluminium alloys such as 7075.

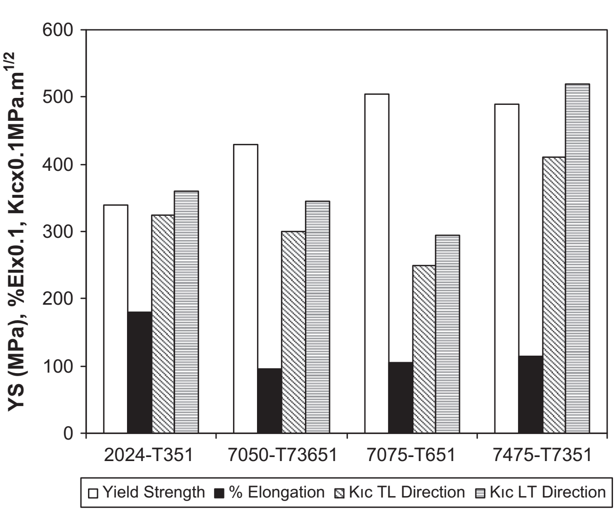

Fig. 2. Comparative representation of yield strength, % elongation, and K_{IC} in different aluminium alloys. The figure is based on [23].

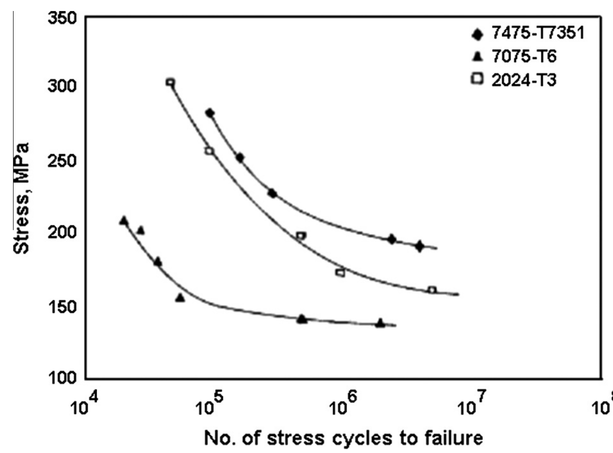

Fig. 3. *S–N* curves for different aluminium alloys [23].

A recent alloy, the 7055-T7751 (Al–8Zn–2.05Mg–2.3Cu–0.16Zr), has a yield stress that may exceed 620 MPa and the estimated weight saving attributed to its use for components in the Boeing aircraft 777 is 635 kg [34]. This alloy provided a nearly 10% gain in strength, with higher toughness and significantly improved corrosion resistance [24]. T77 temper consists of three step ageing process that produces a higher strength and damage tolerance combinations compared to 7050-T76 and 7150-T651 or T7751. The improved fracture toughness is a result of controlled volume fraction of coarse intermetallic particles and uncrystallized grain structure. Good combination of strength and corrosion resistance is attributed to the size and spatial distribution and the copper content of the strengthening precipitates.

There exists a continuous improvement in the mechanical properties of aerospace aluminium alloys. This has resulted in the development of high strength 7xxx alloys (e.g. 7075, 7150, 7055, 7449, in chronological order of application). These high strength alloys are generally used in compression-dominated parts such as upper wing skins where damage tolerance considerations are secondary. However, recent developments show that modifications in solute content and in particular in Zn/Mg/Cu ratios can enable the development of high strength products with significant improvements in damage tolerance such as AA7040, AA7140 and AA7085. 7085 has been developed as the new generation high strength thick plate alloy to be alternative for 7050/7010 products. Due to the higher Zinc and lower Cu contents, higher fracture toughness and slow quench sensitivity were obtained. This product was selected for wing spar applications on the Airbus A380. There is also an effort to obtain a good combination of high strength and good corrosion resistance through the applications of different heat treatment methods [35]. Two important metallurgical principles resulting in improvements are: a decrease in the Mg/Zn ratio, and an overall reduction in saturation of the composition with respect to the theoretical maximum solubility. The strong impact of Mg concentration increases on strength (beneficial) and on toughness (detrimental) is well known. The basis of the Mg/Zn adjustments is the observation that a partial replacement of Mg with

Zn (a slightly less effective hardener per wt.%) enables an increase in toughness while maintaining adequate strength. The overall reduction in solute saturation directly affects the quench sensitivity, which is critical for damage tolerance properties of high solute alloys. AA7056-T79, developed for the upper wing skin of large commercial aircraft is good example of the improvements in strength-toughness balance [34]. On the other hand the addition of Mn and Zr in aluminium alloys can form fine dispersoids which affect recrystallization characteristics and grain structure. These dispersoids retards recrystallization and grain growth. Zr content in aluminium alloys can form $A1_3Zr$ dispersoid, which have a relationship with the matrix and significantly refines the grain size. The addition of Zn increases the strength of the alloy, whereas the addition of Mn increases the fracture toughness of the alloy due to the formation of the secondary phase containing Mn and Fe, which decreases the adverse effects of Fe on fracture toughness [36]. Chemical composition of some of the important 7000 series aluminium alloys are given in Table 3.

Fretting, a special type of wear process that occurs at the contact area between two materials under load and subject to very small amount of relative motion, is another important issue needed to be understood in bolted/pinned aircraft joints. There is a current focus on the prevention of fretting in the aerospace industry since due to fretting, cracks can initiate at stresses (fretting zone), well below the fatigue limit of non-fretted materials and the structure's resistance to fatigue can be decreased by 50–70%. Introduction of compressive residual stresses at the surface of hole, reduction in coefficient of friction, increased surface hardness, changing the surface chemistry and increasing the surface roughness are the main methods that are applied to reduce the nucleation and growth of fretting cracks and improve the fatigue life of aerospace joints and improve fretting resistance [37–42].

4. Developments in aluminium–lithium alloys

Reducing the density of materials is accepted as the most effective way of lowering the structural weight of aircraft. Li (density 0.54 g/cm^3) is one of the few elements that have a high solubility in aluminium. This is significant because, for each 1% added, the density of an aluminium alloy is reduced by 3%. Lithium is also unique amongst the more soluble alloying elements in that it causes a considerable increase in the elastic modulus (6% for each 1%Li added). Additional advantage is that, aluminium alloys containing Li respond to age hardening [43].

The use of aluminium–lithium (Al–Li) alloys in aerospace applications goes back to 1950s with the development of alloy 2020. In the 1980s, 2nd generation of Al–Li alloys were developed. The second generation alloys included the 2090, 2091, 8090 and 8091. The Al–Li alloys 2090, 2091, 8090 and 8091 contain 1.9–2.7% lithium, which results in an about 10% lower density and 25% higher specific stiffness than the 2000 and 7000 series alloys. However, due to technical problems such as anisotropy in the mechanical properties, low toughness, poor corrosion resistance, manufacturing issues (hole cracking and delamination during drilling), 2nd generation Al–Li alloys did not find wide use in aircraft industry. The anisotropy experienced by these alloys is a result of the strong crystallographic textures that develop during processing, with the fracture toughness problem being one of primarily low strength in the short transverse direction [1,21,44,45].

The pressure for higher strength and improved fracture toughness with reduced weight in aircraft applications have resulted in the development of new generation of Al–Li alloys. The new generation of Al–Li alloys provides not only weight savings, due to lower density, but also overcomes the disadvantage of the previous problems with increased corrosion resistance, good spectrum fatigue crack growth performance, a good strength and toughness combination and compatibility with standard manufacturing techniques. This results in well-balanced, light weight and high performance aluminium alloys [1,44,46]. In the new generation (3rd) Al–Li alloys Li concentration was reduced to 0.75–1.8 wt.%. The addition of alloying elements in the 3rd generation Al–Li alloys is used to improve the mechanical properties. Poor corrosion resistance of 2nd generation Al–Li alloys is eliminated in 3rd generation Al–Li alloys by optimising alloy composition and temper. Also Zn additions improved corrosion resistance. The additions of Cu, Li and Mg form the strengthening precipitates and small additions of the dispersoid-forming elements Zr and Mn control the grain structure and crystallographic texture during thermo-mechanical processing. Crack deviation occurs due to high crystallographic texture in addition with slip planarity. Deviation from expected direction of crack propagation makes it difficult to define inspection points and the positioning of crack arresters. It was found that in addition to reduction of the texture components, the severity of slip planarity had to be decreased. This reduction was achieved by decreasing the amount of (Al_3Li) phase. This can be achieved by keeping the amount of Li additions below 1.8 wt ptc. The fracture toughness of 2nd generation Al–Li alloys was often lower than the incumbent 2024 alloy products for designs where damage tolerance is the driving parameter. It was determined that fracture toughness is affected only by insoluble second-phase particles. In 3rd generation Al–Li alloys like 2199 this disadvantageous condition was eliminated by composition optimisation, thermal–mechanical processing and precipitate microstructure control.

Chemical compositions and mechanical properties of some of the widely used Al–Li alloys are shown in Tables 4 and 5 respectively.

Alloy 2195, a new generation Al–Li alloy, has a lower copper content and has replaced the 2219 for the cryogenic fuel tank on the space shuttle where it provides a higher strength, higher modulus and lower density than the 2219. Other alloys, including the 2096, 2097 and 2197, also have lower copper contents but also have slightly higher lithium contents than 2195 [1]. New generation of Al–Li alloys have higher Cu/Li ratio than the second generation alloys (2090 and 2091) as illustrated in Fig. 4.

The new generation of 2199 Al–Li alloys sheet and plates found applications in the aircraft for fuselage and lower wing applications, respectively and the 2099 extrusions for internal structure. It was determined that the 2199-T8E79 plate for the lower wing skin, the 2099-T83 extrusions for lower wing stringers and the 2199-T8 prime sheet for fuselage skin would provide the most benefit for the given applications examined. It is stated that compared to 2024, the 2199 plates have lower density, significantly better stress corrosion and exfoliation corrosion resistance, significantly better spectrum fatigue crack growth performance, better

Table 3
Chemical composition of some 7000 series aerospace aluminium alloys [22].

7000 Series	Cu	Zn	Mg	Mn	Fe	Si	Cr	Zr	Ti	Al
7050	2.3	6.2	2.25	–	⩽0.15	⩽0.12	–	0.1	–	Remainder
7055	2.0–2.6	7.6–8.4	1.8–2.3	0.05	0.15	0.1	0.04	0.08–0.25	0.06	Remainder
7075	1.2–2.0	5.1–6.1	2.1–2.9	0.3	0.5	0.4	0.18–0.28	–	0.2	Remainder
7150	1.9–2.5	5.9–6.9	2.0–2.7	0.1	0.15	0.12	0.04	0.08–0.15	0.06	Remainder
7475	1.2–1.9	5.2–6.2	1.9–2.6	0.06	0.12	0.10	0.18–0.25	–	0.06	Remainder

toughness, and higher tensile yield and compressive yield strengths. The ultimate tensile strength, bearing and shear strengths for the T8E80 temper are similar to those for 2024, while for the T8E79 temper, these strengths tend to be lower. However, this reduction in tensile yield strength provides the higher spectrum fatigue crack growth performance. Thus, one of the two tempers of 2199 may be more suitable for a given application, depending on the design criterion [44].

Al–Li 2099 alloy has low density, high stiffness, superior damage tolerance, excellent corrosion resistance and weldability for use in aerospace structures that require high strength. Alloy 2099 extrusions can replace 2xxx, 6xxx, and 7xxx aluminium alloys in applications such as statically and dynamically loaded fuselage structures and lower wing stringers. 2nd generation Al–Li alloys were susceptible to cracking and delamination during installation of interference fit fasteners as a result of cold working. Low elongation and work hardening properties were the results of these problems. In the 3rd generation Al–Li alloys elongation and cold working capability were improved. Alloy 2099 extrusions have good machining, forming, fastening, and surface finishing properties. The 2099 plate and forgings have better strength, modulus, density and corrosion performance than the7075-T73 and 7050-T74 plate products. The T8E67 temper has much higher strength than the 2024-T3511 or 2026-T3511 with better toughness, much better corrosion resistance (Fig. 5) and lower density. The fatigue crack growth resistance of alloy 2099 also shows improvement with respect to the 2024-T3511, which has been a baseline alloy for fatigue critical components [47].

The effects of normal heat treatments and thermomechanical heat treatments on the mechanical properties and fracture toughness of the 2A97 new generation Al–Li alloy were studied by Yuan et al. [48]. The aim was to improve the relationships of strength, ductility and fracture toughness, and make possible their applications in the aeronautical industries. The Al–Li 2A97 alloy was developed primarily in an attempt to be used for plates and forgings as a promising aerospace material. It was stated that the problem with this alloy is that it yields low ductility and fracture toughness in T8 temper with a high tensile strength, and it yields low strength in T6 temper with a high ductility and fracture toughness. With 4% deformation after low temperature underaging, the ductility and fracture toughness were improved for the 2A97 aluminium–lithium alloy. The K_q value of 43.5 MPa$\sqrt{m}$ in the T8 temper higher than that of 42.5 MPa$\sqrt{m}$ in the T6 temper was obtained, by heat-treatment process and thermomechanical heat-treatment process [48].

Another new generation Al–Cu–Li alloy 2050 was developed to replace the 2000 series and 7000 series alloys where medium to high strength and high damage tolerance are needed [49]. Strength, corrosion resistance, fatigue initiation and crack growth resistance properties were compared and according to the test results it was concluded that the 2050-T84 alloy in addition to its density benefit, offers improvements over the 2024-T351 in static-related properties and corrosion resistance. When compared to incumbent alloy 7050-T7451, the 2050-T84 offers an improved (strength, toughness) balance, at 5% lower density and significantly improved stress corrosion resistance without any redesign and when strength, stiffness and fatigue properties are taken into account, it can lead to weight reduction up to a total of about 10%, depending on the part design drivers.

Table 5
Mechanical properties of some Al–Li alloys [22].

Al–Li alloys	UTS (MPa)	Yield Strength (MPa)	Fracture Toughness, K_{IC} (Mpa m$^{1/2}$)	Elongation (%)
2050-T84	540	500	43(LT)	NA
2090-T83	531	483	43.9	3
2098-T82	503	476	NA	6
2099-T83	543	520	30 (LT) 27 (TL)	7.6
2199-T8	400	345	53	10
8090-T851	500	455	33 (LT), 30 (TL) 12.4 (SL)	12

Al–Li alloy 2198 was developed to replace 2024 and 2524 in aircraft structures where damage tolerance is the critical design factor. It has a wt.% Cu composition ranging from 2.9% to 3.3% and respective of Li from 0.9% to 1.1%. Under constant amplitude loading and stress ratio $R = 0.1$ the fatigue endurance limit is almost 40% below the 2024 yield stress, while for 2198-T351 is only 8% lower than the respective yield stress. When taking into account density, 2198 is superior to 2024 in high cycle fatigue and fatigue endurance limit regimes. For the same normalised applied stresses, 2198 was observed to absorb 2–3 times more energy to fracture than 2024 [50,51]. Comparing the fatigue results in air it was observed that 2524-T3 presented a higher fatigue strength and fatigue limit than the 2198-T851 Al–Li alloy. However, when the alloys were pre-corroded in saline environment they presented similar fatigue behaviour [52].

2060 and 2055 are the newest 3rd generation Al–Li alloys. 2060 has 0.75 wt.% of Li, 3.95 wt.% of Cu and 0.85 wt.% of Mg whereas 2055 has 1.15 wt.% of Li, 3.7 wt.% of Cu and 0.4 wt.% of Mg. The wt.% of the other alloying elements are approximately same for these two alloys. These alloys show improved strength/toughness relationship. Additionally, these alloys exhibit good thermal stability. Both 2055 and 2060 have excellent corrosion performance compared to that of common aerospace aluminium alloys such as 2024-T3 and 7075-T6. Therefore, these alloys could be alternative materials for fuselage, lower wing and upper wing constructions. Trade study analyses show that implementation of Al–Li alloys can save significant weight over the baseline 2000 and 7000 series aluminium alloys. For instance for fuselage skin applications 2060-T8 can save 7% weight compared to that of 2524-T3, for lower wing skin applications 2060-T8 can save 14% weight compared to that of 2024-T351 and for upper wing skin and stringer applications, 2055-T8 can save 10% weight compared to that of 7055-T7751 [47,53]. The 3rd generation Al–Li alloys offers up to 10% weight savings, lower risk and 30% less expensive to manufacture, operate and repair than composite-intensive planes. In addition, these alloys can provide passenger comfort features that are equivalent to composite-intensive planes, such as large

Table 4
Chemical composition of some Al–Li alloys [22].

Al–Li alloys	Li	Cu	Zn	Mg	Mn	Fe	Si	Cr	Zr	Ti	Others
2050	0.7–1.3	3.2–3.9	0.25	0.2–0.6	0.2–0.5	0.1	0.08	0.05	0.06–0.14	0.1	0.2–0.7 Ag
2090	1.9–2.6	2.4–3.0	0.1	0.25	0.05	0.12	0.10	0.05	0.08–0.15	0.15	–
2098	0.8–1.3	3.2–3.8	0.35	0.25–0.8	0.35	0.15	0.12	–	0.04–0.18	0.1	0.25–0.6 Ag
2099	1.6–2.0	2.4–3.0	0.4–1.0	0.1–0.5	0.1–0.5	0.07	0.05	0.1–0.5	0.05–0.12	0.1	0.0001 Be
2199	1.4–1.8	2.0–2.9	0.2–0.9	0.05–0.4	0.1–0.5	0.07	0.05	–	0.05–0.12	0.1	0.0001 Be
8090	2.2–2.7	1.0–1.6	0.25	0.6–1.3	0.10	0.30	0.20	0.10	0.04–0.16	0.1	–

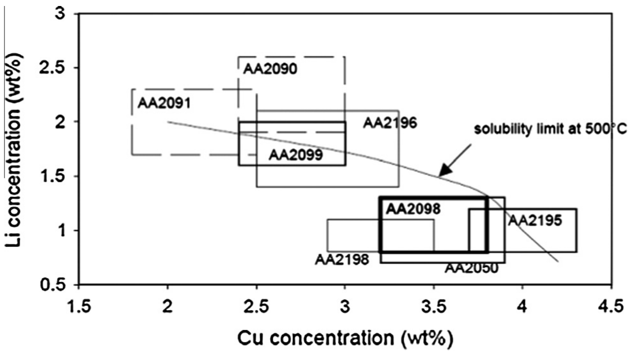

Fig. 4. Positioning of selected Al–Cu–Li alloys in Li and Cu concentrations [34].

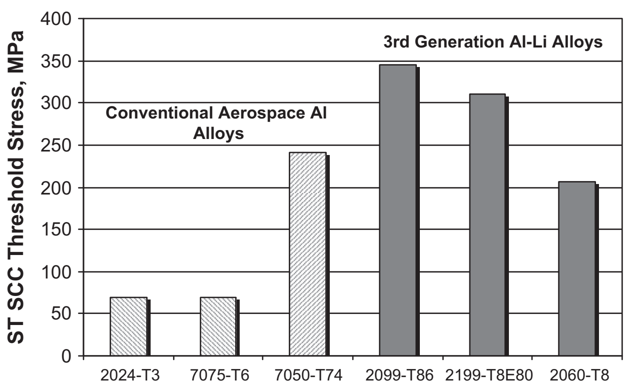

Fig. 5. Comparison of corrosion resistance of Al–Li alloys with 2000 and 7000 series alloys. The figure is based on [47,53].

windows, higher humidity and higher cabin pressure, due to their improved fatigue behaviour. According to the test results in addition to the improvements in material properties, the application of advanced structural design concept resulted in up to 10 times improved damage tolerance performance in critical areas. Beside these advantages aluminium–lithium alloys have fusion welding capacity and standardised use of tooling, mature assembly techniques, repair and maintenance procedures and ease of recycling at the end of the aircraft's life make the Al–Li alloys compete with the polymer composites currently used. While Al–Li alloys offer improvements, delaminations in these alloys play a significant role in their fracture processes. Therefore, a more complete understanding of the factors that affect the behaviour of these delaminations and their corresponding effect on the primary crack behaviour especially near holes need to be well understood [45,54].

5. Developments in joining techniques

Aircraft manufacturers have been continuing their research activities in the field of the construction of aircraft fuselage structures because of the increasing demands on damage tolerance of fuselage structures, increased cost pressure among aircraft manufacturers, and the requirements of airlines for lower aircraft inspection and maintenance costs. New trends in the construction and manufacture of aircraft fuselage have therefore emerged in which welding, bonding, and extrusion are increasingly replacing the use of rivets [55]. The trend of building larger structures with fewer parts has led to demands for thicker and longer plate from which more complex sections can be machined. Alternatively, smaller parts can be joined together and welding appears as the most suitable solution [13]. Weldability of aluminium alloys is presented in Fig. 6. It is shown that all series of aluminium alloys can be friction stir welded.

The riveting is accepted as the traditional technique of joining fuselage and wing structures which are generally made of aluminium alloys. However, riveting increases the weight of the airframe. Riveting also causes stress concentration leading to fatigue crack initiation and growth. Another way of joining these structures is by welding. Since fuselage and wing parts are made of high strength 2000 and 7000 series of aluminium alloys, weldability of these alloys can be relatively very low. Also in traditional welding techniques metal is heated until melting point which causes a large area of heat affected zone (HAZ). HAZ reduces the mechanical properties of the metals resulting in reduced strength and reduced resistance to fatigue. The difficulties with the welding of the high strength aluminium alloys can be listed as follows [1]:

a. The stable surface oxide must be removed by either chemical methods or by thoroughly wire brushing the joint area.
b. Weld cracking or distortion due to residual stresses resulting from high coefficient of thermal expansion.
c. The high thermal conductivity of aluminium requires the high heat input during welding further leading to the possibility of distortion or cracking.
d. Weld cracking due to aluminium's high solidification shrinkage.
e. Aluminium's high solubility for hydrogen when in the molten state leads to weld porosity.
f. Susceptibility of high strength 2000 and 7000 series alloys to weld cracking.

After the invention of Friction Stir Welding (FSW) in 1991 as an alternative way of welding, research effort on the applications of FSW in aircraft manufacturing technology increased substantially. Friction stir welding (FSW) is a solid-state process that operates by generating frictional heat between a rotating tool and the workpiece. A rotating tool with a shoulder and a threaded pin moves along the butting surfaces of two rigidly clamped plates placed on a backing plate as shown in Fig. 7. The shoulder makes firm contact with the top surface of the work piece. Heat generated by friction at the shoulder softens the material being welded. Higher plastic deformation on the metal occurs as the tool is moved along the welding direction. Material is transported from the front of the tool to the trailing edge where it is forged into a joint. Although Fig. 7 shows a butt joint for illustration, other types of joints such as lap joints and fillet joints can also be fabricated by FSW [57].

FSW offers several advantages compared to traditional welding techniques. FSW process takes place in the solid phase below the melting point of the metals to be joined. Problems related to the solidification of a fused material are eliminated. Difficult to fusion weld materials like the high strength 2000 and 7000 series aluminium alloys, could be joined with minor loss in strength.

The main advantages of friction stir welding can be listed as follows:

a. Welding of butt, lap and T joint configurations are possible.
b. No special need for joint preparation is required.
c. 2000 and 7000 series alloys could be welded.
d. Dissimilar alloys could be welded.
e. No crack formation occurs during the fusion and HAZs.
f. No weld porosity occurs.
g. No filler metals needed.
h. For aluminium no requirement for shielding gases.

In general, mechanical properties obtained by FSW are better than for many other welding processes. For example the static properties of the friction stir welded 2024-T351 are between 80%

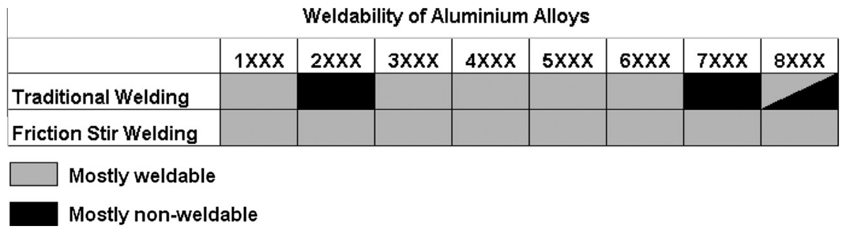

Fig. 6. Weldability of various aluminium alloys. The figure is based on [56].

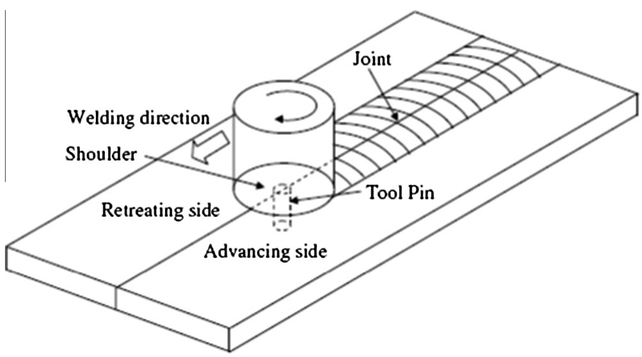

Fig. 7. Schematic of FSW [57].

and 90% of the parent metal, and the fatigue properties approach those of the parent metal [1].

Joints produced by FSW have higher strengths than riveted joints and much lower residual stresses than typical fusion welded joints. In welding 7000 series aluminium alloys, post weld ageing is necessary to stabilise the microstructure in the friction stir welded regions. The selected overaging treatments also improve corrosion resistance of these alloys [58].

Due to the high strength of FSW joints, it allows considerable weight savings in lightweight construction compared to conventional joining technologies. The use of welded instead of riveted joints is also advantageous because of the lower production costs. Therefore, the FSW process has recently been identified as key technology for fuselage and wing manufacturing by leading aircraft manufacturers.

As the large aircraft experience higher stresses and shorter fatigue life, the technology should be applied carefully. There exist several parameters which have influence on the quality and strength of the friction stir weld. This process must be optimised for each specific application. In order to optimise the performance of the FSW joint, it is important to identify the welding parameters. The main FSW process parameters are the followings [59,60]:

a. Tool geometry (shoulder, probe).
b. Clamping system.
c. Axial Load.
d. Tool rotational direction.
e. Plunge depth of probe in workpieces.
f. Plunge speed of the probe in the workpieces at the start position.
g. Dwell time at start of the weld.
h. Tilt angle.
i. Preheating/interpass temperature of workpieces.
j. Control during plunge, dwell and weld periods.
k. Welding speed versus rotation speed.

As mentioned above since there are several tools and operating parameters that affect the quality and strength of the friction stir weld, researches have been invested to understand the effect of these parameters [61–63].

Another welding technique under interest is the laser beam welding of high strength aluminium alloys where relatively small aerospace production of parts is required. With this welding process good weld properties can be obtained at high production speeds. No electrode or filler metal is required and narrow welds with small HAZs are produced. Laser welding produces a concentrated high energy density heat source that results in very narrow heat affected zones, minimising both distortion and loss of strength in HAZ [1].

In laser beam welding radiant energy is used to produce the heat required to melt the materials to be joined. A concentrated beam of coherent, monochromatic light is guided by optical devices and focused to a small spot, for higher power density, on the abutting surfaces of the parts being joined. Dissimilar alloys could be joined in a noncontact process. Pulsed or continuous wave mode lasers are used to join the metals. The main advantages of laser welding are the shape of the weld and good penetration, high precision, high mechanical properties of the weld, high welding speed, low heat input, high flexibility and possibility of automation. Both very local welds and heat-affected zones occur with the help of the high energy density beam, and therefore good mechanical properties with relatively low distortion of the workpiece could be achieved. The main disadvantages are the relatively high cost of investment and the important requirements related to the machining of the parts to assure a precise groove (reduced dimensional tolerances). Higher product quality, in terms of improved in-service properties, could be achieved through: improved tolerances; accurate control of process parameters; selection of new materials; and product redesign. EADS Airbus has invested in laser welding as a replacement for riveting in non-critical applications. In double-sided laser beam welding of T-joints the incident beam position, incident beam angle, and beam separation distance are the most important welding parameters. The incident beam position has great impact on joint quality. 6xxx series Al–Mg–Si alloys are susceptible to hot cracking. Aluminium filler (such as AA4047) wire containing excess silicon is recommended for 6xxx series alloys. It is reported that the crack sensitivity decreases if the Silicon content exceeds 1.5% [64]. One application involves joining stiffening stringers to the skin of the fuselage. The damage-tolerant alloy 6013 is the base material and 4047 is the filler material. The stringers are welded from two sides at 10 m/min, using two 2.5 kW CO_2 laser beams. The joint is designed such that the HAZ is contained in the stringer, and does not impinge on the skin. The process was first used in series production of the Airbus 318, and was then implemented successfully in other aircraft models [65].

6. Conclusions

Aluminium alloys have been successfully used as primary material for the structural parts of aircraft for more than 80 years. Aircraft designers possess considerable experience in the design, production, operation and maintenance of aluminium airframes.

The infrastructure and knowledge base has become mature. However, with the introduction of high performance polymer composites in the application of airframe designs reduced the role of aluminium alloys up to some extent due composites' high specific properties, reduced weight, fatigue performance and corrosion resistance (Boeing 787, Airbus A350). In order for aluminium alloys to remain attractive in the airframe construction and compete with and/or be compatible with currently used polymer composites, research activities on the improvement of structural performance, weight and cost reductions are needed. Recent developments in high strength Al–Zn and Al–Li alloys, damage tolerant Al–Cu and Al–Li alloys, have been successful in improving the static strength, fracture toughness, fatigue and corrosion resistance through the design and control of chemical composition, and/or through the development of more effective heat treatments. It has been seen from this review that major improvements of aerospace aluminium alloys are due to optimised solute content and solute ratios in order to achieve better property balance. The use of new dispersoid-processing combinations results in desired grain structures that provide better damage tolerance. Improvements in understanding and modelling of the hardening system and especially the effect of minor element addition will help improvements in mechanical properties.

Current research activities for both composites and aluminium include: improvement on mechanical properties, reduction of manufacturing, maintenance and repair costs, prevention of corrosion and fatigue and ability to perform reliably throughout its service life.

In order to use the advantage of improvements in mechanical properties of advanced aluminium alloys and sustain the structural integrity in mechanically fastened aircraft structures a special attention should be paid on the fretting fatigue. There is need to understand the fretting behaviour of recently developed Al–Li alloys such as 2050 and 2099 and fibre metal laminates in mechanically fastened aircraft joints.

In addition to weight reduction and improvement on the structural performance the materials, cost reduction through the development on the manufacturing techniques is also a key issue. Manufacturing constitutes the biggest portion of the cost of the airframe. Therefore great effort is being spent to reduce the production costs and part count via introducing high-speed machining, novel assembly techniques such as laser beam welding and friction-stir welding. For example, unlike most conventional aerospace alloys, the fusion weldability of Al–Cu–Li alloys could introduce new opportunities in the fabrication of fuselage. Therefore, in addition to metallurgical developments with the combination of other manufacturing techniques than the riveting will help reach optimised damage tolerant designs.

High strain-rate superplastic forming and casting are also drawing attention as cost effective solutions. Advanced joining techniques will also make aluminium structures more affordable.

The airframes and other structural parts will continue to be composed of different materials including aluminium, titanium, steel, polymer composites and fibre metal laminates depending on the balance of structural and economical factors. Weight saving through increased specific strength and/or stiffness and affordability (procurement, maintenance and repair costs) are the major drivers for the development and selection of materials for civil airframes. In selecting new materials for aircraft applications, there should be no reduction on the levels of safety that is already reached with conventional alloys. Fatigue resistance, corrosion resistance and damage tolerance are all very important mechanical properties of airframe materials that affect the inspection, maintenance and repair costs and this is where modern aluminium alloys could compete effectively with polymer composites.

It is believed that developments of advanced hybrid materials, like fibre metal laminates could provide additional opportunities for aluminium alloys and new material options for the airframe industry.

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