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Review of Recent Advances in High Performance Aluminium Alloys for Aerospace Structures

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***Abstract*. The increasing demand for lightweight, durable, and cost effective aerospace structures has renewed scientific and industrial interest in high performance aluminium alloys. This review aims to systematize and critically evaluate recent developments in aluminium alloys for aerospace structures and applications, with emphasis on the relation between alloy system, processing route, microstructure, functional performance, and service reliability. The study was conducted as a structured narrative review with integrative elements, based on recent peer-reviewed research and review articles published mainly from 2021 to 2026. The literature was classified according to alloy families, representative tempers, advanced processing routes, corrosion and fatigue mechanisms, joining technologies, and sustainability aspects. The synthesis indicates that 2xxx, 7xxx, and aluminium lithium alloys remain the most important alloy groups for aeronautical and space structures, while additively manufactured aluminium alloys are becoming increasingly relevant for lightweight and geometrically complex components. The results also show that alloy performance is controlled by coupled effects of alloying, heat treatment, thermomechanical processing, precipitation state, grain structure, defects, surface condition, and environmental exposure. Corrosion fatigue, stress corrosion cracking, additive manufacturing defects, joining related degradation, and sustainable recycling remain key challenges. The literature suggests that aluminium alloys retain a significant aerospace role because they combine low density, mechanical efficiency, manufacturability, repairability, recyclability, and economic viability. Future progress requires integrated alloy design, defect tolerant processing, environmentally safer surface protection, reliable life prediction, and stronger links between materials development and life cycle sustainability.**

Keywords: aerospace structures, aluminium alloys, mechanical properties, sustainable manufacturing.

I. INTRODUCTION

Aluminium alloys remain a strategically important class of aerospace engineering materials because aircraft and spacecraft structures require a combination of low density, high specific strength, fatigue resistance, corrosion resistance, fracture toughness, manufacturability, inspectability, and long term reliability. The relevance of this topic has increased because aerospace design is increasingly driven by the need to reduce structural mass, fuel consumption, emissions, production cost, and maintenance risk. Recent broad reviews and aircraft materials chapters show that aluminium alloys continue to be used together with titanium alloys and polymer matrix composites rather than being completely displaced by them [1], [2].

The principal aerospace aluminium systems include 2xxx Al-Cu and Al-Cu-Mg alloys, 7xxx Al-Zn-Mg-Cu alloys, and aluminium-lithium systems such as 2050, 2195, and 2198. The 2xxx family is associated with fatigue resistance and damage tolerance, while the 7xxx family provides high strength for heavily loaded structural elements such as spars, frames, stringers, ribs, and fittings [3]. Aluminium-lithium alloys are important because lithium reduces density and can increase elastic modulus, making these alloys attractive for weight critical aeronautical and space applications [4], [5].

Important knowledge gaps remain. First, strength, ductility, fracture toughness, corrosion resistance, and stress corrosion cracking resistance cannot be maximized simultaneously. Second, laboratory properties do not always represent real aerospace service, where cyclic loading, humidity, chloride containing atmospheres, de icing fluids, temperature variation, and surface damage may interact. Third, advanced manufacturing routes such as laser powder bed fusion, wire arc additive manufacturing, additive friction stir deposition, hybrid additive manufacturing, and solid state repair introduce new opportunities but also new qualification challenges [6] - [9].

The purpose of this review is therefore to synthesize recent evidence on aerospace aluminium alloys from a process microstructure property perspective. Unlike a

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purely descriptive overview, the paper connects representative alloys and tempers with processing routes, microstructural features, performance outcomes, limitations, and aerospace relevance. Particular attention is given to high strength 2xxx and 7xxx alloys, aluminium-lithium alloys, additive manufacturing, corrosion mechanisms, joining technologies, and sustainability of aerospace aluminium recycling [10] - [16].

The central proposition of the article is that aluminium alloys remain essential aerospace materials not because of a single superior property, but because of their integrated balance of lightweight design potential, structural efficiency, manufacturability, repairability, corrosion protection capability, recyclability, and economic viability under modern aerospace requirements.

II. Materials and Methods

This study was designed as a structured narrative review with integrative elements. The review procedure was organized to ensure transparency in source selection, thematic classification, and critical interpretation of recent developments in aluminium alloys for aerospace applications. No experimental manufacturing or mechanical testing was performed; the material analysed consists entirely of published scientific data from peer-reviewed research articles and review papers.

The literature search focused primarily on peer reviewed publications from 2021 to 2026. Older sources were considered only when needed for established alloy designations or aerospace context. Scientific databases and publisher platforms consulted included Scopus indexed journals, ScienceDirect, SpringerLink, MDPI, Wiley Online Library, PubMed, Taylor and Francis Online, and Google Scholar. Search terms included aluminium alloys, aerospace applications, aircraft structures, 2024, 2524, 7050, 7150, 7085, 2050, 2195, 2198, Al-Cu-Li, 7xxx, Al-Li, stress corrosion cracking, corrosion fatigue, laser powder bed fusion, wire arc additive manufacturing, additive friction stir deposition, heat treatment, joining, welding, surface protection, and recycling.

The inclusion criteria were peer reviewed publications written in English; clear relevance to aluminium alloys used or potentially applicable in aerospace structures; discussion of composition, microstructure, processing, mechanical behaviour, fatigue, fracture, corrosion, thermal stability, joining, additive manufacturing, surface engineering, or recycling; and publication mainly within the last five years. Both review articles and primary research papers were included in order to combine broad technological synthesis with specific experimental evidence.

The exclusion criteria were non aerospace applications with no transferable materials relevance, publications focused exclusively on non aluminium materials, papers without sufficient microstructural or performance information, and duplicate sources superseded by more recent and more comprehensive literature. Since the article is a review, the results were interpreted qualitatively rather than statistically.

The selected literature was organized into seven thematic groups: general aerospace aluminium alloy development; 2xxx and Al-Cu-Li systems; 7xxx Al-Zn-Mg-Cu systems; additive and hybrid manufacturing; corrosion, stress corrosion cracking, and corrosion fatigue; joining and repair; and sustainability and recycling. For each source, the following information was extracted where available: alloy or alloy family, temper condition, processing route, key microstructural features, main property outcome, aerospace relevance, and limitations. The synthesis also included recent 2026 literature on post processing of additively manufactured aluminium alloys, Al-Cu-Li corrosion, rare earth microalloying, heat resistant alloy design, hybrid additive manufacturing, additive friction stir deposition, laser beam welding, 2xxx fatigue improvement, wire arc additive manufacturing, and aerospace aluminium recycling [17] - [29].

III. Results and Discussion

Because the present article is a review study, the results are not experimental measurements obtained from newly manufactured specimens, but synthesized findings extracted from recent peer reviewed literature. The reviewed data indicate that aluminium alloys remain highly relevant in aerospace engineering because they combine low density, high specific mechanical performance, mature processing routes, good repairability, and relatively favourable cost compared with many competing advanced structural materials [1], [2].

A. Main Aerospace Aluminium Alloy Families

The literature indicates that aerospace aluminium alloy selection should be discussed not only at family level, but also at representative alloy and temper level. Conventional 2xxx alloys such as 2024-T3 and damage tolerant derivatives such as 2524 are used in fatigue sensitive skin and fuselage applications because they provide a useful combination of strength, toughness, and crack growth resistance. Recent work on 2xxx alloys shows that microstructural uniformity can simultaneously improve mechanical and fatigue properties, demonstrating that fatigue performance is strongly linked to precipitate distribution, grain structure, and deformation history [24].

High strength 7xxx alloys such as 7050-T7451, 7150, and 7085 are particularly important for thick plate, wing structures, frames, spars, and highly loaded fittings. Their strengthening response is governed mainly by precipitation in the Al-Zn-Mg-Cu system. However, overemphasis on peak strength may increase susceptibility to stress corrosion cracking, exfoliation corrosion, and quench related property gradients. Therefore, aerospace tempers for 7xxx alloys often prioritize a controlled compromise between strength, fracture toughness, and corrosion resistance [3].

Aluminium-lithium alloys such as 2050, 2195, and 2198 are attractive for advanced fuselage panels, cryogenic tanks, launch vehicle structures, and other weight critical aerospace components. Their performance is controlled by the evolution of strengthening phases such as T1, theta prime, and delta prime, as well as by grain morphology, texture, and anisotropy [4], [5]. Recent corrosion focused literature highlights that Al-Cu-Li alloys require careful control of Cu to Li ratio, ageing condition, grain boundary precipitation, and microalloying additions to reduce intergranular corrosion, exfoliation corrosion, and stress corrosion cracking [18].

Current research focuses particularly on third-generation Al-Li alloys, in which alloying and precipitation control are used to improve strength, fracture toughness, fatigue resistance, and microstructural stability [4], [12] - [14].

Additively manufactured systems include widely processed AlSi10Mg, Al-Mg-Sc-Zr type alloys such as Scalmalloy, experimental Al-Cu and Al-Cu-Li compositions, and emerging high strength printable aluminium based systems. These alloys offer design freedom and material savings, but aerospace implementation depends on process stability, defect control, post processing, and fatigue qualification [6] - [9], [17].

Representative evidence connecting alloy system, processing, microstructural features, property outcome, aerospace relevance, and limitations is summarized in Table I. A complementary data-level comparison of typical mechanical and corrosion-related properties for the principal aerospace aluminium alloy families is provided in Table II. The values are indicative literature ranges rather than certified design allowables because they depend on product form, thickness, temper, surface condition, build orientation, and test environment.

B. Processing, Microstructure, and Functional Performance

Across all alloy families, the dominant result of the review is that properties are controlled by the interaction between alloy chemistry, processing route, microstructure, and service environment. Heat treatment is especially important for precipitation hardening alloys. In 2xxx and Al-Cu-Li alloys, Cu rich and Li containing precipitates control strength and anisotropy; in 7xxx alloys, the ageing response is governed by GP zones, eta prime, and eta precipitates [3] - [5].

Thermomechanical processing also plays a critical role. Rolling, extrusion, forging, solution treatment, quenching, artificial ageing, stress relief, and deformation processing influence recrystallization state, grain morphology, texture, residual stress, dispersoid distribution, and precipitate morphology. In thick 7xxx products, quench sensitivity can generate through thickness property gradients, while in Al-Cu-Li thick plates, inhomogeneous precipitation and crystallographic texture may influence both strength and intergranular corrosion resistance [18].

The reviewed literature therefore suggests that aerospace alloy development should optimize property balance rather than maximize tensile strength alone. The best alloy for a given component is the one that satisfies the combined requirements for strength, fatigue life, fracture toughness, corrosion resistance, joining behaviour, formability, inspection, repairability, cost, and certification.

C. Additive Manufacturing and Advanced Processing

Additive manufacturing has become one of the most active research directions for aluminium alloys. Laser powder bed fusion and selective laser melting can produce complex lightweight components and topology optimized structures, which is attractive for brackets, housings, ducts, heat exchangers, and non primary structural elements. However, high strength wrought alloys remain difficult to process because of hot cracking, porosity, lack of fusion, volatile element loss, residual stresses, anisotropy, and fatigue scatter [6] - [9].

Post processing is therefore not a secondary operation but a central part of additive manufacturing qualification. Recent literature emphasizes heat treatment, hot isostatic pressing, machining, polishing, shot peening, laser peening, and surface finishing as routes for improving density, residual stress state, surface integrity, corrosion resistance, and fatigue performance of additively manufactured aluminium components [17]. Fatigue qualification remains particularly important because pores, unmelted particles, surface roughness, and lack of fusion defects may act as crack initiation sites.

Wire arc additive manufacturing is relevant for large near net shape aluminium structures and repair, but it faces challenges related to heat accumulation, porosity, solidification cracking, microstructural heterogeneity, and distortion. Recent WAAM reviews highlight process improvements such as interlayer rolling, friction stir processing, optimized heat input, hybrid control strategies, and improved path planning for reducing defects and improving dimensional stability [25].

Additive friction stir deposition and friction stir additive manufacturing represent solid state alternatives to fusion based AM. Because these processes operate below the melting point, they can reduce solidification cracking, porosity, and volatile element loss. Recent AFSD literature identifies dynamic recrystallization, refined equiaxed grains, reduced residual stresses, and machine learning guided process control as important directions [21], [22]. The 2195 Al-Li FSAM study also shows that stirring path design can influence texture, grain refinement, hardness distribution, and directional mechanical properties [15].

Hybrid additive manufacturing combines deposition with machining, rolling, friction stir processing, or other post deposition operations. This approach is relevant to aerospace repair because it can reduce thermal and microstructural variations, improve surface quality, and better control dimensional accuracy [20]. However, certification of hybrid AM parts still requires reproducible defect statistics, validated inspection methods, and fatigue data under representative service conditions.

TABLE I PRINCIPAL ALUMINIUM ALLOY FAMILIES FOR AEROSPACE APPLICATIONS

Alloy or System	Temper or Process	Key Microstructural Features	Main Property Outcome	Aerospace Relevance	Main Limitation
2024 / 2524	T3 and related damage tolerant tempers	Cu and Mg based precipitation, elongated grains, fatigue sensitive microstructure	Good fatigue resistance and damage tolerance	Fuselage skins and fatigue critical structures	Moderate corrosion resistance; requires surface protection
7050 / 7150 / 7085	T7 type overaged or controlled ageing tempers	Eta prime and eta precipitates, grain boundary precipitation, quench sensitivity	Very high strength with toughness and SCC trade offs	Spars, frames, stringers, thick plates, fittings	SCC, exfoliation corrosion and property gradients in thick products
2050 / 2198 / 2195	Al-Cu-Li, T8 type states	T1, theta prime and delta prime precipitation, texture and anisotropy	Lower density, high specific strength and stiffness	Advanced fuselage, cryogenic tanks, launch vehicle structures	Cost, anisotropy, corrosion sensitivity and processing complexity
AlSi10Mg and Al-Mg-Sc-Zr	LPBF or SLM plus post processing	Fine cellular or eutectic structures, pores, residual stresses, Sc/Zr grain refinement	Complex lightweight components with improved design freedom	Brackets, housings, ducts, heat exchangers, topology optimized parts	Porosity, surface roughness, fatigue scatter and qualification barriers
Al-Cu-Li-Mg-Ag-Sc-Zr	Selective laser melting	Heterostructure, Li loss, Cu containing precipitates, process sensitive porosity	Potential crack free high strength Al-Li AM parts	Future lightweight aerospace structures	Narrow process window and volatile element control
2195 Al-Li	Friction stir additive manufacturing	Dynamic recrystallization, ultrafine grains, modified texture, precipitate redistribution	Improved grain refinement and path dependent mechanical response	Large Al-Li structures and repair	Path planning, anisotropy and local property variation
7xxx and 6xxx alloys	AFSD and hybrid AM	Solid state deposition, refined equiaxed grains, reduced melting defects	Potential low defect repair and near net shape manufacture	Large scale repair and structural build up	Need for process windows, post deposition heat treatment and fatigue validation
7075 and 2195 scraps	Melt purification or friction stir consolidation	Cleanliness control, grain refinement, precipitate recovery, chip consolidation	Recycled sheets can approach useful aerospace grade properties	Circular aerospace aluminium supply chains	Sorting, impurity control, certification and economic scale up

D. Corrosion, Corrosion Fatigue, and Surface Protection

Corrosion is not a single degradation mode in aerospace aluminium alloys. The reviewed literature indicates a sequence of related mechanisms: pitting corrosion, intergranular corrosion, exfoliation corrosion, stress corrosion cracking, and corrosion fatigue. Pitting often starts at intermetallic particles or local electrochemical heterogeneities and can become a fatigue crack initiation site under cyclic loading [9] - [11].

Intergranular corrosion and exfoliation corrosion are especially relevant for precipitation hardening alloys where grain boundary precipitates and precipitate free zones create local galvanic differences. In Al-Cu-Li alloys, corrosion behaviour is strongly affected by ageing treatment, Cu and Li content, T1 precipitation, grain boundary structure, crystallographic texture, and thermo mechanical history [18]. In 7xxx alloys, corrosion and stress corrosion cracking resistance depend strongly on Zn-Mg-Cu balance, ageing condition, grain boundary precipitation, and the continuity of anodic paths [3].

Stress corrosion cracking is critical for highly stressed 7xxx components and for susceptible Al-Cu-Li states. It couples tensile stress, corrosive environment, and microstructural pathways for crack initiation and propagation. Chloride containing atmospheres, marine exposure, humidity, and residual stresses can all increase susceptibility. This is why aircraft alloy tempers are often selected for durability rather than peak strength alone [3], [18].

Corrosion fatigue is particularly important because aerospace structures operate under cyclic loading in variable environments. The literature shows that crack tip chemistry, loading frequency, humidity, chloride concentration, pit morphology, and pre corrosion history may substantially affect crack growth [10], [11]. Prediction models based on data driven approaches can support life assessment, but their reliability depends on high quality experimental datasets and representative environmental conditions [12].

Table II. Comparative Mechanical and Corrosion Property Ranges for Principal Aerospace Aluminium Alloy Families

Alloy Family / Examples	Representative Condition	Density (g cm-3)	YS / UTS (MPa)	Ductility, Fatigue and Toughness	Corrosion and SCC Behaviour	Typical Aerospace Interpretation
2xxx Al-Cu-Mg: 2024, 2524	T3, T351 and damage-tolerant variants	2.77-2.78	320-390 / 430-480	El. 10-20%; good fatigue and crack-growth resistance; 2524 improves damage tolerance.	Moderate corrosion resistance; susceptible to pitting, intergranular attack and exfoliation; cladding, anodizing or coating normally required.	Best suited to fatigue-sensitive fuselage skins and damage-tolerant panels [1], [10], [11], [24].
7xxx Al-Zn-Mg-Cu: 7050, 7150, 7085	T7451, T7651, T7751 and related overaged tempers	2.80-2.85	430-540 / 480-590	El. 6-13%; very high static strength; toughness and fatigue performance depend strongly on temper and section thickness.	SCC and exfoliation are key limitations in peak-strength states; T7-type tempers improve SCC resistance with a strength trade-off.	Preferred for spars, frames, fittings, ribs, thick plates and heavily loaded metallic structures [1], [3].
Al-Cu-Li: 2050, 2195, 2198	T8, T84, T851 and related thermomechanical states	2.55-2.71	350-520 / 430-560	El. 6-14%; high specific strength and stiffness; anisotropy and texture are important design factors.	Intergranular corrosion, exfoliation and SCC depend on ageing condition, T1 precipitation, Cu/Li ratio and grain-boundary chemistry.	Attractive for advanced fuselage panels, cryogenic tanks and launch vehicle structures where mass saving is critical [4], [5], [18].
AM Al-Si-Mg: AlSi10Mg	LPBF/SLM plus stress relief, HIP, machining or T6-type treatment	2.65-2.68	200-330 / 320-460	El. 2-12%; fatigue scatter is controlled by porosity, lack-of-fusion defects and surface roughness.	Generally moderate-to-good corrosion resistance, but pitting and corrosion fatigue are strongly affected by AM defects and surface finish.	Useful for topology-optimized brackets, housings, ducts and heat exchangers when post-processing and inspection are controlled [6], [7], [17].
AM Al-Mg-Sc-Zr: Scalmalloy-type systems	LPBF/SLM plus ageing or tailored post-processing	2.65-2.70	350-520 / 450-560	El. 5-15%; high specific strength and improved printability; fatigue still depends on defect population and surface integrity.	Usually better intrinsic corrosion response than high-Cu and many 7xxx alloys, but AM porosity, roughness and galvanic contacts remain critical.	Promising for lightweight AM structural and secondary aerospace parts, especially where high strength and design freedom are required [6], [7], [19].

Note: YS - yield strength; UTS - ultimate tensile strength; El. - elongation; SCC - stress corrosion cracking; AM - additive manufacturing; LPBF - laser powder bed fusion; SLM - selective laser melting; HIP - hot isostatic pressing. The values summarize typical published ranges and should not be used as certified aerospace design allowables.

Surface engineering remains essential. Anodizing, conversion coatings, sol gel coatings, organic primers, plasma electrolytic oxidation, rare earth based systems, and hybrid organic inorganic coatings are used or investigated to improve corrosion resistance and service life [10]. At the same time, environmental and regulatory pressures require reduction of hazardous chromate systems and development of safer alternatives. Rare earth microalloying also offers a complementary route for improving thermal stability, precipitate control, and corrosion related performance in selected aluminium systems [19].

E. Joining and Structural Integration

Aerospace structures are assemblies rather than isolated materials; therefore joining technologies strongly influence structural reliability. Conventional joining includes riveting, mechanical fastening, adhesive bonding, fusion welding, and brazing, while advanced approaches include friction stir welding, laser beam welding, hybrid joining, and solid state repair [16].

Friction stir welding is attractive for aluminium alloys because it avoids melting and can reduce solidification cracking and porosity. Nevertheless, it still produces heat affected and thermomechanically affected zones, local softening, texture changes, residual stresses, and possible fatigue hot spots. The fatigue performance of welded joints therefore depends on tool design, heat input, post weld treatment, joint geometry, surface finish, and inspection quality.

Laser beam welding is relevant where high productivity and narrow heat affected zones are required. A 2026 systematic review of laser beam welding of aluminium alloys emphasizes defect mitigation and process optimization, including control of porosity, hot cracking, keyhole instability, shielding, filler strategy, and parameter selection [23]. For Al-Li alloys, joining is especially challenging because lithium volatility, hot cracking tendency, and precipitate modification can degrade joint performance. Thus, welding and repair should be considered together with alloy selection, heat treatment, and fatigue qualification.

F. Interpretation of the Reviewed Results

The sustainability value of aluminium alloys must be supported by recycling and life cycle evidence rather than by general statements alone. Aluminium is recyclable, but aerospace grade recycling is difficult because high strength alloys have narrow compositional limits and require strict melt cleanliness. Recent research on recycled aerospace grade 7075 sheets shows that with aerospace grade melt purification and quality control, recycled products can approach the microstructure and properties of primary sheet material and may offer economic benefits [26].

Aerospace aluminium scrap recycling also depends on energy flow, impurity control, sorting, alloy compatibility, and high end upcycling technologies. Reviews of aerospace aluminium scrap cycles highlight the need to avoid downgrading and to integrate refining, purification, and certification oriented quality control [27]. For Al-Li alloys, direct solid state recycling of machining chips into sheets by double sided friction stir consolidation has been reported as a promising route for recovering high value lightweight alloy material while producing sheets with useful strength and ductility [28].

Life cycle sustainability assessment is becoming increasingly important for aerospace manufacturing. Recent aerospace decarbonization literature links additive, subtractive, and hybrid manufacturing routes to energy consumption, waste, emissions, and circularity [29]. This supports the conclusion that material selection should include not only density and strength, but also resource efficiency, scrap generation, recycling route, process energy, and maintainability.

G. Limitations of the Review

The reviewed evidence suggests that the technological value of aluminium alloys in aerospace engineering is based on property balance rather than superiority in one isolated category. Titanium alloys provide excellent temperature capability and corrosion resistance, and polymer matrix composites offer substantial weight reduction in large integrated structures. Aluminium alloys remain competitive because they offer a mature and certifiable combination of strength, toughness, fatigue resistance, corrosion protection strategies, manufacturability, inspection capability, repairability, recyclability, and cost effectiveness [1], [2].

The strongest practical interpretation is that alloy selection is application dependent. For fatigue sensitive fuselage structures, 2xxx and selected Al-Li alloys remain attractive because of damage tolerance. For highly loaded structural elements, 7xxx alloys are suitable when corrosion and stress corrosion cracking are controlled. For cryogenic tanks and advanced lightweight structures, Al-Li alloys offer density and stiffness advantages. For brackets, ducts, housings, heat exchangers, and complex secondary components, additively manufactured aluminium alloys are increasingly relevant, but only when defects and fatigue performance are controlled.

A second interpretation is that aerospace aluminium alloy research is moving from composition based improvement toward integrated control of composition, processing, microstructure, defects, surface condition, joining, and life cycle performance. This process microstructure reliability coupling gives the present review its practical value for engineering materials selection.

H. Practical and Theoretical Significance

A strategic comparison with polymer matrix composites and titanium alloys shows that aluminium alloys are most competitive in subsystems where balanced cost, manufacturability, inspectability, field repair, fatigue tolerance, and recycling are as important as minimum mass. In fuselage skins, lower wing skins, frames, ribs, stringers, floor beams, bulkheads, tanks, and many secondary structures, 2xxx, 7xxx, and Al-Li alloys provide a well-understood design allowables base and predictable forming, fastening, and repair behaviour. Carbon fibre composites can reduce weight in large integrated fuselage shells, wing boxes, control surfaces, and fairings, but they introduce different design drivers, including impact damage sensitivity, delamination, moisture and thermal effects, lightning strike protection, more demanding nondestructive inspection, and more complex end-of-life recycling [1], [2], [29].

Titanium alloys occupy a different strategic niche. They are preferred in high-temperature or chemically aggressive zones and at composite-metal interfaces, including engine-adjacent structures, pylons, firewalls, landing gear components, highly loaded fittings, fasteners, and areas where galvanic compatibility with carbon fibre composites is advantageous. Their higher density and cost, more demanding machining, and lower general formability limit their use in large-area airframe skins where aluminium or composites are more mass- and cost-efficient [1], [2], [16].

The resulting material strategy is therefore not a simple replacement sequence but a subsystem-level hybrid architecture. Aluminium alloys remain attractive for damage-tolerant pressurized fuselage structure, cryogenic and launch vehicle tanks, metallic wing and internal load-bearing elements, repairable secondary structures, and additively manufactured brackets or ducts. Composites are strongest where large-area integral stiffness and mass reduction dominate, while titanium is strongest where temperature capability, corrosion resistance, high bearing strength, or composite compatibility dominates. This comparison reinforces the main conclusion that aluminium alloys retain aerospace relevance because they occupy a broad, certifiable, economical, and repairable design space rather than because they outperform every competing material in every subsystem.

I. Limitations of the Review

The main limitation of this review is that it is based on published literature rather than new experimental testing. The reviewed studies differ in alloy designation, temper condition, specimen geometry, process route, testing environment, loading regime, and evaluation method. This makes direct quantitative comparison difficult, especially for fatigue life, corrosion fatigue crack growth, fracture toughness, stress corrosion cracking resistance, and additive manufacturing performance.

A second limitation is that some aerospace alloy data, certified processing routes, and design allowables are proprietary or not fully described in open literature. Therefore, the review can identify trends and mechanisms but cannot replace certified design data or material qualification procedures.

A third limitation concerns the rapid development of additive manufacturing, hybrid manufacturing, environmentally safer coatings, and recycling routes. Some promising 2026 results remain at laboratory or early industrial validation level. They should be interpreted as emerging research directions rather than fully established aerospace standards.

J. Practical and Theoretical Significance

From a practical perspective, the results support a material selection approach based on structural function and service environment. High strength 7xxx alloys are appropriate for highly loaded structural elements; 2xxx and Al-Li alloys are appropriate where damage tolerance and weight reduction are important; and AM capable alloys are promising for complex lightweight secondary parts and repair provided that porosity, cracking, anisotropy, post processing, inspection, and fatigue qualification are addressed.

The findings are also relevant to maintenance and life extension. Since corrosion fatigue and surface degradation are major durability concerns, aerospace maintenance programs should combine inspection, protective coatings, corrosion monitoring, structural health monitoring, and predictive models. Data driven crack growth prediction may assist durability assessment, but must be trained and validated on representative alloy, temper, environment, and loading data [12].

From a theoretical perspective, the review highlights the need for models that link precipitation, grain structure, residual stress, defects, surface condition, environmental chemistry, and fatigue crack growth. This integrated approach is essential for next generation aluminium alloys, AM components, solid state repair technologies, and recycled aerospace grade materials.

IV. Conclusions

The literature synthesis indicates, rather than experimentally proves, that aluminium alloys remain essential aerospace engineering materials because they combine low density, high specific mechanical performance, mature processing routes, repairability, corrosion protection capability, recyclability, and economic efficiency. Their importance is not based on a single superior property but on a balanced set of engineering advantages.

The reviewed evidence suggests that the most important aerospace aluminium alloy systems are still 2xxx, 7xxx, and aluminium-lithium alloys. The 2xxx family is relevant for fatigue critical and damage tolerant structures; the 7xxx family is important for highly loaded components requiring high strength; and Al-Li alloys offer additional weight saving and stiffness benefits. However, their performance depends strongly on temper, precipitation state, grain structure, residual stress, surface condition, joining history, and environment.

The practical significance of the review is that aerospace material selection should be based on integrated criteria including strength, fatigue life, fracture toughness, corrosion resistance, stress corrosion cracking susceptibility, thermal stability, formability, joining behaviour, inspection, repairability, cost, and life cycle sustainability. This is especially important because reducing structural mass must not compromise safety, service life, or certification reliability.

At subsystem level, this means that aluminium alloys should be viewed as complementary to composites and titanium rather than as obsolete substitutes: composites dominate where large integrated stiffness and minimum mass are decisive, titanium dominates where temperature, corrosion resistance, and composite-interface compatibility are decisive, and aluminium remains strategically valuable where certified damage tolerance, manufacturability, repairability, and cost efficiency must be combined.

The review also identifies several directions for future research: better strength toughness corrosion balance in 2xxx, 7xxx, and Al-Li alloys; improved corrosion fatigue testing under realistic service environments; qualification of additively manufactured and hybrid manufactured aluminium components; defect mitigation in welding and solid state joining; chromium free surface protection; high value recycling of aerospace scrap; and predictive models for long term structural reliability.

Overall, the literature suggests that aluminium alloys will remain indispensable in aerospace engineering, but their future role will depend on the ability to integrate alloy design, microstructural control, advanced processing, surface protection, joining, recycling, and life cycle assessment into a unified materials engineering approach.

References

[1] S. S. Li, X. Yue, Q. Y. Li, H. L. Peng, B. X. Dong, T. S. Liu, H. Y. Yang, J. Fan, S. L. Shu, F. Qiu, and Q. C. Jiang, "Development and applications of aluminum alloys for aerospace industry," Journal of Materials Research and Technology, vol. 27, pp. 944-983, 2023, https://doi.org/10.1016/j.jmrt.2023.09.274

[2] K. Thavasilingam, A. Senthil Kumar, D. Sakthimurugan, and K. Giridharan, "Aluminum alloys for aircraft structures," in Aerospace Materials, Elsevier, 2025, pp. 385-404, https://doi.org/10.1016/B978-0-443-22118-7.00016-6

[3] B. Zhou, B. Liu, and S. Zhang, "The advancement of 7XXX series aluminum alloys for aircraft structures: A review," Metals, vol. 11, no. 5, Art. no. 718, 2021, https://doi.org/10.3390/met11050718

[4] E. A. Hajjioui, K. Bouchaala, M. Faqir, and E. Essadiqi, "A review of manufacturing processes, mechanical properties and precipitations for aluminum lithium alloys used in aeronautic

applications," Heliyon, vol. 9, Art. no. e12565, 2023, https://doi.org/10.1016/j.heliyon.2022.e12565

[5] G. Xiao, R. An, J. Yang, and J. Ma, "Research progress of new generation of aluminum-lithium alloys alloying," Advanced Engineering Materials, vol. 26, no. 12, Art. no. 2301639, 2024, https://doi.org/10.1002/adem.202301639

[6] P. A. Rometsch, Y. Zhu, X. Wu, and A. Huang, "Review of high-strength aluminium alloys for additive manufacturing by laser powder bed fusion," Materials & Design, vol. 219, Art. no. 110779, 2022, https://doi.org/10.1016/j.matdes.2022.110779

[7] H. R. Kotadia, G. Gibbons, A. Das, and P. D. Howes, "A review of laser powder bed fusion additive manufacturing of aluminium alloys: Microstructure and properties," Additive Manufacturing, vol. 46, Art. no. 102155, 2021, https://doi.org/10.1016/j.addma.2021.102155

[8] S. Dixit and S. Liu, "Laser additive manufacturing of high-strength aluminum alloys: Challenges and strategies," Journal of Manufacturing and Materials Processing, vol. 6, no. 6, Art. no. 156, 2022, https://doi.org/10.3390/jmmp6060156

[9] M. S. Kenevisi, Y. Yu, and F. Lin, "A review on additive manufacturing of Al-Cu (2xxx) aluminium alloys, processes and defects," Materials Science and Technology, vol. 37, no. 9, pp. 805-829, 2021, https://doi.org/10.1080/02670836.2021.1958487

[10] H. Zhu and J. Li, "Advancements in corrosion protection for aerospace aluminum alloys through surface treatment," International Journal of Electrochemical Science, vol. 19, Art. no. 100487, 2024, https://doi.org/10.1016/j.ijoes.2024.100487

[11] Y. Chen, Z. He, H. Li, D. Lu, Y. Song, L. Zhan, S. Pan, and W. Liu, "Corrosion fatigue mechanisms and control technologies in aviation aluminum alloys: A critical review," Chinese Journal of Aeronautics, Art. no. 103496, 2025, https://doi.org/10.1016/j.cja.2025.103496

[12] Y. Peng, Y. Zhang, L. Zhang, L. Yao, and X. Guo, "Prediction of corrosion fatigue crack growth rate in aluminum alloys based on incremental learning strategy," International Journal of Fatigue, vol. 187, Art. no. 108481, 2024, https://doi.org/10.1016/j.ijfatigue.2024.108481

[13] H. Xue, J. Li, Z. Wang, J. Bai, Z. Zhao, and G. Qin, "Improving heat resistance of Al-Cu-Li alloy with the addition of Sc and Si," Science China Materials, vol. 66, pp. 4285-4294, 2023, https://doi.org/10.1007/s40843-023-2664-7

[14] S. Shao, Z. Liang, P. Yin, X. Li, and Y. Zhang, "Microstructure and mechanical properties of Al-Li alloys with different Li contents prepared by selective laser melting," Materials, vol. 17, no. 3, Art. no. 657, 2024, https://doi.org/10.3390/ma17030657

[15] L. Chen, T. Jiang, J. Li, Y. Guo, G. Dai, Z. Sun, L. Zhan, and C. Liu, "Microstructure and mechanical properties of 2195 Al-Li alloy via friction stir additive manufacturing with different stirring paths," Journal of Alloys and Compounds, vol. 1008, Art. no. 176666, 2024, https://doi.org/10.1016/j.jallcom.2024.176666

[16] M. Dada and P. Popoola, "Recent advances in joining technologies of aluminum alloys: A review," Discover Materials, vol. 4, Art. no. 86, 2024, https://doi.org/10.1007/s43939-024-00155-w

[17] J. Dasari and M. A. Xavior, "Review of additive manufacturing and post processing techniques for aluminium alloys with focus on microstructure changes mechanical performance and emerging trends," Discover Mechanical Engineering, vol. 5, Art. no. 48, 2026, https://doi.org/10.1007/s44245-026-00189-9

[18] D.-Y. Liu, N. Liu, C. Gao, W. Zhou, X.-S. Chen, X. Liu, K.-F. Gan, J.-M. Li, C. Cai, J.-F. Li, and Y.-L. Jia, "A review of recent research on the corrosion behaviours and mechanism of Al-Cu-Li alloys," Review of Materials Research, vol. 2, no. 1, Art. no. 100134, 2026, https://doi.org/10.1016/j.revmat.2026.100134

[19] W. Zhao, G. Liu, S. Zhang, Y. Ren, K. Yuan, B. Yu, B. Wang, H. Xing, G. Lv, X. Chen, and W. Ma, "A review of rare earth elements microalloying in aluminum alloys: Mechanisms of microstructure evolution and performance enhancement," Journal of Materials Research and Technology, vol. 41, pp. 2839-2869, 2026, https://doi.org/10.1016/j.jmrt.2026.01.162

[20] Y. Wang, X. Xia, R. Li, T. Wang, and T. Yuan, "A review of additive manufacturing heat-resistant aluminum alloys: Materials, properties and strengthening strategies at high temperature," International Materials Reviews, vol. 70, no. 8, pp. 648-709, 2025, https://doi.org/10.1177/09506608251369181

[21] S. D. Oguntuyi, M. G. R. Mahlobo, K. Nyembwe, P. M. Mashinini, and P. A. Olubambi, "Minimizing thermal and microstructural variations in hybrid additively manufactured aluminum alloys: A review," Advanced Engineering Materials, early view, 2026, https://doi.org/10.1002/adem.202502805

[22] A. Kumar, L. Shi, V. P. Singh, S. Mohapatra, L. Li, C. Wu, S. Mironov, and A. De, "State-of-the-art review of additive friction stir deposition: Microstructural evolution, machine learning applications, and future directions," Current Opinion in Solid State and Materials Science, vol. 40, Art. no. 101243, 2026, https://doi.org/10.1016/j.cossms.2025.101243

[23] E. E. Lindsay, A. Botes, D. Bernard, et al., "Comprehensive strategies for defect mitigation and process optimisation in laser beam welding of aluminium alloys: A systematic review," International Journal of Advanced Manufacturing Technology, vol. 143, pp. 3479-3513, 2026, https://doi.org/10.1007/s00170-026-17596-7

[24] Y. Zhang, B. Gong, Z. Ba, L. Zhang, L. Zong, L. Jiang, Y. Zhu, W. Yang, Z. Jia, and W. Sun, "Simultaneous enhancement of mechanical and fatigue properties in 2xxx aluminum alloys via microstructural uniformity induced by cyclic plasticity," Science China Materials, 2026, https://doi.org/10.1007/s40843-025-3781-8

[25] F. Lambiase, P. B. Yanala, F. Pace, E. Andreucci, et al., "A state of the art review of wire arc additive manufacturing (WAAM) - part 2: Process improvements and industrial applications," International Journal of Advanced Manufacturing Technology, vol. 143, pp. 4623-4654, 2026, https://doi.org/10.1007/s00170-026-17691-9

[26] S. Du, S. Zhang, J. Wang, M. Wang, Z. Lv, Z. Xu, L. Ma, C. Liu, J. Wang, J. Liu, and B. Liu, "Sustainable recycling of aluminum scraps to recycled aerospace-grade 7075 aluminum alloy sheets," Sustainable Materials and Technologies, vol. 41, Art. no. e01100, 2024, https://doi.org/10.1016/j.susmat.2024.e01100

[27] S. Du, S. Zhang, J. Wang, et al., "Energy flow of aerospace aluminum scraps cycle and advanced integration principles for upcycling technologies: A review," Journal of Cleaner Production, vol. 448, Art. no. 141176, 2024, https://doi.org/10.1016/j.jclepro.2024.141176

[28] X. Ge, J. Yu, Y. Sun, Z. Yang, J. Liu, and G. Zhao, "Direct recycling of Al-Li alloy machining chips into sheets with excellent mechanical properties via a double-sided friction stir consolidation process," Journal of Materials Processing Technology, vol. 350, Art. no. 119263, 2026, https://doi.org/10.1016/j.jmatprotec.2026.119263

[29] M. Umar, et al., "A state-of-the-art review on decarbonizing aerospace manufacturing with life cycle sustainability assessment," Renewable and Sustainable Energy Reviews, vol. 234, Art. no. 116857, 2026, https://doi.org/10.1016/j.rser.2026.116857