Mustansiriyah Journal of Materials Engineering and Sustainability
Vol. 02, No. 02, 2026, Pages 42-63
https://mjmes.uomustansiriyah.edu.iq/
Review Article

DOI: https://doi.org/10.31272/mjmes.v2i2.26
ISSN: 3079-9899 (Print)
ISSN: 3079-9902 (Online)

A Comprehensive Extended Review of Advanced Metallic Alloys for Aerospace Structures: Processing, Properties, Recent Advances, and Future Perspectives

Waleed Kadhim Al-Azzawi[1*], Ola Abdullah Abed[1]

[1] College of Electromechanical Engineering, University of Technology-Iraq, Alsinaa Street 52, Baghdad 1006, Iraq.
[*]Email: waleed.k.salman@uotechnology.edu.iq

Article Info
Received 14/06/2026
Revised 26/06/2026
Accepted 27/06/2026
Published 1/07/2026

Abstract (10 PT)

The development of advanced metallic alloys for aerospace applications is continuously progressing to meet new requirements for lightweight construction, energy efficiency, high-temperature operation, durability, and sustainability. The state-of-the-art regarding the most common metallic alloy families currently used in aerospace engineering is presented in this review. These alloys include traditional aluminum alloys, aluminum-lithium alloys, titanium alloys, nickel-based superalloys, and advanced high-entropy alloys (HEAs). The compositions, microstructures, processing methods, potential of additively manufactured parts, mechanical properties, and sustainability characteristics of these alloys were critically evaluated. Third-generation Al-Li alloys provide approximately 2-4% decrease in density and up to 10% increase in stiffness compared to conventional 2xxx and 7xxx aluminum alloys, which makes their use very effective in reducing the weight of structural elements. Titanium alloys still cannot be replaced in aerospace structural applications at medium temperatures, whereas nickel-based superalloys are widely used in turbines operating at temperatures higher than 1100-1200°C. High-entropy alloys demonstrate an outstanding combination of strength, ductility, resistance to corrosion, and high-temperature stability, with several lightweight alloys demonstrating compressive yield strengths higher than 1300 MPa at temperatures close to 1000°C. Additive manufacturing techniques have considerably promoted the adoption of topology-optimized aerospace parts; however, fatigue behavior, qualification, and certification remain problematic issues. Moreover, sustainability concerns, including embodied carbon, recyclability, and lifetime impacts, play a more important role in selecting the optimal alloy. Finally, the gaps in the research regarding long-term fatigue behavior, qualification approaches, manufacturing scalability, and machine learning-based alloy design are discussed and prioritized.

Keywords: Aerospace Alloys; Aluminum Alloys; Titanium Alloys; Nickel-Based Superalloys; High-Entropy Alloys; Additive Manufacturing; Machine Learning

1. Introduction

The aerospace industry presents one of the most challenging fields for structural materials in terms of mechanical load bearing capacity, cryogenic up to extreme (>1200°C) service temperature ranges, corrosion resistance to atmospheric humidity and hydraulic oil, fatigue strength for millions of cycles, and the absolute minimum weight required. There is no single group of materials that can meet every demand; rather, the modern plane presents a complex assembly of specialized alloys chosen for each application point based on their unique combination of properties. In the last hundred years, the field of aerospace alloys has experienced three major transitions. First, the need for jet engines led to the development of Ni-based superalloys for use at temperatures lethal for earlier structural materials, in the 1950s-1960s. Second, since the 1980s, titanium alloys have become the materials of choice for temperature-resilient lightweight structural and propulsion components in favor of steel-based landing gears and structural fittings. Currently, there are two ongoing revolutions happening simultaneously: the development of additive manufacturing techniques in conjunction with all major alloy classes and the development of high-entropy alloys as a completely new class of materials.

This study sets itself apart from prior reviews by introducing four features. First, all alloy properties will be presented in tabular format, providing a quick overview in eight convenient

© 2026 The Author(s). Open access article.
(http://creativecommons.org/licenses/by-nc-nd/4.0/).

reference tables. In addition, peer-reviewed publications covering topics of the latest studies on aerospace materials will be utilized, including those on Al-Ce alloys for L-PBF, fatigue optimization of Ti-6Al-4V via heat treatments, lightweight HEAs, and machine learning methods for alloy optimization. Furthermore, the explicit identification of 10 priority research gaps in the field of aerospace alloys, along with the recommended ways of approaching them, is given here. Finally, environmental sustainability aspects are included in the review to consider mandatory carbon emission reduction targets.

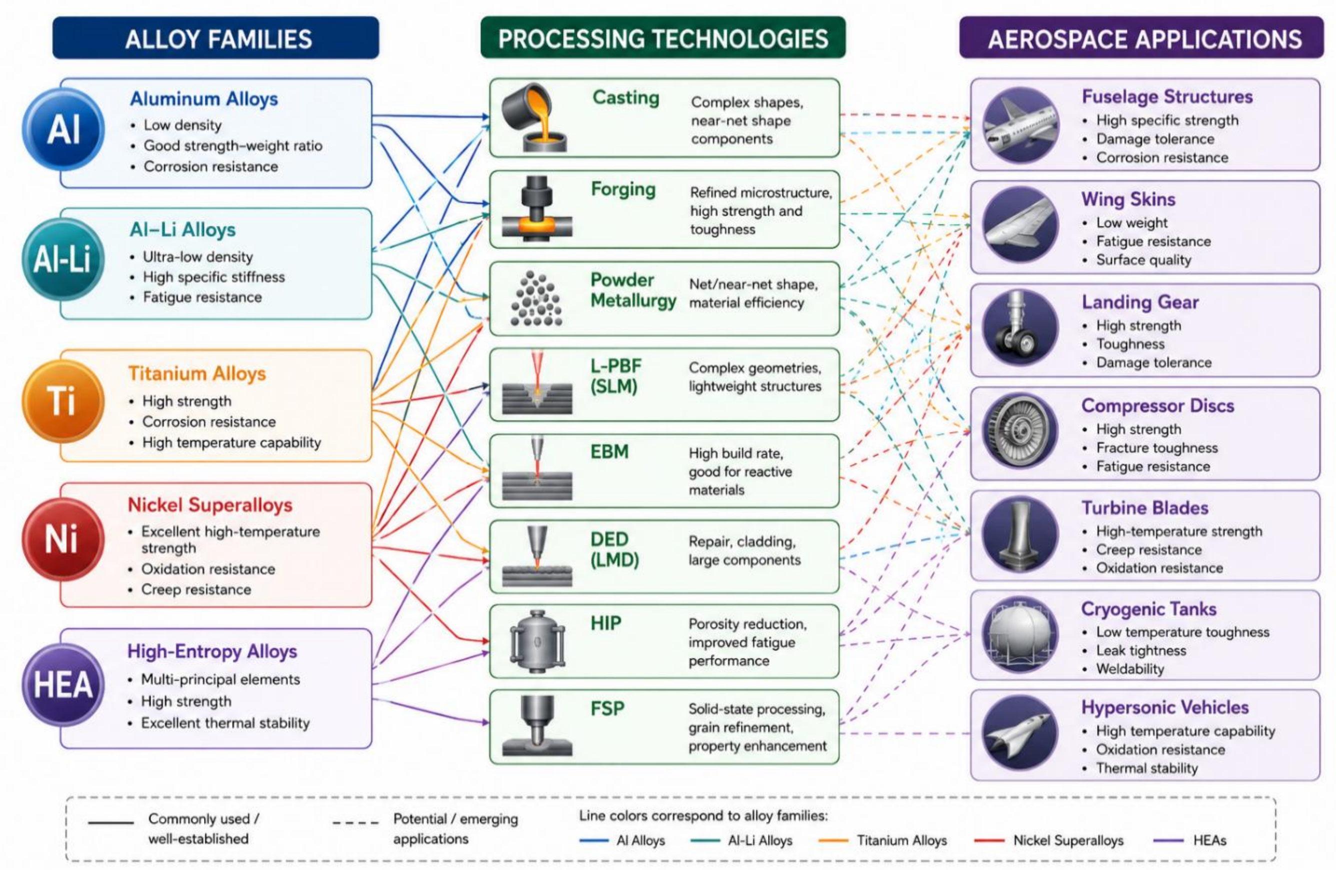

Figure 1. Schematic illustrating the connections between different families of aerospace alloys, advanced processing techniques, and aerospace applications.

1.1 Scope and Objectives

This review focuses on aluminum alloys (2xxx, 6xxx, 7xxx, and aluminum lithium), titanium alloys (alpha, alpha-beta, near-beta, and beta alloys), nickel superalloys (wrought, cast, directionally solidified, and single crystal), and high-entropy alloys (3d transition metal, refractory, and lightweight alloys). This review analyzes compositional trends, processing-structure-performance correlations, the upper bounds for performance, and future perspectives for each group. The processing technologies considered included additive manufacturing, powder metallurgy, friction stir processing, extrusion, and computer-aided design.

1.2 Historical Development of Aerospace Alloys

Aerospace alloys share the same history as aviation. The development of duralumin (Al-3.5Cu-0.5Mg-0.5Mn) in 1909 by Alfred Wilm and the age-hardening process by precipitation of $CuAl_2$ (θ‘) and Al_2CuMg (S') provided designers with an unprecedented structural material of low density and considerable strength. Further improvement of alloy compositions by adding more elements and development of thermo-mechanical processes led to the development of 2xxx series and 7xxx series alloys, which have become the major materials for airframes. The tensile strength of aluminum alloys used in aerospace applications was doubled compared to Duralumin, from approximately 350 MPa to over 700 MPa, whereas the density remained almost the same.

The emergence of jet propulsion technology in 1940 immediately revealed the temperature restrictions of aluminum alloys. The need to create materials that can operate at high temperatures has led to the creation of nickel-based superalloys. These alloys became an evolution product of corrosion-resistant Ni-Cr alloys, which had been used earlier to create turbojet engines. Notably, the development of these alloys was the most impressive engineering work of the previous century. Increasing the gamma-prime phase content, alloying with refractory solid-solution strengthening elements such as rhenium, implementing directional solidification and single crystal casting techniques, and using ceramic thermal barrier coatings made it possible to increase the gas path entry temperature of jet engines from approximately 700°C in 1950 to over 1700°C. As a result, fuel efficiency has improved by 40% over the last 70 years.

In the 1950s, the list of aerospace materials included titanium alloys. The first titanium alloy qualified for application in aircraft in 1954 was Ti-6Al-4V (Ti64). This alloy constitutes approximately 50% of the titanium used in the aerospace industry and represents the best material for general-purpose titanium applications. The development of special beta and near-beta alloys that demonstrate a great potential to be hardened in heavy sections has allowed titanium to be implemented in aircraft landing gears and large forgings. Finally, high-entropy have become the newest members of the aerospace materials family; their definition was proposed in 2004 by Yeh et al. and Cantor et al., and now the number of publications on high-entropy alloys exceeds 10,000 articles as of 2025.

Various review papers have dealt with individual types of alloys, such as conventional aluminum alloys, titanium alloys, superalloys based on nickel, or high-entropy alloys. Nevertheless, many of the previously conducted investigations have been concerned with only one type of alloy, a particular manufacturing process, or performance-related features. The current review is distinguished from previously published ones because it combines conventional aerospace alloys, generation III aluminum-lithium alloys, high-entropy alloys, additive manufacturing techniques, sustainability factors, and computational alloy design tools into one comparative analysis. Along with the presentation of recent literature up until early 2026, this review includes comparative analyses of different families of alloys, life cycle assessment, additive manufacturing evaluation, and recommendations for further research.

2. Literature Selection Methodology

This review involved the implementation of a structured literature survey to improve transparency, reproducibility, and comprehensiveness.

A range of relevant publications were searched using major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar.

Combinations of the following key terms and phrases were used as search strategies.

"Aerospace alloys," "aluminum alloys," "aluminum-lithium alloys," "titanium alloys," "nickel-based superalloys," "high-entropy alloys," "additive manufacturing," "CALPHAD," "machine learning," "life cycle assessment," and "sustainability."

Articles were considered only if they were published from 2000 to the beginning of 2026, and preference was given to publications dating from 2020 to 2026.

The primary search returned approximately 530 publications; after excluding duplicates and conducting title and abstract screening, only 186 publications were left for full-text analysis.

Based on the following inclusion criteria, more than 120 peer-reviewed articles were selected for further detailed analysis:

- • Relevance to aerospace metallic alloys;
- Availability of quantitative mechanical property data
- Processing or application of materials in industry discussion
- Peer-reviewed journal publications.

3. Advances in Aluminum Alloys for Aerospace Applications

Among all metallic alloys, aluminum alloys constitute the largest share in terms of volume percentage, with an estimated 70 to 80 percent of structural weight being constituted by such alloys in the case of old-generation wide-body aircraft, and 50 to 65 percent in more recent aircraft designs where certain amounts of aluminum have been substituted with carbon fiber reinforced composite materials and titanium. The unique features of aluminum alloys, including low density, relatively high strength, good formability, well-developed material supplies, and reliable qualification data, make these alloys suitable for use in both primary and secondary fuselage constructions.

Table 1. Mechanical Properties of Key Aerospace Aluminum Alloys

Alloy / Series	Density (g/cm³)	UTS (MPa)	Yield Str. (MPa)	Elongation (%)	Max. Temp. (°C)	Corr. Resist.	Primary Aerospace Use	Fatigue Strength (MPa)	Fracture Toughness (MPa√m)
2024-T3	2.78	483	345	18	150	Moderate	Fuselage skins, wing lower panels	138	34
2024-T351	2.78	470	325	20	150	Moderate	Structural frames, bulkheads	138	34
7075-T6	2.81	572	503	11	120	Good (clad)	Wing upper panels, spars	150	29
7150-T77	2.83	614	538	11	120	Very Good	Wing covers, stringers	150	32
7475-T761	2.81	524	441	12	125	Excellent	Fuselage skins, formers	140	42
2050-T84	2.70	520	460	10	175	Good	Lower wing, fuselage frames	150	36
2099-T83	2.63	448	414	6	150	Good	Extrusions, stringers	160	30
2198-T8	2.69	480	430	8	175	Good	Fuselage skins, floor panels	150	35
6061-T6	2.70	310	276	12	150	Excellent	Secondary structure, fittings	100	30
Al-Li 2195	2.71	558	524	8	177	Good	Cryogenic tanks, LOX/LH2 vessels	165	33

3.1 High-Strength 7xxx and 2xxx Series Alloys

The 7xxx series, which consists of Al-Zn-Mg-Cu alloys, exhibits the highest mechanical strength among commercial aluminum alloys. The main precipitate responsible for strengthening is $MgZn_2$ (η′), which is formed upon aging, contributing to the development of the yield strength. The most important variables related to their design include the Zn/Mg ratio (which dictates the volume fraction and hence strength of the precipitate), Cu content (which increases corrosion resistance due to decreased grain boundary precipitation), and heat treatment (which determines the size and spacing of the precipitates). Overaging produces T73 and T76 tempers, which compromise up to 10-15% of the peak strength achieved in the T6 state, yet significantly increase stress-corrosion resistance – a necessary property in wing skins, where there are tensile loads acting throughout the service lifetime. The T77 temper, resulting from retrogression and re-aging, achieves near T6 strength while improving the corrosion resistance to that of T73, which represents a breakthrough documented by Zhou et al. (2021).

Damage tolerance, specifically fracture toughness and fatigue crack growth resistance, is considerably better in the 2xxx series (consisting of Al-Cu-Mg alloys) than in the 7xxx series for the same strength level, accounting for the use of 2xxx alloys for applications where damage tolerance is an important aspect of design. The 2024-T3 alloy has been a staple of lower wing skins for over 70 years; its replacement 2524-T3 alloy, which features an improved microstructure and reduced impurities, maintains the same high strength while increasing the fracture toughness and fatigue performance. More recently, the Al-Cu-Li alloy 2198-T8 was successfully qualified for fuselage skins on Airbus A350. This alloy reduces weight by 2-3% compared to 2024-T3 without compromising fatigue resistance.

3.2 Aluminum-Lithium Alloys

Third generation Al-Li alloys comprise the best-performing aluminum alloy compositions, which feature a reduced density (2.63 to 2.71 g/cm³ versus 2.77 to 2.83 g/cm³ for conventional alloys), coupled with enhanced elastic modulus (+5 to +10% relative to conventional Al alloys). A reduction in alloy density of 3%, together with a 6% increase in elastic modulus, was achieved for each weight percent decrease in lithium. These third-generation Al-Li alloy systems feature excellent specific stiffness owing to their unique composition. In addition, third-generation compositions with restricted Li of 1.0 to 1.9 wt.% to prevent negative impacts of texture and poor short transverse toughness of previous Al-Li alloys have been able to attain toughness and corrosion resistance similar to conventional alloys of 2xxx and 7xxx series. Examples of such alloys include 2050, 2099, 2195, 2196, and 2198 alloys.

3.3 Additive Manufacturing of Aluminum Alloys

In particular, the AM of aluminum alloys has its own problems, which are based on high reflectivity, high thermal conductivity, and a tendency to hot tears in high-strength alloy compositions. Aluminum alloys were designed specifically for AM technologies, particularly Al-Si eutectic and hypoeutectic compositions (AlSi10Mg, AlSi7Mg, Al-Si12). These alloys are highly suitable for AM technologies because they have high-quality solidification properties. However, their mechanical properties are rather limited: tensile strength does not exceed 200-350 MPa. The printing of stronger 2xxx and 7xxx series aluminum alloys, whose tensile strength is 400-700+ MPa, poses additional difficulties associated with their wide solidification range and tendency to hot tear. In this context, some possible strategies include inoculation with titanium boride, titanium hydride, or zirconium nanoparticles for grain refinement; alloy design with eutectics that would narrow the solidification range; or heat treatment after printing.

One of the newest aluminum alloys designed for the L-PBF process is the family of Al-Ce alloys reviewed in Liu et al., 2024. The low solubility of Ce in the solid-state results in the formation of thermally stable intermetallic $Al_{11}Ce_3$ particles with a strong resistance to coarsening even at 300°C. Consequently, the L-PBF of these alloys results in the formation of finely crystallized alloys characterized by outstanding thermal stability and enhanced mechanical properties compared to regular Al-Si alloys in higher temperature regimes, thus opening up new possibilities for their aerospace structural applications. It should also be noted that according to Yao and Xie, 2024, the addition of LaB6 nanoparticles successfully refines grain structure of L-PBF 2024 aluminum alloy and enhances its tensile strength.

4. Titanium Alloys: Innovations and Improvements

Titanium alloys come in second place in weight among metallic alloy systems employed in aerospace, making up about 7-15% of the structural weight in current passenger airplanes and 25-35% in more sophisticated military planes, in which saving on weight outweighs the increased cost of such materials. The unique combination of lightweightness (density 4.43-4.65 g/cm^{3}or 57% of the density of steel), strength (600-1400 MPa), resistance to corrosion, and high-temperature capacity (–550-600°C in the case of near-alpha alloys) places titanium alloys between aluminum and nickel-based alloys in the system of aerospace materials. The properties of the most commonly used titanium alloys are shown in Table 2.

Table 2. Mechanical Properties and Applications of Key Aerospace Titanium Alloys

Alloy	Class	Density (g/cm³)	UTS (MPa)	Yield (MPa)	Elong. (%)	Max. Temp. (°C)	Fatigue Limit (MPa)	Aerospace Use
Ti-6Al-4V	α+β	4.43	950	880	14	315	620	Blades, discs, airframe
Ti-6Al-2Sn-4Zr-2Mo	Near-α	4.54	1000	940	10	450	650	Compressor discs
Ti-5Al-5V-5Mo-3Cr	Near-β	4.65	1200	1100	8	450	700	Landing gear, frames
Ti-10V-2Fe-3Al	β	4.65	1170	1100	10	300	650	Structural forgings
Ti-3Al-2.5V	α+β	4.48	620	520	15	250	420	Hydraulic tubing
Ti-6Al-2Nb-1Ta	Near-α	4.51	900	800	12	400	600	Engine casings
Ti-15V-3Cr-3Sn-3Al	Metastable-β	4.77	1210	1175	8	300	680	Springs, fasteners
IMI 834	Near-α	4.55	1030	910	7	550	600	Compressor blades
Ti-1100	Near-α	4.50	950	880	8	600	590	High-temp. compressor

Third-generation Al–Li alloys can offer a density reduction of approximately 2–4% along with a stiffness enhancement of up to 10% as compared to the traditional 2xxx and 7xxx series alloys.

However, their wide utilization is still restricted owing to the higher cost of Li alloying, lower fracture toughness for some tempers, and higher defect sensitivity. On the other hand, traditional 2xxx and 7xxx series alloys enjoy a database of qualified experience and lower costs.

Table 3. Additional Comparison between Al–Li and Conventional 2xxx and 7xxx Alloys

Property	Al-Li	2xxx	7xxx
Density (g/cm3)	2.55–2.65	2.75–2.80	2.78–2.85
Elastic Modulus (GPa)	75–80	72–74	71–73
Fatigue Resistance	High	Moderate–High	High
Fracture Toughness	Moderate	High	Moderate
Corrosion Resistance	Very Good	Moderate	Moderate
Relative Cost	2–4×	1×	1.2×
Machinability	Moderate	Excellent	Good
AM Compatibility	Moderate	Limited	Limited

4.1 Ti-6Al-4V: Processing and Fatigue Optimization

Ti-6Al-4V, also known as Ti64, is the most widely investigated and technologically developed titanium alloy that constitutes approximately 50% of the total titanium usage in the aerospace industry. This dual-phase alpha-beta alloy with the HCP phase being alpha-stabilized by aluminum and the BCC phase being beta-stabilized by vanadium allows for tailoring its microstructure by means of thermomechanical processing to achieve desired combinations of strength, ductility, and fracture toughness. Equiaxed microstructures (obtained from processing below the beta transus temperature) provide the best high-cycle fatigue properties because they prevent the initiation of short cracks. The lamellar Widmanstätten microstructure (obtained when processed above the beta transus temperature) provides optimal fracture toughness and resistance to fatigue crack propagation. Finally, a bimodal microstructure consisting of primary equiaxed alpha in a transformed beta matrix provides a good compromise between both mentioned parameters and is most frequently used in structural applications.

Additive manufacturing of Ti64 alloys has been thoroughly studied in recent years. As-built Ti64 parts produced using the L-PBF method have a columnar microstructure of prior beta grains with a fine acicular martensitic (α') structure that provides high strength but low ductility. A post-build heat treatment process is necessary to decompose the residual martensite, achieve the alpha-beta equilibrium composition, and restore the ductility properties. Heat treatment performed above the beta transus, followed by controlled cooling and aging, was proven by Beal et al. (2024) to result in fatigue properties comparable to those of wrought Ti64. Moreover, Laskowska et al. (2025) demonstrated that heat treatment in the range 850–1000°C for 1h allowed achieving an optimal balance between α' martensite decomposition into equilibrium alpha-beta phases and the maintenance of sufficiently strong properties in both Ti-6Al-4V and Ti-6Al-7Nb alloys obtained using the L-PBF method.

4.2 High-Strength Beta and Near-Beta Alloys

Beta and near-beta titanium alloys, such as Ti-5Al-5V-5Mo-3Cr (Ti5553), Ti-10V-2Fe-3Al (Ti-10-2-3), and Ti-15V-3Cr-3Sn-3Al, have a tensile strength of 1100–1300 MPa in the aged state, which is considerably greater than that of Ti64, although at the price of inferior high-cycle fatigue properties and increased dependence on surface and notching effects. The increased hardenability characteristic of these alloys compared to their alpha-beta counterparts makes them suitable for consistently forging sections up to 200 mm thick, which makes them vital for applications such as landing gear beam forgings, wing attachments, and actuators. The development of Ti5553 to replace Ti-10-2-3 for the Boeing 787 landing gear parts exemplifies this trend.

4.3 High-Temperature Titanium and TiAl Intermetallic

The limitation of oxygen uptake and creep limits the capability of traditional titanium alloys to operate above 550-600°C. Near-alpha alloys such as IMI 834, Ti-6Al-2Sn-4Zr-2Mo (Ti6242S), and Ti-1100 extend this limitation to the highest possible level with respect to conventional titanium alloys and are used in compressor discs and blades for operation at high pressures. In the case of operation at higher temperatures, L10 TiAl-based alloys (gamma TiAl) provide density values in the range of 3.9–4.2 g/cm³ and strengths of 800–850°C, making TiAl intermetallic alloys lighter than their nickel superalloy equivalents when used in LPT blades in engines such as those on the GEnx (Boeing 787) and LEAP engines (Airbus A320neo / Boeing 737 MAX). Being quite brittle, TiAl alloys require careful alloying for increased ductility (addition of Nb, Mo, and Cr) and special processing technology (investment casting and HIP).

4.4 Titanium-Based High-Entropy Alloys

HEAs based on titanium containing elements such as Zr, Nb, Mo, Ta, Al, and Hf along with titanium itself belong to the recent innovations considered in detail by Ma et al. (2020). Such complex HEAs utilize the best properties of both biocompatibility and corrosion resistance from titanium alloys, as well as the microstructure stability and strength at elevated temperatures offered by the HEA concept. For example, Ti-Zr-Nb-Mo-V and TiAlVNbMo BCC-structured HEAs demonstrate yield compressive strengths of 1200-1500 MPa without sacrificing substantial ductility (compressive strain of 8%-15%), whose performance is much better than that achieved for binary or ternary beta-titanium alloys of similar compositions. L-PBF processing of titanium HEAs is a recent topic, and some of its issues include controlling the composition of the feedstock, sensitivity to oxidation during processing, and optimizing heat treatment after build-up.

5. Nickel-Based Superalloys: Performance and Development

Nickel-based superalloys are the best structural metal materials commercially available, making it possible for gas turbines to operate at temperatures that enable the efficiency of today's aviation industry. This is due to the ability of these materials to withstand stresses of several hundred megapascals when operating at temperatures well above 1000°C, which accounts for about 90% of their melting temperature – and there are no other materials that can achieve such results as nickel-based superalloys do. This is made possible through seven decades of alloy engineering that involves increasing the gamma prime phase fraction, solid solution strengthening by refractory additions, single crystal growth, and thermal barrier coatings.

Table 4. Key Properties of Aerospace Nickel-Based Superalloys by Generation

Alloy	Generation	Density (g/cm³)	UTS at 20°C (MPa)	Creep Rupture Str. (MPa) *	γ' Vol. Frac. (%)	Re Content (wt%)	Max. Temp. (°C)	Primary Application
IN 718	Wrought	8.19	1375	—	15–20	0	650	Discs, shafts, casings
IN 738LC	1st Gen. CC	8.17	1100	125 (980°C/150h)	40	0	980	Industrial turbine blades
Mar-M247	1st Gen. DS	8.57	1100	140 (1050°C/137 MPa)	60	0	1020	HP blades, vanes
PWA 1480	1st Gen. SX	8.70	1200	155 (1050°C/100h)	70	0	1050	HP turbine blades
CMSX-4	2nd Gen. SX	8.75	1240	180 (1050°C/137 MPa)	70	3	1100	HP blades, adv. engines
René N6	3rd Gen. SX	8.85	1300	195 (1100°C/137 MPa)	68	5.75	1150	HPT blades, LEAP-X
TMS-238	6th Gen. SX	8.80	1400	200 (1100°C/137 MPa)	62	4.6	1200	Research, next-gen engines
HAYNES 282	Wrought	8.25	1090	—	20–25	0	900	Casings, rings, seals
CM 247 LC	Directional	8.56	1050	160 (1050°C/100h)	62	0	1050	Blades, vanes

* Creep rupture values under stated conditions; direct comparison requires identical T/stress/time parameters. The density and UTS of SX alloys vary with heat treatment and crystal orientation; values represent typical [001] orientation room-temperature tensile data.

5.1 Gamma-Prime Strengthening and Alloy Generations

The mechanical properties of nickel superalloys under hot conditions depend critically on the presence of coherent, ordered precipitates with an L12 structure, having a chemical formula of $Ni_3(Al, Ti, Ta)$. These gamma-prime (γ') precipitates are stronger than the γ matrix up to approximately 800°C. This unusual flow stress behavior of gamma-prime precipitates stems from the thermally activated cross-slip of dislocations from the {111} slip planes to the {100} cube planes locking their movements. However, at higher temperatures, this unusual property vanishes, and creep resistance depends on diffusion. To minimize the rate of creep, refractory solutes with a large atomic radius and relatively low diffusivity (W, Mo, Re, and Ru) are used as strengthening components. Introduction of rhenium into single crystal blade alloys has caused drastic changes in their properties in steps of approximately 30°C for each generation, going from 0% (first generation) to 3% (second generation), to 5-6% (third generation), but resulting in increased density and expense. Recently introduced sixth-generation experimental alloys (such as TMS-238 developed by NIMS, Japan), containing both rhenium and ruthenium, exhibit creep properties some 60°C better than those of second-generation alloys.

The wrought superalloy IN 718, although it offers relatively modest gamma-prime (γ') hardening effects and cannot be used at temperatures as high as those of single-crystal blade alloys, occupies the most firmly established position among high-temperature alloys used in aviation owing to its superior properties, as well as weldability and machineability, and to a rich qualification base accumulated many years ago. It combines extremely good combinations of strength, ductility, and creep resistance. Owing to its ease of processing, IN 718 is extensively used in applications such as turbine discs and shafts, casings, and rings for both military and commercial engines. Its history of application in GE engines has been exhaustively documented by Schafrik et al. (2001).

5.2 Thermal Barrier Coating Systems

The most highly developed nickel superalloys are not capable of withstanding such temperatures without any coating on their surface at the stage of first-stage turbine blade operation. Thermal barrier coatings (TBC), which consist of a metallic bond coating, alpha-Al_2O_3 thermally grown oxide layer, and YSZ top coating, allow working at metal temperatures 100–150°C below the combustion gas temperature. TBC provide thermal protection as well as oxidation resistance. YSZ is currently the leading material for TBC up to 1150°C, since higher temperatures lead to phase transition (tetragonal to monoclinic + cubic) in YSZ, causing its spalling. Nowadays, extensive research on developing new TBC materials is ongoing since the desire to increase the combustion temperatures still exists.

High-entropy ceramics (HECs), which are oxides with multi-principal-element cation sublattices, have become promising candidates for future TBCs. Yu and Mu (2021) provided an extensive review of the topic. In particular, several HEA-based and rare-earth zirconate TBCs were discussed, which provided lower thermal conductivity, greater stability at temperatures above 1200°C, and better cycle resistance than conventional YSZ. Due to the multi-cation structure of high-entropy oxides, there arise more scattering sites, which decrease the thermal conductivity to less values than in YSZ. Arshad et al. (2022) expanded the discussion on oxidation protection by high-entropy coatings, showing that HEA compositions are more resistant to cyclic oxidation and provide better mechanical properties than MCrAlY bond coats.

5.3 Additive Manufacturing of Nickel Superalloys

The challenges and commercial benefits associated with AM of nickel superalloys include not only difficult aspects such as hot cracking when solidifying in high-gamma-prime composition materials, heterogeneous structure due to sequential thermal effects on each deposited layer, and sensitivity to oxidation during the fabrication process, but also the economic feasibility of rebuilding worn turbine blades and vanes through deposition of only a few grams of material with directed energy in an exact manner. Such an opportunity would provide economic advantages over the purchase of a new component, whose cost is in the range of thousands of dollars. It has already been proven by various engine manufacturers, such as GE Aviation, Rolls-Royce, and Pratt & Whitney, that AM can be used to manufacture repaired turbine components. With respect to newly manufactured turbine components, AM allows for the production of channels with impossible wall thicknesses, aspect ratios, and distribution of holes for film cooling in conventionally cast components.

5.4 Future Directions: Cobalt-Based and HEA-Inspired Superalloys

The search for materials other than nickel as a matrix material in superalloys has recently been spurred by the realization, made in 2006, that the intermetallic of Co-Al-W also forms the same L12 ordered gamma-prime strengthening phase as found in nickel superalloys. The potential advantages of cobalt-based superalloys with a gamma-prime strengthening phase include their ability to have a higher melting temperature and higher oxidation resistance than nickel superalloys, albeit at the expense of increased density and lower creep resistance. Another class of superalloys being explored, inspired by HEAs, is based on alloys with a gamma-gamma-prime structure containing five or more transition metals. These types of alloys allow access to a large chemical space that cannot be accessed with Ni-X superalloys, and the use of CALPHAD and machine learning for predictive designs in nickel superalloys other than HAYNES 282 has been shown in several papers.

6. Emerging High-Entropy Alloys in Aerospace

Despite the excellent performance of HEAs in terms of strength, ductility, and environmental durability, industrial applications of HEAs in the aerospace industry are not yet widely used. Numerous issues must be solved before the industrial use of HEAs becomes feasible: lack of experience in the long-term application of HEAs, insufficient information on the fatigue and creep behavior of HEAs, challenges connected with the scale-up of processing methods in laboratories, and the lack of qualification protocols. In addition, certification demands from aerospace authorities require statistically validated data on mechanical properties and manufacturing process repeatability. Selected mechanical and thermal properties of the most studied HEAs are listed in Table 5.

Table 5. Mechanical Properties of Representative High-Entropy Alloy Systems

HEA System	**Phase**	**Density (g/cm^3)**	**Fracture/UTS (MPa)**	**Yield Str. (MPa)**	**Hardness (HV)**	**Max. Temp. (°C)**	**Test Mode**	**Aerospace Application**
CoCrFeMnNi (Cantor)	FCC	7.96	805	360	180	600	Tensile (T)	Cryogenic structures, LH2 tanks
AlCoCrFeNi	BCC+FCC	6.70	1400	1200	485	900	Tensile (T)	High-strength coatings, structural
AlCoCrFeNi2.1 (EHEA)	FCC+B2	6.86	1187	940	—	800	Tensile (T)	Eutectic: ductility + strength
CrMnFeCoNi (annealed)	FCC	7.96	750	450	140	600	Tensile (T)	Wear-resistant structural
NbMoTaW	BCC	13.8	1269 (C)	1058 (C)	443	1200+	Compressive (C)	Ultra-high-temp turbine/hypersonic
HfNbTaTiZr	BCC	10.9	—	929 (C)	300	1000+	Compressive (C)	Nuclear, hypersonic structures
TiZrNbHfTa	BCC	9.94	—	1000 (C)	380	1000+	Compressive (C)	Refractory structural HEA
AlTiVCrNb (LWHEA)	BCC	5.10	—	1350 (C)	530	1100	Compressive (C)	Lightweight high-temp structural
TiZrNbMoV (LWHEA)	BCC	6.50	—	1480 (C)	480	1100	Compressive (C)	Lightweight refractory HEA
Al0.5CoCrCuFeNi	FCC+BCC	7.06	1300	1100	400	900	Tensile (T)	Corrosion-resistant coatings
TiAlVNbMo (LWHEA)	BCC	5.30	—	1270 (C)	490	1100	Compressive (C)	Aerospace L-PBF structural
CrCoNi (MEA)	FCC	8.00	960	424	—	700	Tensile (T)	Superior toughness vs. Cantor

(C) = compressive test; tensile strength of BCC refractory HEAs is near zero owing to room-temperature brittleness.

6.1 Thermodynamic Design Principles and Core Effects

These include high-entropy stabilization of solid solutions, significant lattice distortion, sluggish diffusion, and the cocktail effect. High entropy results from the high configurational entropy of a five-element equimolar alloy ($\Delta Smix > 1.5R$), which reduces the Gibbs free energy of the disordered solid solution, thereby inhibiting the formation of intermetallic compounds. Lattice distortion results from the atomic size difference between the various metals in an alloy occupying different crystal lattice sites, which results in fluctuating stresses that inhibit dislocation glide. This, together with the increased solid solution strength, leads to improved resistance to plastic deformation compared to traditional binary solid solutions. Additionally, owing to sluggish diffusion, which is orders of magnitude slower for an HEA than for a similar conventional alloy, there is reduced grain growth and phase separation.

CALPHAD thermodynamic analysis, density functional theory (DFT) computations, and machine learning approaches are now essential for navigating the massive compositional space of HEAs. Odetola et al. (2024) conducted a detailed review of such strategies, highlighting the power and weaknesses of CALPHAD analysis in predicting phase equilibria within complex alloys, where binary interactions can be inaccurately known. The most recent paper on this topic by Odetola et al. (2025) highlights some counter-examples where, even though the CALPHAD heuristics predict stability within a single phase of certain alloys, in practice, the formation of intermetallic phases is observed.

6.2 FCC High-Entropy Alloys: Strength, Ductility, and Cryogenic Performance

HEAs structured on the FCC lattice, exemplified by the CoCrFeMnNi Cantor alloy, provide a remarkable balance between strength and ductility that increases at cryogenic temperatures, a feature that is diametrically opposed to that of conventional alloys that become embrittled at low temperatures. At 77 K (liquid nitrogen temperature), the CoCrFeMnNi alloy exhibits a fracture toughness higher than 200 MPa√m with a tensile strength greater than 800 MPa; consequently, it can be considered one of the strongest and most ductile structural metal alloys. Such outstanding behavior under cryogenic conditions makes it highly suitable for applications in aerospace engineering in terms of storing and transporting LNG, LOX, and LH_2 tanks and pipelines. The principle behind such outstanding cryogenic properties of these alloys involves a significantly improved TWIP effect owing to the low stacking fault energies associated with FCC lattices with multiple components.

6.3 BCC and Refractory High-Entropy Alloys

RHEAs contain refractory elements such as W, Mo, Nb, Ta, Hf, Zr, V, and Cr with very high melting points. They offer maximum strength compared to other HEAs, making them viable replacements for Ni superalloys in aerospace engineering under extreme temperature conditions. Compressive yield strengths greater than 1200 MPa can be attained with NbMoTaW at 1000°C, which is the operating temperature at which superalloys no longer possess any usable strength. However, brittle-to-ductile transitions and oxidation problems associated with tungsten and molybdenum in RHEAs limit their widespread application in engineering. Light-weight RHEAs (LWRHEAs), discussed by Li et al. (2025) and Wang et al. (2025), overcome the issue of high density in conventional RHEAs by replacing the heavy elements with light elements (Al, Ti). Thus, the density of AlTiVCrNb is ~5.1 g/cm³ compared to 8.1–9.0 g/cm³ of nickel superalloys, yet it retains its strength at 1000°C.

6.4 HEA Fatigue, Creep, and Environmental Resistance

According to Chen et al. (2024), there have been numerous studies on HEA fatigue properties; thus, a thorough meta-analysis was conducted on the subject, summarizing over 100 studies on HEA fatigue properties and identifying the main microstructural factors that determine HEA fatigue behavior. It should be emphasized that the fatigue properties of HEAs are generally better than those of conventional alloys owing to the prevention of dislocation channeling through a persistent slip band leading to crack formation due to dislocations moving through the fluctuating lattice potential energy landscape of HEA. Consequently, dislocations experience increased drag, thus preventing localized plastic deformation and fatigue cracks at lower levels. FCC HEAs have shown the best fatigue limit of 0.4-0.5 x UTS, which is similar to the fatigue limits of conventional austenitic stainless steels. Additionally, BCC HEAs typically demonstrate even greater fatigue limits owing to their sharp stress-life curves. There is insufficient information on the long-term creep properties of HEAs, which is a crucial issue in high-temperature applications where HEAs may be utilized.

The corrosion properties of HEAs vary according to their composition and environment, but are generally better than those of conventional alloys in identical environments. According to Arun et al. (2024), CoCrFeMnNi and AlCoCrFeNi HEAs demonstrate greater passive film stability and higher pitting potentials than the conventional stainless steel AISI 316 L owing to the presence of a multi-element composition of passive oxides that can provide multiple redundant routes for passivation. In addition, Gelchinski et al. (2022) demonstrated the effectiveness of HEAs as coatings to prevent corrosion and oxidation.

7. Processing Technologies: A Cross-Family Perspective

The performance characteristics of an aerospace alloy cannot be dissociated from the process employed in the manufacture of the alloy. The process not only dictates the final shape but also the overall mechanical performance owing to its effect on the alloy microstructure in terms of grain size, precipitates, texture, and residual stresses. Table 6 presents a performance comparison between different processing techniques.

Table 6. Comparison of Key Processing Technologies for Aerospace Metallic Alloys

Process	Compatible Alloys	Resolution / Precision	Build Rate	Cost Index	Porosity Level	Post-Proc. Required	Main Aerospace Advantage
Casting (Investment)	Ni, Al, Ti	Low (±0.5 mm)	High	Low	Medium	HIP, machining	Complex shapes, turbine blades
Forging (Hot Die)	Al, Ti, Ni	Medium	Medium	Medium	Negligible	Machining, HT	High mechanical properties
Powder Metallurgy (HIP)	Ni, Ti, HEA	Medium-High	Low	High	Very Low	Machining	Fine grain, disc alloys
L-PBF (Laser AM)	Al, Ti, Ni, HEA	Very High (±0.05 mm)	Low-Medium	Very High	Low (optimized)	HT, HIP, machining	Complex geometry, topology optimized
EBM (Electron Beam)	Ti, Ni, HEA	High (±0.1 mm)	Medium	High	Very Low	Machining	Low residual stress, Ti-6Al-4V
DED (Directed Energy)	All alloys	Medium (±0.2 mm)	High	Medium	Low	Machining	Repair, large structures
Friction Stir Processing	Al, Mg, Cu	N/A (surface)	Medium	Low	N/A	None typically	Microstructure refinement
Extrusion	Al, Mg, Ti	Medium	Very High	Very Low	Negligible	Stretching, HT	Profiles, stringers, frames
Spark Plasma Sintering	HEA, ceramics	High	Low	High	Very Low	Machining	HEA consolidation, lab scale

7.1 Additive Manufacturing: Transition to Production

The shift of metal AM from prototyping towards qualified production of aerospace components is the main production trend of the 2020s. This process was extensively covered by Blakey-Milner et al. (2021), who described the current state of certification and qualifications of the technology as being characterized by the certification and qualification gap, that is, the difference between the available level of qualification according to ASTM F42 and AMS standards on the one hand and the level of technological possibilities. Gradl et al. (2022) offered an in-depth look at the AM process selection in aerospace production, highlighting the necessity of choosing the AM technique depending on the complexity, metallurgical specifics, and scale of production.

Yusuf et al. (2019) considered the certification issues related to metal AM in aerospace, focusing primarily on the following issues: proving statistical equivalence to baseline properties of materials produced via forging, dealing with AM's inherent variability, and achieving sufficient fatigue properties in components with complex internal geometries, which could be hard to predict and evaluate. The advances made since the publication of this paper have been significant, especially if we consider the case of GE Aviation's LEAP engine fuel nozzles produced by L-PBF, with up to 316 nozzles per engine.

Table 6A. Comparative Additive Manufacturing Challenges Across Aerospace Alloy Systems

Alloy	Cracking	Porosity	Residual Stress	Qualification
Al	High	Moderate	Moderate	Limited
Ti	Low	Low	High	Advanced
Ni	Moderate	Moderate	High	Moderate
HEA	High	High	High	Pre-qualification

The additive manufacturing characteristics of alloys used in aerospace applications are highly varied depending on the type of alloy. Aluminum alloys are highly susceptible to hot cracking because of their wide solidification range. On the other hand, titanium alloys show good printability properties but suffer from high residual stress. Nickel-based superalloys have a problem of solidification cracking with high γ' content, while HEAs have limited application at the lab scale level only.

7.2 Powder Metallurgy and Spark Plasma Sintering

The processing techniques associated with PM have distinct benefits when dealing with materials such as HEAs and superalloys, whose compositions exhibit segregation upon standard ingot casting. Fully dense and homogeneous parts can be formed using hot isostatic pressing (HIP) of premixed powders, resulting in grain sizes that cannot be attained in ingots owing to segregation issues and giving parts adequate fatigue strength to operate in rotating discs. The most common method for small-scale HEA fabrication in a laboratory environment is spark plasma sintering (SPS), which involves passing a pulsating electrical current through a powder compact at very high heating and compression rates within seconds to a few minutes. This approach allows for the formation of dense alloys from multicomponent powders without an extended period of exposure to high temperatures, which would lead to material segregation and phase formation.

7.3 Friction Stir Processing and Surface Engineering

A technology based on friction stir welding known as friction stir processing (FSP) results in significant microstructural refinement of the surface layer, accomplished through plasticizing and mixing of the material using a rotating, non-consumable tool without any melting involved. Recent developments in FSP have been discussed by Hewidy (2025). These developments include grain refinement from a few tens of micrometers to sub-micrometer size ranges in Al, Cu, and Mg alloy systems; dispersion and re-distribution of coarse particle constituents; and fatigue resistance, corrosion resistance, and wear resistance enhancements due to microstructural refinement. Friction stir processing (FSP) is a unique technique in aerospace engineering for (1) enhancing the fatigue performance of friction stir welded joints by performing the process on the weld nugget, (2) increasing the wear resistance at attachment sites by reinforcing aluminum alloy structures with ceramic or intermetallic particles, and (3) eliminating subsurface defects in aluminum alloy structures without inducing any thermal distortion.

7.4 Computational Design: CALPHAD, DFT, and Machine Learning

The incorporation of computation into the alloy discovery process has resulted in a significant acceleration of material discovery efforts by several orders of magnitude. For instance, CALPHAD predicts the thermodynamic behavior of multi-component alloys, such as phase equilibria, solidification, and heat treatment behavior; for five-component systems, there has been significant progress made in improving their accuracy owing to the expansion of the interaction parameter database for binary and ternary systems. First-principles calculations using DFT yield atomic-level properties such as the stacking fault energy, elastic constant, and vacancy formation energy, which can then be inputted directly into constitutive equations. Finally, machine learning models, using the increasing amount of data about HEAs' properties, have shown promising prediction capability when predicting property-composition relationships, matching the prediction power of physics-based modeling with a significantly reduced computational overhead.

Rahman et al. (2025) provided a comprehensive review of machine learning for different alloys where they covered advances made from simple regression modeling to complex architectures such as graph neural networks and large language models for materials science. The key limitation to the effectiveness of ML models is the availability of quality data, and although there are many experimental measurements in the aerospace alloy literature, most of them exist in incompatible databases, tested under various test conditions, and without adequate microstructure data for interpreting scatter among property measurements. In another work, Liu et al. (2024) showed the application of high-throughput computation methods in designing alloys for AM, where CALPHAD-based composition screening reduced experimentation by an order of magnitude.

8. Comparative Analysis Across Alloy Families

For a thorough comparative analysis of these four alloys, it should be understood that each fills its own niche in the family of aerospace materials and that all four are found in any aircraft that has been constructed recently. The selection of the most appropriate one is dependent on the result of a multi-criteria optimization that factors in performance, weight, thermal properties, cost, ease of manufacturing, and sustainability.

Table 7. Master Comparative Matrix of Key Aerospace Alloy Families. (Data compiled from Dursun and Soutis (2014), Pollock and Tin (2006), Miracle and Senkov (2017), Laskowska et al. (2025), Li et al. (2025), and references therein.)

Property	Aluminum Alloys	Titanium Alloys	Ni-Based Superalloys	High-Entropy Alloys	Al-Li Alloys
Density (g/cm³)	2.6–2.9	4.4–4.9	8.1–9.0	5.0–14 (varies)	2.5–2.7
UTS Range (MPa)	270–720	600–1400	900–1500	800–1800	450–760
Yield Str. (MPa)	200–650	500–1300	800–1400	700–1700	400–700
Elongation (%)	6–22	6–15	2–12	2–50 (FCC)	4–12
Elastic Modulus (GPa)	69–79	100–120	200–220	140–210	75–80
Max. Service Temp. (°C)	150–175	300–600	900–1200	600–1200+	175–200
Thermal Conductivity (W/mK)	100–200	6–21	10–12	8–18	100–160
Corrosion Resistance	Good	Excellent	Excellent	Superior	Very Good
Fatigue Resistance	Moderate	High	Very High	High	Moderate–High
AM Compatibility	Moderate	Excellent	Moderate	Emerging	Moderate
Weldability	Moderate	Difficult	Difficult	Limited data	Moderate
Relative Material Cost	Low (1×)	High (5–8×)	Very High (20–50×)	Very High (variable)	Medium (2–4×)
Qualification Readiness	Fully qualified	Fully qualified	Fully qualified	Pre-qualification	Qualified (selected)
Primary Application	Airframe, fuselage	Engine, airframe	Turbine blades/discs	Next-gen components	Lightweight airframe

Several key insights can be gained from this comparative analysis. First, each of the alloy families plays an important role, and none of them compete with the others; specifically, aluminum alloys are the most appropriate choice for low-cost structures that carry moderate loads, titanium alloys span the space between aluminum and nickel alloys in terms of both density and operating temperatures, nickel alloys are indispensable in extreme operating conditions, and HEAs are unique owing to their superior performance in specific areas. Second, the additive manufacturing capability appears to be highest for titanium alloys, while it is quickly improving in other alloy families. Third, HEAs show the best results with respect to the maximum performance potential, especially when considering the mechanical properties at high temperatures and corrosion resistance. Finally, the concept of sustainability considerations has historically received limited attention in aerospace material selection, although their importance is increasing rapidly; this should change.

9. Sustainability and Life-Cycle Considerations

The sustainability initiative of aviation, which includes regulatory compliance (ICAO CORSIA, EU ETS), economics of fuel prices, and voluntary commitments made by airline carriers and original equipment manufacturers, is gradually becoming a major consideration in material selection for aerospace applications. This is because of the basic relationship between structure weight and fuel burn (~ 0.03 to 0.05 kg of fuel/hour fuel burn saving per kg of reduced structure weight, depending on the type of aircraft). Weight savings is the only sustainability opportunity that material engineers can take advantage of. For every 1% reduction in weight, there was a 0.75% reduction in fuel burn. This indicates that any material development that results in weight savings leads to lower carbon emissions.

Apart from weight savings, three other sustainability aspects are becoming important in aerospace material evaluation. The recyclability of aluminum materials is fairly easy because the materials preserve their recyclability through repeated processing without requiring significant energy costs. However, it is difficult for titanium alloys, whose kroll extraction is highly energy-consuming, and for nickel-based superalloys, whose components (strategic and toxic) need to be separated first. Similarly, for HEAs, the presence of multiple principal elements makes closed-loop recyclability difficult. Embodied carbon, or the amount of carbon dioxide equivalents emitted through the processing of each alloy family, varies significantly, with titanium having the highest (about 35 kg CO_2eq/kg), followed by nickel (about 11 kg CO_2eq/kg), and then aluminum (about 8 kg CO_2eq/kg for primary, less than 1 kg CO_2eq/kg for recycled). Finally, the end-of-life option for materials, whether remanufactured, recycled, or scrapped, closes the sustainability circle.

The above quantitative factors show that lightweight materials do not automatically have low environmental impact during their manufacture. Therefore, future approaches to alloy selection must consider operating fuel savings, carbon emissions, and recyclability.

10. Extended Literature Summary

An expanded list of 30 important articles reviewed in this paper is given in Table 9 based on the author, date, topic of the study, methodology used, and findings obtained.

11. Research Gaps and Priority Actions

Although the extent of scientific research into aerospace metallic alloys is indeed extensive, there exist numerous gaps in knowledge that still require urgent attention. Table 10 presents a detailed examination of the ten most important knowledge gaps that include the affected alloy family, knowledge status, priority, and suggested course of research.

Four main factors were used to prioritize the research gaps highlighted by this study:

- Impact on flight safety
- Technology Readiness Level (TRL)
- • Industry's need for implementation urgency
- • Sustainability

Significant gaps include issues that directly impede the process of component qualification or deployment, while medium-priority gaps deal with optimization and future alloy formulation.

12. Economic Considerations for Emerging Aerospace Alloys

The economic viability of using new alloy systems is becoming increasingly relevant for the aerospace industry, especially in the case of commercial air transport, where high production rates are achieved and profit margins are small. While third-generation Al–Li alloys offer some benefits in reducing the structural mass and fuel economy, the cost of producing these alloys is still about twice or even four times as high as that of regular aluminum alloys owing to the cost of adding lithium, the need for more accurate control of composition, and restricted logistics. The production of HEAs is associated with additional expenses in most cases because it requires vacuum melting, powder atomization, spark plasma sintering, or additive manufacturing processes. In addition, some refractory HEAs include expensive elements, such as tantalum, hafnium, and tungsten. However, the economic evaluation of the materials should not be reduced to the initial cost. The reduction in structural weight, longer service periods, better oxidation resistance, and increased durability will compensate for higher material costs during the entire lifespan of aerospace parts. Thus, life cycle analysis is required before implementing the technology on an industrial scale.

Table 8. Lifecycle Assessment Indicators for Aerospace Alloy Families

Material	Embodied Carbon (kg CO_2eq/kg)	Recyclability	Energy Demand (MJ/kg)
Aluminum	8	Excellent	150
Recycled Aluminum	<1	Excellent	15
Titanium	35	Moderate	700
Ni Superalloys	11	Moderate	250
HEAs	15–40	Limited	Variable

Table 9. Extended Literature Summary

Author(s)	Year	Study Focus	Methodology	Key Findings
Fan, Q.	2025	High-temperature alloys in aerospace: future innovations	Literature review; property analysis	High-temp alloys essential for aerospace; cost & longevity remain key challenges
Ivanov et al.	2024	High-entropy alloys: brief review & aerospace perspectives	Systematic review; compositional analysis	HEAs exhibit superior mechanical characteristics; promising for future aerospace structures
Kotadia, H.R. et al.	2021	L-PBF AM of Al alloys: microstructure and properties	Review of 200+ experimental studies	Highlights AM potential and limitations for high-strength Al aerospace alloys
Gloria, A. et al.	2019	Aeronautic alloys: state of the art and perspectives	Comparative review across Al, Ti, Ni alloys	Significant advances in alloy performance; optimizing service life remains a challenge
Zhou, B. et al.	2021	Advancement of 7XXX series Al alloys for aircraft	Review + microstructural analysis	Heat treatment optimization critical for 7xxx aerospace performance
Pollock, T. M. & Tin, S.	2006	Ni-based superalloys for advanced turbine engines	Review of chemistry, microstructure, properties	Ni superalloys sustain >1000°C; gamma-prime microstructure is key
Blakey-Milner et al.	2021	Metal AM in aerospace: comprehensive review	Review of 400+ studies across AM processes	AM transitioning from prototyping to production; technical challenges remain
Feng, R. et al.	2021	High-throughput design of lightweight HEAs	CALPHAD + experimental validation	Identifies precipitation-strengthened lightweight HEAs with enhanced high-temp strength
Tsai, M.H. & Yeh, J.W.	2014	High-entropy alloys: a critical review	Critical review of HEA fundamentals	Foundational definition of HEA core effects; lattice distortion and sluggish diffusion
Gradl, P.R. et al.	2022	Robust metal AM process selection for aerospace	Case studies across L-PBF, EBM, DED	Framework for AM process selection based on geometry and metallurgical requirements
Adomako, N.K. et al.	2022	Electron & laser-based AM of Ni-based superalloys	Review of microstructure heterogeneity	AM Ni superalloys show microstructural heterogeneity requiring careful HT optimization
Dursun, T., Soutis, C.	2014	Recent developments in advanced aircraft Al alloys	Review of Al alloys from 2xxx to Al-Li	2xxx and 7xxx remain dominant; Al-Li offers density and stiffness advantages
Behera, A. et al.	2023	Ni-based superalloys for aero turbine blades	Review; alloy evolution and processing	Single-crystal alloys offer best creep performance; AM enables blade repair applications
Liu, Y. et al.	2024	L-PBF of Al-Ce alloys: microstructure & properties	Review of L-PBF Al-Ce literature	Al-Ce alloys show strong potential for high-temp aerospace Al AM applications
Laskowska, D. et al.	2025	AM of Ti-6Al-4V and Ti-6Al-7Nb microstructure	L-PBF experiments + heat treatment trials	Heat treatment at 850–1000°C enabled martensite decomposition and property tailoring.
Yao, Z. & Xie, Z.	2024	L-PBF of 2024 Al alloy modified with nano-LaB6	Experimental: grain refinement & tensile testing	LaB6 additions refine grains from 10.3 to 9 µm; tensile strength reaches 251 MPa.

Author(s)	Year	Study Focus	Methodology	Key Findings
Wang, Y. et al.	2025	Lightweight HEAs: structure, properties & applications	Comprehensive review; density classification	LWHEAs exhibit superior corrosion resistance and mechanical properties for aerospace applications.
Odetola, P.I. et al.	2024	HEA thermodynamic design & computational modeling	CALPHAD + DFT + ML review	CALPHAD with ML has accelerated HEA design, and thermodynamic criteria have counterexamples.
Yusuf, S.M. et al.	2019	Impact of metal AM on aerospace industry	Review of AM certification landscape	Metal AM transitioning to production; certification frameworks are the critical bottleneck
Parveez, B. et al.	2022	Scientific advancements in composite materials for aircraft	Review of composites and metallic hybrid systems	The mechanical and corrosion challenges in hybrid systems require further research.
Rahman, A. et al.	2025	Machine learning approaches for diverse alloy systems	Review of ML models across alloy families	ML accelerates alloy discovery, and data scarcity is the primary constraint.
Li, G. et al.	2025	Lightweight refractory HEAs: a review	Review of composition, processing, properties	Refractory HEAs exhibit promising high-temperature properties and require manufacturing optimization.
Schafrik, R. et al.	2001	Alloy 718 in GE aircraft engines: past & next 5 years	Application review; historical case study	Alloy 718 dominates disc applications; AM repair is a near-term application
Arshad, M. et al.	2022	High-entropy coatings for high-temperature use	Review of HEC processing, properties	HEA coatings improve oxidation and corrosion resistance for turbine applications.
Yu, J. & Mu, R.	2021	High-entropy thermal barrier coatings: review	Review of HEA-TBC research	HEA-TBCs outperform YSZ in thermal stability & cycling durability
Trzepieciński, T. et al.	2024	Metallic materials for structural panels	Current trends review	Al and Mg alloys can reduce structural weight by 20–40%.
Ma, N. et al.	2020	Ti-based HEAs: methods, properties & applications	Review of Ti-HEA literature	Ti-HEAs combine aerospace performance with biocompatibility.
Arun, S. et al.	2024	HEAs: comprehensive review Part II	Review of microstructure, properties, applications	HEAs excel in wear and corrosion resistance; extreme-temp applications are viable
Chen, S. et al.	2024	Fatigue behavior of high-entropy alloys	Review & meta-analysis of HEA fatigue data	HEA lattice distortion suppresses dislocation channeling; improves HCF and LCF performance
Beal, C. et al.	2024	AM Ti-6Al-4V microstructure tailoring for fatigue	L-PBF + heat treatment experiments	Post-build HT above the β-transus enables fatigue life matching wrought Ti-6Al-4V.

Table 10. Priority Research Gaps in Aerospace Metallic Alloys

Research Gap	Alloy(s) Affected	Current State	Importance Level	Recommended Research Action
Long-term in-service fatigue data (>10^8 cycles)	All families	Lab coupon data only	Critical	Standardized multi-lab round-robin testing protocols under realistic load spectra
Scalable AM process for HEAs	HEAs	Lab-scale SPS/arc-melt only	Critical	Develop L-PBF / DED parameter databases for 10+ HEA compositions
Comprehensive multi-alloy comparative studies	All families	Single-alloy studies dominant	High	Standardized test protocols; shared open-access materials databases
Creep-fatigue interaction under thermal cycling	Ni superalloys, HEAs	Limited thermal-mechanical fatigue data	Critical	Thermo-mechanical fatigue rigs with in situ characterization
HEA recyclability and lifecycle cost	HEAs	No recycling infrastructure	High	Process development for multi-element recovery; life-cycle assessment models
Qualification / certification pathways for AM	Ti, Ni, HEA AM parts	ASTM/AMS gaps for AM alloys	Critical	Industry-academia consortia to fill ASTM F42 / AMS 4999 gaps
Sustainability integration in alloy design	All families	Performance-only evaluation	Medium-High	Embed LCA, recyclability, and carbon footprint in alloy selection frameworks
Machine learning for small datasets	HEAs	ML limited by data scarcity	High	Federated / transfer learning; active learning for alloy property prediction
Coating-substrate compatibility at >1200°C	Ni superalloys, HEAs	TBC spallation a known issue	Critical	In situ synchrotron study of TGO growth in HEA-TBC systems
Radiation resistance of aerospace HEAs	Refractory HEAs	Primarily nuclear literature	Medium	Proton/neutron irradiation campaigns on candidate HEA compositions

Importance levels: Critical = design-limiting gap with no adequate current solution; High = significant gap limiting deployment; Medium-High = important for long-term field advancement.

13. Conclusions

This exhaustive review draws from over 30 papers published prior to early 2026 to provide a richer data-driven review of the four metallic alloy families that comprise modern aerospace material engineering. The major takeaways include the following:

1. Al alloys continue to play an important role in creating efficient airframes. Third-generation aluminum lithium alloys (AL-Li; 2050, 2099, 2195, 2198) are qualified for use in applications that require a 2-4% decrease in density without sacrificing structural integrity. Additive manufacturing (AM) of aluminum alloys poses challenges owing to the lack of ductility in 2xxx and 7xxx aluminum; however, inoculation techniques have been effective, with Al-Ce alloys showing particular promise for high-strength AM aluminum parts.
2. Titanium alloys represent the best choice of material for lightweight parts operating at moderate temperatures. Laser powder bed fusion of titanium-6aluminum-4vanadium (Ti-6Al-4V) is nearly capable of delivering a fatigue performance equivalent to that of wrought metal. Beta-type alloys allow for thick-section applications such as landing gears. Titanium HEAs are the latest frontier of material design for structural applications under high temperatures.
3. Nickel-based superalloys are unmatched in their capability for extreme temperature turbine applications. Single-crystal sixth-generation nickel-based superalloys can function up to approximately 1200 °C. Thermochemically bonded ceramic top coats made of HEAs constitute a critical part of next-generation thermal barrier coatings (TBC). Amenable to AM for repairs.

4. High-entropy alloys are one of the most promising emerging alloys for the future aerospace industry. Nevertheless, their commercialization is associated with great challenges in areas such as processing, oxidation resistance, economics, and certification.
5. Additive manufacturing (AM) represents the largest leap forward in process innovation for all four alloy types mentioned above. It allows engineers to produce component designs, internal architectures, and buy-to-fly ratios that are unavailable using traditional machining techniques. The gap between certification standards and capabilities constitutes a major limiting factor for widespread adoption.
6. Material modeling tools, such as CALPHAD modeling, DFT modeling, and machine learning (ML), play crucial roles in accelerating the pace of alloy development. Machine learning predictions are accurate but currently limited by the lack of quality training datasets. Curated open-access databases represent the most impactful investment for the materials research community.
7. Sustainable engineering practices and considerations remain underutilized when selecting and developing new alloys for aerospace applications. Factors such as weight reduction, recyclability, embodied carbon, and end-of-life disposal strategies should be integrated alongside the traditional criteria of structural performance.
8. HEA material design, AM process development, and ML-assisted computational methods have brought us to the verge of another transformative shift in aerospace engineering— one that might result in the widespread adoption of multi-element alloys for turbine stages, structural primary members, and cryogenic storage.

Acknowledgements

The author(s) thanks the University of Technology for supporting the current investigation.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

The Author Contributions section should specify the exact contributions of each author in a narrative form. For instance:

Authors A.B. and C.D: proposed the research problem.

Author A.B.: developed the theory and performed the computations.

Author C.D.: verified the analytical methods and investigated [a specific aspect] and supervised the findings of this work.

Both authors discussed the results and contributed to the final manuscript.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

References

[1] L. Li et al., "Low-cycle fatigue of Ni-based single crystal superalloy with film cooling holes," Fatigue Fract. Eng. Mater. Struct., vol. 47, no. 2, pp. 532–548, 2024. https://doi.org/10.1111/ffe.14178

[2] Y. Li et al., "Lifetime Prediction of Single Crystal Nickel-Based Superalloys," Appl. Sci., vol. 15, no. 1, Art. no. 201, 2025. https://doi.org/10.3390/app15010201

[3] G. Li, Z. Wu, Y. Dong, et al., "Lightweight refractory high-entropy alloys: A review," J. Mater. Res. Technol., vol. 35, pp. 3183–3204, 2025. https://doi.org/10.1016/j.jmrt.2025.02.003

[4] O. N. Senkov, D. B. Miracle, K. J. Chaput, and J. P. Couzinie, "Development and exploration of refractory high entropy alloys," J. Mater. Res., vol. 33, no. 19, pp. 3092–3128, 2018. https://doi.org/10.1557/jmr.2018.153

[5] O. N. Senkov, G. B. Wilks, J. M. Scott, and D. B. Miracle, "Mechanical properties of Nb25Mo25Ta25W25 alloy at room and elevated temperature," Intermetallics, vol. 19, no. 5, pp. 698–706, 2011. https://doi.org/10.1016/j.intermet.2011.01.004

[6] B. Gludovatz, A. Hohenwarter, D. Catoor, E. H. Chang, E. P. George, and R. O. Ritchie, "A fracture-resistant high-entropy alloy for cryogenic applications," Science, vol. 345, no. 6201, pp. 1153–1158, 2014. https://doi.org/10.1126/science.1254581

[7] D. B. Miracle and O. N. Senkov, "A critical review of high entropy alloys and related concepts," Acta Mater., vol. 122, pp. 448–511, 2017. https://doi.org/10.1016/j.actamat.2016.08.081

[8] M. Tokarewicz and M. Gradzka-Dahlke, "Review of Recent Research on AlCoCrFeNi High-Entropy Alloy," Metals, vol. 11, no. 8, Art. no. 1302, 2021. https://doi.org/10.3390/met11081302

[9] B. Cantor, I. T. H. Chang, P. Knight, and A. J. B. Vincent, "Microstructural development in equiatomic multicomponent alloys," Mater. Sci. Eng. A, vols. 375–377, pp. 213–218, 2004. https://doi.org/10.1016/j.msea.2003.10.257

[10] Q. Fan, "High-Temperature Alloys in Aerospace Applications and Future Innovations," Mater. Today

Adv., vol. 27, Art. no. 100590, 2025. https://doi.org/10.1016/j.mtadv.2025.100590

[11] T. M. Sonar, M. A. Ivanov, et al., "High entropy alloys and future perspectives in aerospace," Journal of Physics: Conference Series, vol. 2543, Art. no. 012011, 2024

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

[13] T. M. Pollock, "Alloy design for aircraft engines," Nature Materials, vol. 15, no. 8, pp. 809–815, 2016. https://doi.org/10.1038/nmat4709

[14] B. Blakey-Milner et al., "Metal additive manufacturing in aerospace: A review," Materials & Design, vol. 209, Art. no. 110008, 2021. https://doi.org/10.1016/j.matdes.2021.110008

[15] R. Feng et al., "High-throughput design of high-performance lightweight HEAs," Nature Communications, vol. 12, Art. no. 4329, 2021. https://doi.org/10.1038/s41467-021-24523-9

[16] J. W. Yeh, S. K. Chen, S. J. Lin, et al., "Nanostructured high-entropy alloys with multiple principal elements," Advanced Engineering Materials, vol. 6, no. 5, pp. 299–303, 2004. https://doi.org/10.1002/adem.200300567

[17] T. Dursun and C. Soutis, "Recent developments in advanced aircraft aluminium alloys," Materials & Design, vol. 56, pp. 862–871, 2014. https://doi.org/10.1016/j.matdes.2013.12.002

[18] D. Laskowska, B. Balasz, and L. Zurawski, "Metallographic structure of L-PBF Ti-6Al-4V and Ti-6Al-7Nb," Materials, vol. 19, no. 1, Art. no. 80, 2025. https://doi.org/10.3390/ma19010080

[19] Z. Yao and Z. Xie, "L-PBF of 2024 aluminum alloys modified using Nano-LaB6," Materials, vol. 17, no. 13, Art. no. 3367, 2024. https://doi.org/10.3390/ma17133367

[20] P. I. Odetola et al., "High entropy alloys: Thermodynamic design and computational modeling," Heliyon, vol. 10, no. 22, Art. no. e39660, 2024. https://doi.org/10.1016/j.heliyon.2024.e39660

[21] S. M. Yusuf, S. J. Cutler, and N. Gao, "Impact of metal additive manufacturing on aerospace," Metals, vol. 9, no. 12, Art. no. 1286, 2019. https://doi.org/10.3390/met9121286

[22] B. Parveez et al., "Scientific advancements in composite materials for aircraft," Polymers, vol. 14, no. 22, Art. no. 5007, 2022. https://doi.org/10.3390/polym14225007

[23] A. Rahman, M. S. Hossain, and A. Siddique, "Machine learning approaches for diverse alloy systems," Journal of Materials Science, vol. 60, pp. 12189–12221, 2025. https://doi.org/10.1007/s10853-025-11154-4

[24] R. E. Schafrik and R. Sprague, "Saga of gas turbine materials," Advanced Materials & Processes, vol. 162, no. 3, pp. 33–36, 2004.

[25] M. Arshad et al., "High-entropy coatings for high-temperature applications," Coatings, vol. 12, no. 5, Art. no. 691, 2022. https://doi.org/10.3390/coatings12050691

[26] N. Ma, S. Liu, et al., "Research progress of titanium-based high entropy alloy," Frontiers in Bioengineering and Biotechnology, vol. 8, Art. no. 603522, 2020. https://doi.org/10.3389/fbioe.2020.603522

[27] S. Chen, X. Fan, W. Li, and P. K. Liaw, "Fatigue behavior of high-entropy alloys," arXiv, Art. no. 2401.07418, 2024. https://doi.org/10.48550/arXiv.2401.07418

[28] C. Beal, M. A. Moshier, H. Asgari, and P. Phanichphant, "Additively manufactured Ti-6Al-4V microstructure tailoring for fatigue," Fatigue & Fracture of Engineering Materials & Structures, vol. 47, pp. 1684–1699, 2024. https://doi.org/10.1111/ffe.14316

[29] H. Long, S. Mao, Y. Liu, et al., "Microstructural and compositional design of Ni-based single crystalline superalloys," Journal of Alloys and Compounds, vol. 743, pp. 203–220, 2018. https://doi.org/10.1016/j.jallcom.2018.01.224

[30] R. Branco, F. Berto, A. Kotousov, et al., Mechanical Behaviour of Aluminium Alloys. Basel, Switzerland: MDPI Books, 2018. https://doi.org/10.3390/books978-3-03897-321-8

[31] 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

[32] A. Behera, A. K. Sahoo, and S. S. Mahapatra, "Ni-based superalloy in aero turbine blade: A review," Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, vol. 238, no. 3, pp. 1041–1059, 2024. https://doi.org/10.1177/09544089231219104

[33] K. Gancarczyk et al., “Crystal structure of CMSX-4 single-crystal turbine blades,” Materials, vol. 18, no. 5, Art. no. 919, 2025. https://doi.org/10.3390/ma18050919

[34] R. C. Reed, *The Superalloys: Fundamentals and Applications*. Cambridge, U.K.: Cambridge University Press, 2006.

[35] R. Schafrik, D. D. Ward, and J. Groh, “Application of Alloy 718 in GE aircraft engines,” in *Superalloys 718, 625, 706 and Various Derivatives*, TMS, 2001, pp. 1–11.

[36] J. Yu and R. Mu, “Research status of high entropy thermal barrier coatings,” Frontiers in Materials, vol. 8, Art. no. 816069, 2021. https://doi.org/10.3389/fmats.2021.816069

[37] N. K. Adomako, N. Haghdadi, and S. Primig, “AM of Ni-based superalloys: A review of microstructure heterogeneities,” Applied Materials Today, vol. 27, Art. no. 101400, 2022. https://doi.org/10.1016/j.apmt.2022.101400

[38] M.-H. Tsai and J.-W. Yeh, “High-entropy alloys: A critical review,” Materials Research Letters, vol. 2, no. 3, pp. 107–123, 2014. https://doi.org/10.1080/21663831.2014.912690

[39] S. Arun, N. Radhika, and B. Saleh, “Potential of high entropy alloys: Microstructure, properties and applications, Part II,” Journal of Alloys and Compounds, vol. 991, Art. no. 174472, 2024. https://doi.org/10.1016/j.jallcom.2024.174472

[40] B. Gelchinski, I. A. Balyakin, et al., “High-entropy alloys as protective coatings,” Journal of Physics: Conference Series, vol. 2241, Art. no. 012009, 2022.

[41] P. R. Gradl, D. C. Tinker, A. Park, et al., “Robust metal AM process selection for aerospace,” Journal of Materials Engineering and Performance, vol. 31, pp. 6013–6044, 2022. https://doi.org/10.1007/s11665-022-06850-0

[42] A. Hewidy, “Recent advances in friction stir processing for microstructural refinement,” Mechanical Engineering Advances, vol. 3, Art. no. 100012, 2025.

[43] Y. Liu, Y. Li, M. Wang, and Z. Chen, “Review of laser powder bed fusion microstructure for Al-Ce alloys,” Materials, vol. 17, no. 20, Art. no. 5085, 2024. https://doi.org/10.3390/ma17205085

[44] M. Liu, C. Lei, Y. Wang, B. Zhang, and X. Qu, “High-throughput preparation for alloy composition design in AM,” Materials Today Communications, vol. 38, Art. no. 107785, 2024. https://doi.org/10.1016/j.mtcomm.2023.107785

[45] T. M. Pollock and S. Tin, “Nickel-based superalloys for advanced turbine engines,” Journal of Propulsion and Power, vol. 22, no. 2, pp. 361–374, 2006. https://doi.org/10.2514/1.18239

[46] A. Gloria, R. Montanari, M. Richetta, and A. Varone, “Alloys for aeronautic applications: State of the art and perspectives,” Metals, vol. 9, no. 6, Art. no. 662, 2019. https://doi.org/10.3390/met9060662

[47] Y. Wang et al., “Light weight high entropy alloys: Structure, properties, and applications,” cMat, Art. no. e70014, 2025. https://doi.org/10.1002/cmt2.70014

[48] M. Richetta and A. Varone, “Additive manufacturing of aluminum alloys for aeronautic applications,” Metals, vol. 13, no. 4, Art. no. 716, 2023. https://doi.org/10.3390/met13040716

[49] Y. Xiao et al., “Research progress of new generation aluminum-lithium alloys,” Advanced Engineering Materials, vol. 26, Art. no. 2301639, 2024. https://doi.org/10.1002/adem.202301639

[50] T. Trzepiecinski and S. M. Najm, “Current trends in metallic materials for structural members,” Materials, vol. 17, no. 3, Art. no. 590, 2024. https://doi.org/10.3390/ma17030590

[51] M. Brewer et al., “Recent advances in joining technologies of aluminum alloys,” Discover Materials, vol. 4, Art. no. 58, 2024. https://doi.org/10.1007/s43939-024-00155-w

[52] R. Sliwa, B. Pawlowska, T. Balawender, and M. Zwolak, “Extrusion of lightweight aluminum and magnesium alloys for aviation,” Key Engineering Materials, vol. 926, pp. 523–536, 2022.

[53] J. C. Williams and E. A. Starke Jr., “Progress in structural materials for aerospace systems,” Acta Materialia, vol. 51, no. 19, pp. 5775–5799, 2003. https://doi.org/10.1016/j.actamat.2003.08.023

[54] M. H. Mosallanejad et al., “Additive manufacturing of titanium alloys: Processability, properties, and applications,” Advanced Engineering Materials, vol. 25, Art. no. 2301122, 2023. https://doi.org/10.1002/adem.202301122

[55] T. Pasang et al., “Additive manufacturing of titanium alloys—Enabling re-manufacturing,” Microelectronics Engineering, vol. 270, Art. no. 111935, 2023. https://doi.org/10.1016/j.mee.2022.111935

[56] P. Pushp et al., “Additive manufacturing of titanium alloys for aerospace,” Review of Materials Research, vol. 1, no. 1, Art. no. 100003, 2022. https://doi.org/10.1016/j.revmat.2021.100003

[57] G. Mi, Y. Tan, H. Chen, P. Li, and X. Zhang, “Additive manufacturing of 600°C high-temperature titanium alloys,” Journal of Aeronautical Materials, vol. 44, no. 1, pp. 15–30, 2024. https://doi.org/10.11868/j.issn.1005-5053.2023.000106

[58] Y. He et al., “Enhanced low cycle fatigue of selective laser melting Ti-6Al-4V,” Journal of Materials Science & Technology, vol. 180, pp. 129–140, 2024. https://doi.org/10.1016/j.jmst.2023.09.017

[59] R. R. Boyer, “An overview on the use of titanium in the aerospace industry,” Materials Science and Engineering A, vol. 213, nos. 1–2, pp. 103–114, 1996. https://doi.org/10.1016/0921-5093(96)10233-1

[60] C. Leyens and M. Peters, Eds., *Titanium and Titanium Alloys: Fundamentals and Applications*. Weinheim, Germany: Wiley-VCH, 2003.

[61] G. Lütjering and J. C. Williams, *Titanium*, 2nd ed. Berlin, Germany: Springer, 2007. https://doi.org/10.1007/978-3-540-73036-1

[62] L. Han, P. Li, S. Yu, et al., “Creep/fatigue failure of Ni-based superalloy turbine blade,” International Journal of Fatigue, vol. 154, Art. no. 106558, 2022. https://doi.org/10.1016/j.ijfatigue.2021.106558

[63] P. Caron and T. Khan, “Evolution of Ni-based superalloys for single crystal applications,” Aerospace Science and Technology, vol. 3, no. 8, pp. 513–523, 1999. https://doi.org/10.1016/S1270-9638(99)00108-X

[64] E. P. George, D. Raabe, and R. O. Ritchie, “High-entropy alloys,” Nature Reviews Materials, vol. 4, no. 8, pp. 515–534, 2019. https://doi.org/10.1038/s41578-019-0121-4

[65] F. Otto et al., “Tensile properties of CoCrFeMnNi high-entropy alloy,” Acta Materialia, vol. 61, no. 15, pp. 5743–5755, 2013. https://doi.org/10.1016/j.actamat.2013.06.018

[66] G. Laplanche et al., “Superior mechanical properties of medium-entropy CrCoNi,” Acta Materialia, vol. 128, pp. 292–303, 2017. https://doi.org/10.1016/j.actamat.2017.02.036

[67] M. Dada, P. Popoola, and N. Mathe, “Recent advances of high entropy alloys for aerospace: A review,” World Journal of Engineering, vol. 20, no. 1, pp. 43–74, 2023. https://doi.org/10.1108/WJE-01-2021-0040

[68] M. Han and Z. P. Lu, “Development and applications of lightweight HEAs: A review,” Advanced Engineering Materials, vol. 27, Art. no. 2501170, 2025. https://doi.org/10.1002/adem.202501170

[69] J. Hu, X. Li, et al., “An overview on fatigue of high-entropy alloys,” Materials, vol. 16, no. 24, Art. no. 7552, 2023. https://doi.org/10.3390/ma16247552

[70] A. Sasi, R. J. Vikram, and K. Dash, “Corrosion and oxidation of HEAs in extreme environments,” Journal of Applied Physics, vol. 138, no. 2, Art. no. 020701, 2025. https://doi.org/10.1063/5.0273671

[71] Q. S. Pan et al., “Recent progress in oxidation behavior of high-entropy alloys,” APL Mater., vol. 10, no. 12, Art. no. 120701, 2022. https://doi.org/10.1063/5.0127584

[72] H. Wu, J. Yu, Z. Jia, et al., “Progress of refractory high entropy alloys,” J. Aeronaut. Mater., vol. 44, no. 2, pp. 45–59, 2024. https://doi.org/10.11868/j.issn.1005-5053.2023.000178

[73] H. Song et al., “Refractory high entropy alloys: From fundamental research to engineering,” J. Mater. Res. Technol., vol. 32, pp. 3562–3585, 2024. https://doi.org/10.1016/j.jmrt.2024.08.180

[74] S. Lee, S. S. Sohn, et al., “Accelerating HEA design via machine learning: Yield strength prediction,” Materials, vol. 19, no. 1, Art. no. 196, 2026. https://doi.org/10.3390/ma19010196

[75] “Latest advancements in high-entropy alloys: Design, properties and applications,” Materials, vol. 18, no. 24, Art. no. 5616, 2025. https://doi.org/10.3390/ma18245616

[76] M. C. Gao, J.-W. Yeh, P. K. Liaw, and Y. Zhang, Eds., High-Entropy Alloys: Fundamentals and Applications. Cham, Switzerland: Springer, 2016. https://doi.org/10.1007/978-3-319-27013-5

[77] M. Vaidya, G. M. Muralikrishna, and B. S. Murty, “High-entropy alloys by mechanical alloying,” J. Mater. Res., vol. 34, no. 5, pp. 664–686, 2019. https://doi.org/10.1557/jmr.2019.37

[78] M. Dada, High Entropy Alloys for Aerospace Applications. London, U.K.: IntechOpen, 2019. https://doi.org/10.5772/intechopen.85821

[79] S. Zhu et al., “Accelerating CALPHAD-based phase diagram predictions using ML potentials,” arXiv preprint arXiv:2411.15351, 2024.

[80] S. Bordignon et al., “Alloys innovation through machine learning: A statistical review,” Sci. Technol. Adv. Mater.

Methods, vol. 4, Art. no. 2326305, 2024. https://doi.org/10.1080/27660400.2024.2326305

[81] Z. Guo, Z. Chen, Y. Zeng, et al., “Refractory high-entropy alloys by selective laser melting,” Acta Aeronaut. Astronaut. Sin., vol. 44, 2023. https://doi.org/10.7527/S1000-6893.2023.29518

[82] P. F. Rodrigues et al., “Design of additive manufactured shape memory alloy for aerospace,” in Proc. Euro PM2025, 2025.

[83] ASM International, ASM Handbook, Volume 2: Properties and Selection of Nonferrous Alloys. Materials Park, OH, USA: ASM International, 1990.

[84] ASM International, ASM Aerospace Specification Metals Database. Materials Park, OH, USA: ASM International, 2024.

[85] R. J. H. Wanhill, S. Barter, and L. Molent, Fatigue of Beta Processed Titanium Alloys. Cham, Switzerland: Springer, 2019. https://doi.org/10.1007/978-94-024-1285-0

[86] A. P. Mouritz, Introduction to Aerospace Materials. Cambridge, U.K.: Woodhead Publishing, 2012.

[87] M. J. Donachie and S. J. Donachie, Superalloys: A Technical Guide, 2nd ed. Materials Park, OH, USA: ASM International, 2002.

[88] R. R. Boyer, G. Welsch, and E. W. Collings, Eds., Materials Properties Handbook: Titanium Alloys. Materials Park, OH, USA: ASM International, 1994.