Development of High (Ultra-High) Strength Aluminum Alloys and Their Materials (Postprint)

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Abstract

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Full Text

Development of High-Strength and Ultra-High-Strength Aluminum Alloys and Their Materials

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I. International Development Trends of High-Strength Aluminum Alloys

1. History and Current Status of High-Strength Aluminum Alloys High-strength aluminum alloys generally refer to copper-containing 2xxx series and zinc-containing 7xxx series aluminum alloys, with the latter containing high zinc, magnesium, and copper also known as ultra-high-strength aluminum alloys. These materials have undergone five generations of development overall.

Materials define aviation, with each generation of materials enabling a new generation of aircraft and equipment. Aluminum alloy materials have met the design requirements of aircraft and weapon systems across different eras. Modern aluminum alloy materials are developing toward larger specifications, higher homogeneity, and superior comprehensive properties.

In 1906, German scholar A. Wilm discovered the precipitation hardening phenomenon in Al-Cu-Mg alloys, obtaining a crucial means of age strengthening for aluminum alloys and making their application in aviation possible, thus heralding the development of aviation aluminum alloys. Over the subsequent 100+ years, aluminum alloys became the primary structural material for aircraft, with each generation of materials driving a new generation of aircraft and powerfully advancing aviation development. To date, aluminum alloys widely used in the aviation industry mainly involve two series: Al-Cu (2xxx series) and Al-Zn-Mg-Cu (7xxx series). Other series such as Al-Mg-Si (6xxx series) and Al-Li alloys also have certain applications, but overall usage is relatively small and application scope limited. In aerospace applications, the above series are complemented by 3xxx, 5xxx, and 8xxx series aluminum alloys, while 5xxx series aluminum alloys are extensively used in railway transportation.

High-strength and ultra-high-strength aluminum alloys have continuously developed primarily against the backdrop of aviation demands. As aircraft design concepts have innovated, the manufacturing of advanced aircraft components has placed increasingly higher requirements on aluminum alloy materials, particularly the modern demands for lightweight, spacious, comfortable, long-life, high-reliability, and low-cost aircraft, which continuously drive the development of large-scale aluminum alloy materials with high comprehensive performance. Based on the development history of aluminum alloy materials, aviation aluminum alloys can be divided into five generations overall: the first generation of high static strength aluminum alloys, the second generation of high-strength corrosion-resistant aluminum alloys, the third generation of high-strength high-toughness aluminum alloys, the fourth generation of ultra-high-strength high-toughness corrosion-resistant and medium-strength damage-tolerant aluminum alloys, and the new generation of high-strength high-toughness high-quenchability aluminum alloys. The characteristic properties, microstructures, and typical representatives of each stage are shown in Table 1 .

From the early 20th century to the late 1950s, the discovery of precipitation hardening produced the first generation of high static strength aluminum alloys, meeting the initial aircraft design requirements aimed at improving safety factors, reducing structural weight, and increasing range. During this period, it was first discovered that in Al-Cu-Mg (2xxx series) alloys, quenched supersaturated solid solutions could age-precipitate high-density lath-shaped Al Cu (’ , Figure 1a [Figure 1: see original paper]) and Al CuMg (S’) strengthening phases with significant precipitation hardening effects. Based on this, naturally aged aviation aluminum alloys such as 2017, 2014, and 2024 were developed. Subsequently, in Al-Zn-Mg-Cu (7xxx series) alloys, spherical MgZn (’ , Figure 1b) age-precipitation strengthening phases with remarkable hardening effects were discovered through quenching-ageing heat treatment, leading to the development of 7075-T6 (artificial peak ageing) and 7178-T6 alloys. Alloys such as 2024-T3, 7075-T6, and 7178-T6 constituted the first generation of aviation high-strength and ultra-high-strength aluminum alloys, representing milestone achievements in aluminum alloy development and application.

In the 1960s, aircraft accidents caused by fatigue and corrosion failure prompted aircraft design to demand fatigue resistance and corrosion resistance from high-strength aluminum alloys. Researchers invented over-ageing heat treatment technology in 7xxx series aluminum alloys, making grain boundary precipitates discontinuously distributed, reducing alloy strength while improving stress corrosion resistance. This led to the development of 7075-T73 alloy materials, enabling 7xxx series alloys to meet not only static strength requirements but also corrosion resistance demands. To reduce the significant strength loss from T73 treatment, 7075-T76 alloy was subsequently developed. The 7075-T73 and 7075-T76 alloys became representatives of the second generation of high-strength corrosion-resistant aluminum alloys.

In the 1970s, aircraft safety design imposed fracture toughness requirements on aviation high-strength aluminum alloys. As research on the effects of Fe and Si impurities on aluminum alloy toughness deepened, the United States successfully developed low-impurity 7475 alloy in the early 1970s to reduce coarse primary phases and excess phases, achieving both high strength and excellent fracture toughness. In the mid-1970s, with deeper understanding of microalloying elements such as Cr, Mn, and Zr, Alcoa developed low-impurity 7050-T74 alloy microalloyed with Zr under the support of the U.S. Navy and Air Force, while Europe developed the comparable 7010-T74 alloy. Using coherent/semi-coherent Al Zr phases to replace incoherent Cr and Mn dispersoids improved recrystallization inhibition. These alloys exhibited high strength, stress corrosion resistance, and fracture toughness. The 2xxx series alloys also advanced from 2024 by reducing Fe and Si impurity content, improving alloy purity and metallurgical quality, leading to 2124, 2224, and 2324 alloys. Alloy purification and microalloying theories and technologies drove the development of the third generation of high-strength high-toughness aluminum alloys.

From the late 1970s to the late 1980s, the energy crisis prompted aircraft design toward aggressive weight reduction, while weapon systems demanded increased range and payload. The need for high specific strength and high specific modulus materials drove the development and application of aluminum-lithium alloys. Due to their low density and high specific modulus, Al-Li alloys attracted great interest from materials researchers. With advances in Al-Li alloy melting and casting technology, foreign countries intensified research on second-generation Al-Li alloys. The United States and Europe developed second-generation Al-Li-Cu alloys such as 2090, 2091, 8090, and 8091, while Russia developed lower-density Al-Li-Mg alloys including 1420 and 1421. The 1421 alloy could be welded and used, and both 1420 and 1421 found relatively widespread application in Russian military aircraft and spacecraft.

From the late 1980s to the late 1990s, damage tolerance design for aircraft imposed comprehensive requirements on crack propagation rate, fracture toughness, stress corrosion resistance, and fatigue resistance of aluminum alloys. Through optimization of main alloy compositions and precise heat treatment control technology, alloys could reduce the width of precipitation-free zones, achieve further microstructural refinement and homogenization, and increase crack propagation resistance, giving rise to the fourth generation of 2xxx and 7xxx series aluminum alloys with high comprehensive performance and high damage tolerance. Although Alcoa and Boeing developed the modified 7050 alloy 7150 in the late 1970s, it was not until the 1980s that Alcoa successfully developed the 7150-T77 three-stage ageing heat treatment technology, first achieving the goal of meeting required fracture toughness and corrosion resistance without sacrificing alloy strength, enabling widespread application of 7150 alloy. The successful development of 7150-T77 alloy represented an epoch-making advancement in aviation aluminum alloy research. Subsequently developed 7055-T77 aluminum alloy is currently the highest-strength aviation aluminum alloy in use. Alloys with comparable performance developed concurrently with Alcoa' s 7055 include Pechiney' s 7449 alloy. With advances in main alloy composition optimization and precise control technology, Alcoa successfully developed damage-tolerant 2524-T3 alloy through further reduction of Fe and Si impurities, addition of microalloying elements, adjustment of main alloy composition, and adoption of advanced heat treatment systems. The ultra-high-strength high-toughness 7055 alloy and high damage-tolerance 2524 alloy are typical representatives of the fourth generation of aviation aluminum alloys.

During the same period, with research on Al-Li-Cu alloys and development of microalloying technology, the United States and Russia conducted research on third-generation Al-Li alloys. Russia mainly developed 1460 alloy, while the United States developed the Weldalite series and 2097 and 2197 Al-Li alloys. The 2097-T861 alloy has been applied to the rear fuselage bulkhead and mid-fuselage longeron of F-16 aircraft. The 2198-T8x alloy possesses high strength, high damage tolerance, and high thermal stability, along with good formability and weldability, making it an excellent third-generation Al-Li alloy. Using this alloy can further reduce structural weight and save costs. The 2050-T851 plate up to 152mm thick not only outperforms 7050-T7451 but also has lower density, with improved strength, toughness, fatigue crack propagation resistance, and heat resistance, enabling 5% weight reduction when replacing 7050 alloy. High-strength aluminum alloys have developed into a flourishing landscape of diverse varieties.

In the early 21st century, advanced aircraft design requirements for technological advancement, economy, and comfort have demanded component integration and large-scale manufacturing, eliminating riveting and welding to achieve structural weight reduction and improved safety. This has created demand for developing large-scale/thick-section materials requiring aluminum alloys with ultra-high strength, high toughness, high quenchability, high damage tolerance, and high formability.

The high quenchability requirement for thick-section materials has driven the development of new-generation high-strength high-toughness alloys such as 7085, 7185, and 7285. Alloys developed concurrently with Alcoa' s 7085 include Pechiney' s 7140 alloy and Aleris' s 7081 alloy. Achieving high microstructural uniformity is a major challenge in designing and preparing high-quenchability materials.

To meet the requirements of large aircraft such as the A380 for improved strength and damage tolerance of 2x24 alloy materials, Alcoa and Pechiney successively developed 2026 and 2027 alloys with high strength and damage tolerance characteristics. Their extrusions (12-82mm thick) and plates (12-55mm thick) show 20-25% and 10% performance improvements over 2024 alloy, respectively.

To meet advanced welding (laser welding, friction stir welding) and creep age forming manufacturing requirements for fuselage skins and wing panels (skins) of large aircraft such as the A330/340/A380, Pechiney developed Al-Mg-Si series aluminum alloys including 6056/6156, 2022, and 2023, while Alcoa improved 7055 aluminum alloy (7055-HDT) to adapt to the high comprehensive performance requirements for strength, toughness, corrosion resistance, and damage tolerance needed for upper wing panel creep age forming. Currently, the world' s largest passenger aircraft A380 uses ultra-high-strength 7055 aluminum alloy for its integral upper wing panel, measuring 33m long, 2.8m wide at its maximum, with double-curvature aerodynamic requirements on the outer surface and thickness varying from 3mm to 28mm with complex internal stiffener structures. This structure greatly improves fuselage reliability, durability, damage tolerance, and load-bearing capacity, extending aircraft service life to 40-50 years. Nevertheless, both the United States and the European Union have established plans for further developing aluminum alloys with high service performance and formability, aiming to develop technologies for locally selective reinforcement of large integral frame-beam primary load-bearing structural components and creep age forming of integral panel components to achieve aircraft weight reduction and efficiency enhancement (such as Alcoa-Boeing' s "Aviation 20/20 Initiative" and the EU' s integral component manufacturing program).

Microalloying in aluminum alloys attracted great interest after the 1990s. With deepening research on the microalloying mechanisms of Zr and Sc in aluminum alloys, Russia and the United States developed a series of 5xxx (Al-Mg), 2xxx, and 7xxx series aluminum alloys containing Zr and Sc, which have been applied in fighter aircraft, carrier-based aircraft, and spacecraft.

Worth special mention is the continuous development of heat-resistant aluminum alloys for supersonic aircraft, particularly with the increasing high-speed/high-acceleration performance of military aircraft. Representative alloys include 2618 (Al-Cu-Mg-Fe-Ni series) and 2219 alloy developed by Alcoa in the late 1950s. The latter is also widely used in aerospace, primarily for fuel tanks and rocket forging rings. Both 2219 and 2519 are also used for various components, fasteners, and skins of supersonic aircraft. In the mid-1980s, 2219 evolved into 2519 alloy, which is widely used as armor for amphibious assault vehicles. The 2618 aluminum alloy remains in use in military aircraft and was extensively adopted by the European Concorde supersonic passenger aircraft, mainly for manufacturing heat-resistant skins and structural components to meet the aerodynamic heating environment requirements of Mach 2+ flight. However, with the Concorde' s exit from commercial service, major aviation manufacturing nations currently have no plans to develop new-generation supersonic passenger and transport aircraft, reducing civilian demand for Al-Cu-x series heat-resistant aluminum alloys, though supersonic military aircraft development will still maintain certain demand.

In the mid-1990s, the discovery of microalloying effects of Ag in 2xxx series aluminum alloys forming new atomic clusters or phases led to the successful development of prototype alloys C415 and C417. These alloys exhibit excellent plasticity and toughness while capable of long-term use at 200°C. High damage-tolerance 2139-T8xx plate containing 0.15-0.6% Ag and up to 152mm thick outperforms 2x24-T3xx products with good heat resistance, finding application in supersonic military aircraft. Recent research indicates that trace elements such as Si may partially replace expensive Ag while providing good heat resistance in Al-Cu series alloys, warranting special attention.

Current preparation of high-strength and ultra-high-strength aluminum alloys generally follows the process shown in Figure 2 [Figure 2: see original paper]. Every stage of this process affects the formation and evolution of multi-phase microstructures in aluminum alloys, ultimately determining material properties and their uniformity.

Composition design → Raw material extraction → Melting → Melt purification → Semi-continuous casting → Ingot homogenization → Thermoplastic processing (rolling, extrusion, forging) → Solution treatment → Transfer → Quenching (roller-bottom spray, continuous belt spray, vertical) → Pre-deformation (stretching, compression) → Ageing treatment (single-stage, double-stage overageing, multi-stage retrogression and re-ageing).

The characteristic microstructure of high-strength and ultra-high-strength aluminum alloys features: micron-scale crystalline phases formed during solidification, submicron or nano-scale dispersoids precipitated at high temperatures, and nano-scale metastable phases precipitated during ageing; the matrix structure includes solid solutions, substructures, grain boundaries, precipitation-free zones (PFZ), vacancies, and dislocations. Multi-scale second phases and complex matrix structures determine aluminum alloy properties (Figure 3 [Figure 3: see original paper]).

Coarse primary phases dominate alloy fracture. Micron-scale primary phases form first in the aluminum melt during solidification but cannot be eliminated during processing. Non-equilibrium crystalline phases form during non-equilibrium solidification when main alloying elements (Zn, Mg, Cu) cannot fully enter the aluminum matrix, existing as aluminides or eutectic phases in the solidified structure. After homogenization-deformation-solution heat treatment, these gradually dissolve into the aluminum matrix, with the remainder becoming residual crystalline phases. Fe and Si impurity elements in aluminum melts form insoluble primary phases and difficult-to-dissolve non-equilibrium crystalline phases, representing another important cause of reduced material toughness.

Dispersoids inhibit matrix recrystallization, thereby dominating matrix structure, texture, and grain boundaries, and synergistically affecting material toughness and stress corrosion resistance. Dispersoids are submicron or nano-scale aluminum compound second phases precipitated from aluminum melts containing transition or rare earth elements during semi-continuous casting and homogenization heat treatment.

Intragranular age-precipitated phases dominate alloy strengthening and toughening, while grain boundary age-precipitated phases dominate localized (stress) corrosion cracking. Nano-scale metastable age-precipitated phases form through precipitation after solution quenching and ageing treatment. With increasing ageing temperature and time, the morphology, structure, and composition of precipitated phases undergo complex changes. As the quantity of age-precipitated metastable phases increases, aluminum alloy strength increases, but corresponding enrichment of precipitated phases at grain boundaries makes grain boundary fracture the dominant fracture mechanism, reducing alloy fracture toughness and corrosion resistance (stress corrosion resistance). Regulating intragranular and grain boundary age-precipitation states can identify optimal balance points among strength, toughness, and stress corrosion resistance.

The plastic deformation temperature, degree, and speed during alloy processing determine microstructural characteristics of the matrix, playing an important role in subsequent solution and age heat treatment.

Reviewing the development history of high-strength and ultra-high-strength aluminum alloys reveals that aircraft and spacecraft structural design and high-performance aluminum alloy material development have mutually promoted each other, continuously improving equipment structural efficiency and aluminum alloy material properties.

2. Development Trends of High-Strength Aluminum Alloy Materials

The international research trend for aviation, aerospace, and transportation aluminum alloys focuses on developing large-scale materials with high comprehensive performance. The development of new high-strength aluminum alloys and performance improvement of existing materials both relate to innovative composition design, which must combine theoretical calculations with practical experience. The preparation of large-scale high-performance aluminum alloys faces challenges requiring development of series preparation technologies to achieve microstructural refinement, metastabilization, and performance homogenization. Key areas include large ingot high-purity melting and homogeneous casting technology, uniform flow processing technology for large-scale aluminum alloys, and fine regulation technology for microstructure and property homogeneity through heat treatment. Furthermore, to reduce or avoid property degradation during manufacturing, integration of material preparation and component manufacturing is important, requiring development of integrated forming/property preparation and processing technology.

(1) Development of New-Generation High-Performance Aluminum

Alloys

Innovative aluminum alloy composition design must combine phase diagram and first-principles calculations, moving beyond traditional "trial-and-error" alloy design methods. Starting from characteristic microstructures affecting strength, toughness, modulus, corrosion resistance, fatigue resistance, damage tolerance, and heat resistance, research should explore the effects of main alloying element content and ratios and microalloying elements. Integrating microstructural evolution simulation during casting and thermomechanical processing, forming finite element simulation, equipment improvement, and performance evaluation systems can establish principles and technologies for fine microstructural regulation during material preparation. Combining theoretical calculation, simulation, and limited experiments can greatly shorten development time and improve efficiency for new alloy grades and applications. Development should focus on high-performance 2xxx and 7xxx aluminum alloys, high-strength high-toughness high-modulus low-density Al-Li alloys, and laminated hybrid aluminum matrix composites.

(2) Homogeneous Preparation of Large-Scale High-Performance Aluminum Alloys

High-strength and ultra-high-strength aluminum alloys contain high alloying element content and large specifications, making macro/meso-scale heterogeneity in structure and performance increasingly significant. Non-uniform flow, temperature, and stress fields during solidification, processing, and heat treatment cause macro-scale composition segregation in large ingots, meso-scale heterogeneity from non-equilibrium crystalline phases and impurities, macro/meso-scale heterogeneity in deformation and recrystallization structures of thick-section materials, and macro/meso-scale heterogeneity in heat-treated microstructures and residual stresses. Research must investigate both material-intrinsic properties caused by alloy composition and multi-field distribution heterogeneity caused by processing environments to establish key preparation technologies for macro/meso-scale microstructural homogenization in melting, casting, plastic processing, and heat treatment.

1) High-Purity Melting and Homogeneous Casting of Highly Alloyed Large Ingots

Large-scale/thick-section high-performance aluminum materials require stable production of high-quality large ingots first. Due to high alloying degrees, wide crystallization ranges, severe oxidation and gas absorption, and susceptibility to gas inclusions and composition macro/micro-segregation, ultra-high-strength aluminum alloys for aviation applications are prone to cracking during casting with low yield rates. Melting and casting technology for thick flat ingots and large-diameter highly alloyed homogeneous ingots remains a focus of global aluminum processing.

High-purity cast billets require minimal impurity and hydrogen content. Current aviation materials require hydrogen content controlled at no more than

0.10 mL/100g Al, inclusions controlled at 0.02 mm^2/kg (PodFa), and maximum particle size not exceeding 3 m.

No hot or cold cracking and high yield rates are required. For 7xxx series aluminum alloy ingots 600mm thick and 800mm in diameter, yield rates must exceed 85%, average grain size across the entire thickness must not exceed 350 m, and macro-segregation must be less than 5%.

Therefore, in-depth research on large ingot solidification theory and processes is needed to predict microstructure, surface characteristics, stress-strain distribution, and deformation behavior. Advanced aluminum melt multi-stage purification and grain refinement casting technologies must be developed, such as bottom electromagnetic stirring, isothermal melting, electromagnetic-ultrasonic composite field casting, oil-gas mixed lubrication casting, micro-vibration casting, and short-mold casting.

2) Uniform Flow Plastic Processing of Large-Scale Billets

While possessing large equipment, corresponding plastic processing technologies for large-scale billets must be developed. For rolling mills with 600-850mm opening and over 4000mm width, extrusion presses of 12,500 tons and over 600mm diameter, and forging presses of 40,000-80,000 tons, the technology must not only ensure geometric dimensions, precision, and surface quality of plates, profiles, and forgings but also achieve deep, uniform plastic deformation to control and obtain desired microstructures. Therefore, systematic research is needed on strong strain plastic processing technologies such as forging-rolling, angular rolling, and asymmetric rolling for aluminum alloy thick plates; isothermal extrusion for profiles; and isothermal forging for die forgings.

Low through-thickness performance of aluminum alloy thick plates is a challenge requiring solutions in global aluminum processing. Developing asymmetric internal shear rolling is a worthwhile technical approach. The snake rolling technology developed by Koblenz, Germany, differs from flat rolling and traditional asymmetric rolling, enabling simultaneous uniform shear deformation in both surface and interior layers of thick plates, eliminating the different microstructures remaining in the mid-layer due to insufficient deformation penetration, and significantly improving through-thickness microstructural and property uniformity. Furthermore, the shear textures and texture components generated by snake rolling will cause a series of changes in plate strength, toughness, corrosion resistance, fatigue resistance, damage tolerance, and forming properties, making this technology’ s development particularly noteworthy.

3) Heat Treatment Regulation for Microstructure and Property Uniformity in Large-Scale Materials

Large-scale aluminum alloy heat treatment is characterized by: non-uniform precipitation of equilibrium phases at grain boundaries and phase boundaries during solution treatment, severely reducing quenchability and material properties and creating performance “short-board” effects; non-uniform distribution of quenching internal stresses, with quench depth and residual stress control having opposite cooling rate requirements; non-uniform heating between surface and core; and difficulty in multi-stage ageing regulation.

Thick-section aluminum materials still exhibit non-uniform residual stress distribution even after pre-stretching. Wide thin plates often have poor flatness and large residual stresses after quenching. Large extruded profiles experience shape distortion and non-uniform properties after quenching. Ultra-long hollow profiles show non-uniform properties between top and bottom after vertical quenching. Therefore, in-depth research is needed on technologies for controlling quench depth, residual stress, and plate shape, including roller-bottom solution quenching-pre-stretching for thick plates, horizontal continuous quenching for hollow profiles, pre-compression for forgings, and roller leveling for thin sheets.

Although Alcoa’s T77 retrogression and re-ageing technology has achieved great success in regulating strength, toughness, and corrosion resistance of aluminum alloys, its narrow ageing temperature change window cannot solve the problem of macro/meso-scale microstructural and property heterogeneity caused by faster surface heating/cooling than the center and non-uniform second phases in thick-section materials during multi-stage ageing. Therefore, integrated thick-plate age heat treatment technology utilizing multiple factors including temperature, time, and external fields to produce integral effects must be developed.

(3) Integrated Forming/Property Preparation and Processing of High-Performance Aluminum Alloy Materials/Components

Using large-scale aluminum alloy materials to manufacture integral components achieves weight reduction, greatly improved material utilization, and clear integration trends between material and component manufacturing technologies. However, the manufacturing process for large integral components is extremely complex and can easily cause material property degradation, requiring development of specialized integrated forming/property preparation technologies.

First, aluminum alloy materials with high service performance and formability must be developed. Based on this, integral component manufacturing technologies such as local selective reinforcement of frame-beam primary load-bearing structural components, creep age forming of integral panel components, superplastic forming and solid-state diffusion bonding, laser welding, and friction stir welding must be advanced.

II. Domestic Development Status of High-Strength Aluminum Alloy Materials

China’ s high-strength and ultra-high-strength aluminum alloy R&D has been primarily driven by domestic aerospace engineering needs and propelled by foreign technology development, roughly experiencing five development stages with gradually narrowing gaps with international levels. A research community combining institutes, universities, and enterprises has been formed, covering aircraft design, aerospace equipment design, material design and preparation, component design and manufacturing, and application research. China possesses a certain foundation of talent reserves for high-strength aluminum alloy research. In recent years, to promote transformation of scientific achievements, various departments, enterprises, research institutes, and universities have actively explored collaborative innovation mechanisms, such as the "Chinalco Joint Laboratory," the Ministry of Education' s "High-Performance Aluminum Engineering Research Base," and the "National Aluminum Alloy Collaborative Innovation Platform."

China' s high-strength aluminum alloy materials developed and produced in different eras have supported the development and batch production of various fighter aircraft, missiles, satellites, and spacecraft, accumulating rich production technology and process experience that has made significant contributions to national security. With the launch of major projects such as large aircraft and manned spaceflight, through foreign technology introduction, digestion, absorption, and domestic manufacturing, a series of internationally advanced equipment and processing bases for high-strength aluminum alloy production have been essentially established.

However, China' s overall foundation for aluminum alloy R&D is relatively weak. Before the large aircraft program launch, aluminum alloy research essentially followed a reactive, piecemeal approach. China has very few aluminum alloy grades and extremely limited specifications. Aluminum alloys required for large aircraft design have basically not undergone airworthiness certification; batch production quality is unstable, lacking domestic aviation standards; and large-scale thick-section products exhibit large performance non-uniformity. Production enterprises lack research capabilities for aerospace and transportation aluminum alloys, with weak professional technical personnel and equipment conditions, and lack long-term R&D planning.

Currently, constrained by lagging development of melt purification technology, multi-stage age heat treatment equipment for thick-section material uniformity control, and related technologies, the development and production of aluminum alloys for major national projects such as large aircraft have been affected. Aluminum alloy purity cannot meet requirements, resulting in low fracture toughness and fatigue performance—for example, 2524-T3 alloy properties are difficult to meet design requirements. Due to three-stage ageing equipment just entering engineering construction, large-scale 7055-T7751 and 7150-T7751 plates cannot yet be produced. China' s Al-Li alloy research lags considerably, lacking Al-Li alloy grade design technology and equipment/technology for producing large-scale profiles and plates.

From the perspective of continuous R&D capability, China urgently needs to construct a high-performance aluminum engineering research base (platform), establish a market economy-dominated research and production system, reduce or eliminate planning orientation and arrangement by a few government officials, strengthen strategic research on airworthiness certification and intellectual property protection for civil aircraft materials aligned with international standards, and establish a global market operation mechanism with multi-department consultation and reporting. Long-term planning for next-generation high-strength aluminum alloy and key preparation technology innovation in basic and applied research is needed.

1. Research Status of High-Strength Aluminum Alloy Materials

China' s high-strength aluminum alloy material research is briefly introduced below from the perspectives of basic research, applied basic research, research teams, and talent reserves.

(1) Current Status of Basic and Applied Basic Research

The national "973" Program basic research closely integrates with national demand backgrounds, investigating fundamental issues of high-strength and high-strength corrosion-resistant aluminum alloys. The aviation aluminum "973" Program studies high-strength high-quenchability, ultra-high-strength high-toughness high-corrosion-resistant, medium/high-strength high-corrosion-resistant damage-tolerant, and high specific strength/high specific modulus aluminum alloys. China' s aluminum alloy research primarily focuses on large aircraft projects and third/fourth generation military model engineering, basically reaching the level of Europe and the United States in the late 1980s, marked by the application of third-generation high-purity aluminum alloys in the J-11B fighter. China' s high-strength aluminum alloy research development history and current status are shown in Table 2 .

The main funding sources for China' s high-strength aluminum alloy basic research are Natural Science Foundation projects, Aluminum 973 Program projects, and General Armament Department pre-research fund projects. Applied basic research is mainly funded through the 863 Program and model supporting projects from the State Administration of Science, Technology and Industry for National Defense.

In the past decade, almost no Natural Science Foundation projects involving innovative aluminum alloy composition design have been approved. This indicates both a lack of initiative among Chinese applicants and project management departments for source innovation in aluminum alloys, and acknowledges the objective fact that aviation aluminum alloy development from composition innovation to application requires massive financial and human resources investment, typically over ten years, which is difficult to achieve through individual efforts relying solely on Natural Science Foundation applicants.

The Aluminum 973 Program personnel and units constitute an important force in China' s aluminum alloy basic research. The first phase (1999-2004, Basic Research on Improving Aluminum Quality) focused on fundamental issues of formability and strength-toughness regulation for China' s first and second generation aluminum materials. The second phase (2005-2010, Basic Research on High-Performance Aluminum Materials and Efficient Aluminum Resource Utilization) focused on fundamental issues of purification, external field ingot casting, and thermomechanical processing to improve service performance for third-generation aluminum materials. The third phase (2012-2016, Basic Research on Aviation High-Performance Aluminum Alloys) focused on fundamental issues of composition, microstructure design, and homogeneous preparation for new-generation high-performance large-scale aluminum alloys for large aircraft, optimizing and innovating compositions for three important aviation aluminum alloys needed for aircraft primary structures, developing new-generation high-performance aluminum alloys, and solving principle and technical challenges in homogeneous preparation of large-scale aluminum materials to meet China' s aviation industry development needs.

Nevertheless, significant gaps remain between China' s aviation aluminum alloy basic and applied basic research support conditions and operation mechanisms compared with foreign countries. After breakthroughs in key new alloy technologies, European and American countries can conduct application research and engineering research using advanced equipment based on material maturity, often managing to apply new alloys to corresponding aircraft. Their "alloy development-engineering research and application-formal production application" system is very complete and effective. While China has basically secured equipment conditions for aluminum alloy melting, casting, extrusion, rolling, and forging, and has launched engineering and application research for third and fourth generation aluminum alloys, it lacks applied basic research and efficient operation mechanisms for application research.

(2) Research Teams and Talent Reserves

Under national industry-university-research-application policies and through collaborative model supporting projects and Aluminum 973 Program implementation, a research community combining universities, research institutes, and enterprises has been formed, covering aircraft design, material design and preparation, component design and manufacturing, and application performance research. The main characteristic research groups include:

Central South University possesses an aluminum alloy research team of over 200 people, with long-term accumulation in aluminum alloy phase diagram calculation and design, rapid composition-performance scanning testing, texture simulation and control, material preparation technology and equipment development, and engineering application, forming comprehensive advantages in high-performance aluminum alloy material and application research.

Shanghai Jiao Tong University has formed an academic team researching new principles and methods for aluminum alloy purification including electromagnetic purification, pulsating degassing, spray degassing, and ceramic plate filtration, proposing microstructure refinement methods using strong electric pulse melt treatment.

Northeastern University has formed a research team on electromagnetic casting of ultra-high-strength aluminum alloys, dedicated to developing principles and methods for large-scale electromagnetic ingot preparation.

Beihang University' s research team has long-term accumulation in aluminum alloy microalloying, age strengthening, and corrosion experimental research.

Beijing University of Technology has formed a research team in aluminum alloy microalloying design and material preparation with good working accumulation.

Beijing General Research Institute for Nonferrous Metals has formed a technical team on ultra-high-strength aluminum alloy strengthening/toughening and ingot spray deposition, dedicated to independent R&D of high-quenchability high-strength high-toughness aluminum alloys.

Institute of Metal Research, Chinese Academy of Sciences, has advantages and professional talent in high-resolution electron microscopy analysis of aluminum alloy microstructures, fatigue damage, and fracture research.

AVIC Beijing Institute of Aeronautical Materials has formed a team for aviation aluminum alloy service performance testing, analysis, and evaluation, with outstanding advantages in damage-tolerant aluminum alloy research.

Aircraft design institutes including Shenyang Aircraft Corporation, Xi' an Aircraft Corporation, Chengdu Aircraft Corporation, and COMAC have formed China' s professional teams for aviation aluminum alloy application. Aerospace First Academy, Second Academy, and 061 Base each have distinctive aluminum alloy application research characteristics.

Chinalco subsidiaries including Northeast Light Alloy, Southwest Aluminum (Group), Northwest Aluminum (Group), and Nannan Aluminum Processing are China' s production bases for high-strength aluminum materials, forming R&D bases and teams for China' s high-performance aluminum material production technology.

The high-strength aluminum alloy research team includes academicians, Thousand Talents Program recruits, Chang Jiang Scholars, National Science Fund for Distinguished Young Scholars, and national-level candidates in the New Century Talents Project, forming a multi-generational team dominated by young and middle-aged experts and researchers. China's high-strength aluminum alloy research talent reserve has a relatively broad foundation.

Overall, the above universities, research institutes, and enterprises have formed China' s discipline group for high-strength aluminum alloy material R&D, possessing state key laboratories in nonferrous metals (State Key Laboratory of Nonferrous Metal Materials Processing, State Key Laboratory of Powder Metallurgy, State Key Laboratory of High-Performance Complex Manufacturing), national defense key laboratories (National Defense Science and Technology Key Laboratory of Light-Weight High-Strength Structural Materials), national engineering research centers (National Engineering Research Center for Light Alloy Precision Forming, National Engineering Research Center for Powder Metallurgy), national enterprise technology centers, and the national 2011 Aluminum Alloy Collaborative Innovation Platform, equipped with internationally advanced experimental instruments.

To promote transformation of scientific achievements, aerospace departments, aluminum production enterprises, research institutes, and universities have established the national 2011 Program industry-university-research-application collaborative innovation mechanism. Chinalco and Central South University jointly established the “Chinalco Joint Laboratory,” with Chinalco investing 100 million RMB to build the joint laboratory and conduct R&D at Central South University, focusing on basic theory and forward-looking, strategic key technology research, co-building major technology R&D and transfer platforms to directly address major national and enterprise needs and economic and social demands, forming a technology transfer model transitioning from single technology, single project, and single research group studies to holistic, long-term, strategic cooperative research.

With support from the Ministry of Education, Ministry of Finance, and Hunan Provincial Government, Central South University, together with Chinalco, Beijing General Research Institute for Nonferrous Metals, Beijing Institute of Aeronautical Materials, Beijing Aeronautical Manufacturing Technology Research Institute, COMAC, Shenyang Aircraft Corporation, Xi’ an Aircraft Corporation, and relevant universities for aviation aluminum alloy research, has constructed a high-performance aluminum engineering research base from alloy design and material preparation to component manufacturing. The base includes series software for phase diagram calculation, material thermodynamic calculation, and forming simulation, a 10 trillion operations computing platform, a 20-ton advanced melting and casting trial production line, plastic deformation trial production lines including 4000-ton isothermal die forging, 800-ton/2500-ton multi-function extrusion, and 1550mm wide rolling mills, heat treatment trial production lines including roller-bottom solution-quenching and precision ageing, and high-performance aluminum component forming trial production lines including vacuum tank age forming, multi-energy field stir welding, high-speed milling, and chemical milling.

2. Industrial Production Status, Capacity, and Technical Reserves

China’ s industrial production technology for high-strength aluminum alloys developed alongside the growth of China’ s aerospace industry, based on imitation of Soviet and American materials. Aluminum alloy materials developed and produced in different eras have supported various weapon systems’ development and batch production, making important contributions to national defense security. Considerable production technology and process accumulation exists for aviation aluminum alloys. With the launch of major aviation projects such as large aircraft, through foreign technology introduction, digestion, absorption, and domestic manufacturing, a series of internationally advanced equipment has been essentially established.

Through basic research, applied basic research, and various model supporting material development and production, China has accumulated technical reserves for high-strength aluminum alloy preparation, possessing over 300 patents for high-performance aluminum alloy materials.

(1) Industrial Production Status and Capacity

Over the decades, China has made great progress in aluminum alloy research and development, forming batch production capacity for first, second, and third-generation aluminum alloys, developing series alloy materials such as LC4, LC9, LY12, 2A12, 2A16, 7A04, 7B04, 7A50, and 7B50, with series heat treatment states. Taking the third-generation fighter J-11B as an example, the aluminum alloys used are mostly third-generation high-purity high-corrosion-resistant materials that have been fully localized, forming supply capacity for batch fighter production. This first realization of domestic high-purity aluminum alloy batch application in a model has improved the overall level of domestic aviation aluminum alloy production and application, accelerated upgrading of domestic aviation aluminum alloys, and enriched advanced material systems for fighters.

The development and production of high-performance large-scale third-generation, fourth-generation, and new-generation high-quenchability aluminum alloys for large aircraft projects are centered on Northeast Light, Southwest Aluminum, Northwest Aluminum, and Nannan Aluminum, with typical large-scale 7050 aluminum alloy ingots reaching 800mm in diameter for round ingots and 600mm thickness for flat ingots; typical ultra-thick 7050-T7451 aluminum alloy pre-stretched plates exceeding 150mm thickness; 2219 aluminum alloy round ingots reaching 1320mm; and typical 7085 alloy free forgings reaching 300mm thickness. However, these materials exhibit large performance non-uniformity, high residual stresses, and large batch-to-batch performance fluctuations requiring continued research.

In terms of equipment, China has essentially established a series of internationally advanced equipment for large-scale high-performance aluminum alloy production for aerospace engineering. To address insufficient capacity for aviation aluminum alloy thick plate and large integral die forging production equipment, through foreign introduction, digestion, absorption, and domestic manufacturing, hot rolling mills of 4300mm, 3950mm, and 4100mm width with 800mm, 600mm, and 850mm opening have been built at Northeast Light, Southwest Aluminum, and Nannan Aluminum; 6000-ton, 12000-ton, and 10000-ton pre-stretching machines; an 80,000-ton forging press at Erzhong; Southwest Aluminum possesses 12,500-ton extrusion and 40,000-ton forging presses; Northwest Aluminum has established a 4500-ton reverse extrusion press; and Nannan Aluminum has built a 40-meter roller-bottom quenching furnace and 38-meter three-stage ageing furnace, essentially forming an internationally advanced equipment series for large-scale high-performance aluminum alloy production. Additionally, many departments and local governments have accelerated investment in high-strength aluminum alloy production, creating a flourishing situation in thick plate production that requires vigilance against potential future disorderly competition.

(2) Technical Reserves

Through basic research, applied basic research, and various model supporting material development and production for aerospace and transportation aluminum alloys, China has accumulated technical reserves for high-strength aluminum alloy preparation, with over 300 patents for high-performance aluminum alloy materials, mainly in:

1) Characteristic microstructure design and regulation technology for high-performance aluminum alloys. Through characteristic microstructure design for different service performance requirements, exploring multi-phase multi-stage strengthening/toughening and interface synergistic effects, several prototype high-performance aluminum alloys with high strength-toughness-corrosion resistance, high strength-toughness-fatigue resistance, and high strength-toughness-heat resistance have been independently designed and developed.
2) High-efficiency purification principles and technology for aluminum and aluminum alloys. Research on non-metallic inclusion composition in aluminum melts has revealed the formation, precipitation, and growth patterns of Fe and Si intermetallic compounds with temperature. Metal impurities in primary aluminum melts have been reduced by half, removal rates of non-metallic inclusions above 10 m exceed 80%, and hydrogen content can be controlled at 0.10 mL/100g Al. New high-efficiency online purification and filtration technologies have been established to meet ultra-high-strength corrosion-resistant fatigue-resistant aluminum alloy melt quality requirements, laying a necessary foundation for developing high-performance aluminum alloys characterized by high purity.
3) Multi-external field regulation casting technology for high-performance aluminum alloys using electromagnetic, ultrasonic, and vibration fields, solving large ingot cracking problems and establishing necessary foundations for regulating solidification microstructure uniformity.
4) Multi-stage homogenization and solution heat treatment technology for high-performance aluminum alloys, enabling uniform dispersoid distribution and reduced recrystallization fraction, laying foundations for regulating meso-scale microstructural uniformity and improving toughness and corrosion resistance.
5) Spray quenching-pre-stretching residual stress reduction technology for medium-thick plates, laying foundations for reducing residual stresses in high-uniformity large-scale materials to improve toughness, corrosion resistance, and finished product processing rates.
6) Precipitation formation, evolution, and strengthening/toughening regulation technology for high-strength aluminum alloys, developing various urgently needed high-strength aluminum alloy materials. Innovative ageing

heat treatment principles and technologies including strong strain and retrogression ageing and high-temperature pre-ageing have been developed, establishing relationships among alloy composition, impurity elements, processing parameters, and properties to meet urgent needs for high-performance aluminum alloys in “Project 11,” nuclear industry, remote sensing satellites, and Shenzhou spacecraft.

3. Bottleneck Problems in High-Strength Aluminum Alloy Development and Production Overall, China’ s high-strength aluminum alloy development has essentially followed a path of tracking and imitating foreign materials. Constrained by R&D and production equipment conditions, until the late 1990s, China’ s high-strength aluminum alloy development level lagged foreign countries by at least 10 years, while production capacity and level lagged by at least 25 years. In the first decade of the 21st century, with enhanced comprehensive national strength and increased S&T investment, China’ s advanced aluminum alloy development gap with foreign countries has rapidly narrowed. With the launch of major projects such as large aircraft, production equipment levels are rapidly improving. Currently, the urgent problem is that the comprehensive performance and uniformity of high-performance aluminum alloys for large aircraft cannot meet design requirements. Bottleneck problems in development and production include:

1) Intellectual property issues when producing foreign new-grade alloys such as 7055, 7085, and 2524 aluminum alloys.
2) Overall melt purification technology and equipment have not yet reached international advanced levels. Melting is the first step in preparing high-performance aluminum alloys, with melt quality exerting strong metallurgical hereditary effects. China’ s large aircraft project selects mainstream third and fourth-generation high-purity aviation aluminum alloys developed in the 1990s, representing today’ s highest production level with extremely high purification index requirements. Although supporting work for advanced aviation aluminum alloys has started, gas content, inclusion content, and inclusion size in highly alloyed aluminum melts remain higher and larger than foreign products, with poor stability, becoming a bottleneck constraining stable production of high-performance aluminum alloys.
3) Lack of multi-stage age precision heat treatment equipment and related technology for regulating microstructure and property uniformity of thick-section ultra-high-strength high-toughness corrosion-resistant aluminum alloys. Ageing is the final process in aluminum alloy preparation, regulating second-phase precipitation behavior that affects strength, toughness, corrosion resistance, fatigue resistance, and even quenchability. International large aircraft use ultra-high-strength high-toughness corrosion-resistant aluminum alloys as the first choice for upper wing main panels, with large material specifications and high strength requirements (e.g.,

A380 upper wing main panel: 33m long, 2.8m wide, 615 MPa tensile ultimate strength, the highest strength index for cast metallurgy wrought aluminum alloys). Large-scale ultra-high-strength high-toughness corrosion-resistant aluminum thick plates require T77 three-stage age heat treatment. Alcoa is currently the only company worldwide with T77 heat treatment industrial production equipment, supplying all international large aircraft manufacturers' 7xxx series T77 state high-end products. To break free from dependence on key materials, China must solve the bottleneck of multi-stage age precision control heat treatment production equipment and related technology.

4) Lack of systematic material preparation technology and process research, poor product quality stability, and inability to meet airworthiness certification requirements. In recent years, digestion and absorption of newly introduced production equipment have not been fully completed, related process technologies have not yet formed systematic frameworks, and some large key production equipment requires 1-2 years for completion. Meanwhile, insufficient early investment preparation for airworthiness certification has prevented establishment of complete applicable management and intellectual property strategic systems. Aligning China's large aircraft aluminum alloy material system with international standards requires solving bottlenecks of unsystematic preparation technology research, poor product quality stability, and inability to meet airworthiness certification requirements.

5) Serious lack of engineering research severely hinders continuous innovation capability for new-generation high-strength aluminum alloys and preparation technologies. A major cause of the gap between China and foreign countries is the lack of engineering research, failing to form a complete innovation chain integrating "high-performance aluminum experimental development-key preparation technology R&D-engineering research." Many new alloys have been developed but few have been applied, with low material maturity, poor quality and performance stability, and no independent material system or systematic process technology and specifications, seriously affecting China' s economic development and national defense construction. Breaking through engineering technology is an urgent priority for developing China' s high-strength aluminum alloy industry.

III. Recommendations for High-Strength Aluminum Alloy Material Development

The focus of international aviation industry competition is ensuring high reliability, lightweight, and long life of aircraft; military equipment also requires lightweight and high reliability. Currently, China's main problems are that comprehensive performance and uniformity of large-scale materials cannot meet design requirements, and new-generation aluminum alloy development lags. Therefore, China’ s aluminum alloy development should first follow material development laws, combine with national strategic demand objectives, and determine development directions. While tracking and imitating, we must dare to surpass; adhere to close industry-university-research-application integration; address bottleneck problems in development and production; and quickly establish a market-dominated research platform. The bureaucratic system of government-led S&T project approval and reward systems and platform construction should be reformed.

1. Develop New High-Strength Aluminum Alloys and High-Performance Homogeneous Preparation Technology Based on China’ s aluminum alloy R&D reality and international development trends, China’ s strategic goals should involve two aspects: first, preparing urgently needed high-performance large-scale homogeneous materials for major projects; second, developing new-generation aluminum alloys for future aircraft, high-speed rail, and equipment (such as high-strength high-toughness high-quenchability, ultra-high-strength high-toughness corrosion-resistant, and high damage-tolerant aluminum alloys for aircraft primary structures).

To achieve these strategic goals, macro/meso-scale microstructural property homogeneous composition design and large-scale material homogeneous preparation technology, as well as material/component forming/property integrated preparation technology, must be developed. Specific aspects include:

1) Integrated design principles and technology for aluminum alloy materials. Moving beyond traditional “trial-and-error” composition design, starting from characteristic microstructures affecting properties, integrating phase diagram and first-principles calculations, microstructural evolution simulation during casting and thermomechanical processing, forming finite element simulation, equipment design and virtual manufacturing, and performance evaluation systems. Through theoretical calculation, simulation, and limited experiments, new compositions and preparation technologies for extreme service environments can be developed, greatly strengthening the scientific basis for aluminum alloy R&D and accelerating new alloy development and application. Focus on developing high-performance 2xxx and 7xxx aluminum alloys, high-strength high-toughness high-modulus low-density Al-Li alloys, and laminated hybrid aluminum matrix composites.

2) Aluminum alloy high-purity technology. Reducing Fe, Si and other impurity content, improving alloy purity and melt cleanliness to enhance fracture toughness, fatigue performance, and corrosion resistance. Fe and Si impurity reduction amounts should be determined based on service performance requirements. Multi-stage degassing and inclusion removal. Current aviation materials require hydrogen content below 0.10 mL/100g Al, inclusions controlled at 0.02 mm^2/kg (PodFa), with maximum particle size not exceeding 3 m.

3) Large-scale high-performance aluminum alloy homogeneous preparation technology. Using large rolling mills over 4m wide, extrusion presses over 10,000 tons, and forging presses over 30,000 tons, employing strong strain plastic deformation, isothermal extrusion, and isothermal forging to produce thick-section large-scale plates, large complex extrusions, and forgings to meet component manufacturing needs.

4) Aluminum alloy microstructure and property homogeneous heat treatment technology. First, through multi-stage homogenization to reduce or eliminate non-equilibrium crystalline phases, homogenize composition, and enable fine, uniform, coherent dispersoid precipitation. Through multi-stage solution treatment to control recrystallization fraction, forming fibrous structures with substructures. Multi-stage quenching enhances surface heat transfer, improving uniform cooling efficiency between surface and core to increase quench depth. For thick-section materials with different surface and core heating/cooling rates, multi-stage ageing (including integral ageing) regulates microstructure and property uniformity by utilizing time-temperature-precipitation relationships. Therefore, in-depth research is needed on quench depth and residual stress coordinated control technologies including roller-bottom solution quenching-pre-stretching for thick plates, continuous quenching for hollow profiles, pre-compression for forgings, and stretch leveling for thin sheets.

5) Material/component forming/property integrated preparation technology. Using large-scale aluminum alloy materials to manufacture integral components achieves weight reduction and improved reliability with greatly increased material cost-effectiveness. However, manufacturing large-scale high-performance aluminum alloy complex components is extremely complex and can easily compromise material properties. Therefore, advanced integral component plastic processing and joining technologies such as precision die forging, isothermal extrusion, laser welding, and friction stir welding must be developed, along with new integrated material/component manufacturing technologies such as local selective reinforcement of large integral frame-beam primary load-bearing structures, creep age forming of integral panels, and superplastic forming and diffusion bonding of complex components.

2. Countermeasures and Measures for Developing Large-Scale High-Strength Aluminum Alloy Materials (1) Quickly Break Through Melt High-Purification and Multi-Stage Age Precision Heat Treatment Technologies for Industrial Aluminum Alloy Preparation

Addressing technical bottlenecks in large aircraft and other major project aluminum alloy development and production: overall melt purification indexes have not yet met design requirements; multi-stage age precision heat treatment equipment and production technology for regulating microstructure and property uniformity of thick-section ultra-high-strength high-toughness corrosion-resistant aluminum alloys is missing; and residual stress detection, analysis, and reduction methods and technologies fall far from aviation engineering requirements. However, several domestic universities, research institutes, and enterprises have certain preliminary research foundations. Therefore, based on existing basic research, process research, and equipment conditions, market support and promotion should be quickly provided.

(2) Accelerate Development of New-Generation High-Strength Aluminum Alloys

Under urgent demand for structural weight reduction and energy conservation in China’ s aerospace and transportation industries, unprecedented challenges are posed to aluminum alloy materials science and engineering. The theories required to create new-generation high-performance aluminum alloys have surpassed current understanding of materials science in some aspects, representing both a challenge and innovation target for Chinese aluminum alloy researchers. China has shown good momentum and research results in new-generation high-strength aluminum alloy research, and should quickly combine with production enterprises and application departments for collaborative innovation in material development, preparation, and application.

(3) Establish a Market-Dominated Aluminum Alloy R&D Model to Promote and Accelerate High-Performance Aluminum Alloy Industrial Technology Development

China’ s previous aluminum alloy research was always demand-driven with temporary task assignments, lacking overall strategic deployment and planning, and without establishing an innovation system according to market economy operation, resulting in capable people and units being unable to obtain projects. Considering domestic and foreign aluminum alloy development experience and based on aluminum alloy development laws and China’ s major project needs, a market-dominated aluminum alloy R&D model should be quickly established, introducing competition mechanisms to support those who produce results first, continuously stimulating innovation capability building in China’ s aluminum alloy research.

(4) Research Intellectual Property Breakthrough and Protection Strategies in Airworthiness Certification to Align Civil Aviation Aluminum Alloy Material Systems with International Standards

Research qualification application and certification for civil aircraft material qualified suppliers during airworthiness certification, organize aviation aluminum alloy development and production enterprises to conduct equipment and product certification investigations, accumulate corresponding data and information as required, and enable Chinese products to quickly enter world markets.

3. Development Roadmap Recommendations for High-Strength Aluminum Alloy Materials

1) Continue engineering and industrialization research on aerospace advanced aluminum alloys under development, strengthen mechanism research on existing equipment process technologies, ensure product quality uniformity and stability can meet national major project equipment and component development and future batch production market demands, especially meeting C919 aircraft airworthiness certification requirements.

2) Emphasize forward-looking and basic research layout for new-generation aluminum alloys, deeply analyze and grasp international aviation aluminum alloy development concepts and intellectual property situations, clarify objectives, and concentrate resources to seize commanding heights for future development.

3) Attach great importance to airworthiness certification and intellectual property protection strategy research for civil aviation aluminum alloys, determine military and civilian material confidentiality strategies, and gradually establish a Chinese aluminum alloy material system considering both military and civilian needs.

4) The aviation aluminum alloy industry features high technical thresholds, high comprehensive integration, and capital intensity, while global market space is very limited. Relevant policies should be formulated to utilize market regulation and incentive mechanisms to support advantageous enterprises and research units, avoid unnecessary project support, and use aviation aluminum alloy preparation technology as a platform to upgrade and develop China' s aluminum processing industry.

In summary, recommended development routes for China' s high-strength aluminum alloy materials are shown in Figure 4 [Figure 4: see original paper] for reference.

(Development route recommendation diagram, see next page)

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.