Development of High-Strength Aluminum Alloys and Their Fabrication and Processing Technologies (Postprint)

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Abstract

This paper briefly reviews the theoretical foundations for the development of high-strength aluminum alloys and their material preparation and processing technologies both domestically and internationally. It introduces and discusses the research hotspots and developments in related technologies for various processes of large-scale high-performance aluminum alloy materials, including composition design, melting, homogenization, solution treatment, quenching, pre-stretching, and aging. Furthermore, it proposes recommendations for the development and application of such aluminum alloys in China.

Full Text

Preamble

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Development of High Strength Aluminum Alloys and Processing Techniques for the Materials

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ABSTRACT: The fundamental theories for the development of high strength aluminum alloys and processing techniques for the materials are briefly reviewed in this paper. It specifically focuses on alloying design, casting, homogenization, solution treatment, quenching, pre-stretching and ageing that have been extensively studied recently. Based on these discussions, some perspectives and suggestions have been proposed, which will benefit the development and applications of high strength aluminum alloys.

KEY WORDS: high strength aluminum alloy, aluminum structural material, aluminum alloying design, aluminum processing

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1 Development History of High-Strength Aluminum Alloys

High-strength aluminum alloys generally refer to the copper-containing 2××× series and zinc-containing 7××× series aluminum alloys. The latter are further classified into medium-strength 7××× alloys (such as 7020, 7011, 7051, etc.) and high-strength 7××× alloys (such as 7050, 7010, 7075, etc.) [1,2]. To date, aluminum alloys widely used in the aviation industry mainly involve the 2××× series (Al-Cu) and 7××× series (Al-Zn-Mg-Cu). Other series, such as Al-Mg-Si (6××× series) and Al-Li alloys [3,4], also find some applications, but their overall usage is relatively small. In the aerospace field, in addition to the above series, 3×××, 5×××, and 8××× series aluminum alloys are also included, while 5××× series aluminum alloys are extensively used in railway, highway, and water transportation.

High-strength aluminum alloys have been continuously developed primarily driven by aviation demands. The century-long history of aluminum materials parallels that of aviation, with aluminum alloys meeting the evolving requirements of aircraft and cutting-edge equipment across different eras. As aircraft design concepts continue to innovate, the manufacturing of advanced aircraft components has placed increasingly higher demands on aluminum alloys, particularly driven by modern aircraft development needs for lightweight design, spaciousness, comfort, long service life, high reliability, and low cost [5]. Based on the composition-processing-microstructure-performance characteristics of aluminum alloys, the development history of aviation aluminum alloys can be broadly divided into five stages: first-generation high static strength alloys, second-generation high-strength corrosion-resistant alloys, third-generation high-strength, high-toughness, and corrosion-resistant alloys, fourth-generation high-strength, high-toughness, corrosion-resistant, and high damage-tolerant alloys, and the new generation of high-strength, high-toughness, low quench-sensitive alloys. The performance characteristics, key technologies, microstructural features, and typical alloys for each stage are summarized in Table 1 .

From the early 20th century to the late 1950s, the first generation of high static strength aluminum alloys emerged following the discovery of precipitation hardening effects and the development of peak ageing technology. In 1906, Wilm [6] first discovered the precipitation hardening phenomenon in Al-Cu alloys. Al-Cu-Mg alloys, after quenching, form supersaturated solid solutions that precipitate high-density Al_2Cu ( ) and Al_2CuMg (S) phases during subsequent aging, leading to substantial hardness improvements and heralding the development of high-strength aluminum alloys. In 1923, Sander and Meissner [7] further discovered that Al-Zn-Mg alloys, through quenching and artificial aging heat treatment, form $MgZn_2$ (phase) as the main strengthening phase, which is smaller and more dispersedly distributed than the   and S phases in Al-Cu-Mg alloys, resulting in more significant precipitation hardening effects. Figure 1 [Figure 1: see original paper] shows a schematic diagram of the structural evolution of the classic   (Al_2Cu) phase [2]. Research [2] indicates that in the initial stage of aging, GP zones are only one or two atomic layers thick, but their density can reach 10^{17}-10^{18} cm^{-3}, providing high strength to the alloy.

Subsequently, high-strength aluminum alloys such as 7075-T6 and 7178-T6 were developed through artificial peak aging. The 2024-T3, 7075-T6, and 7178-T6 alloys met the initial aircraft design requirements for improved safety factors, reduced structural weight, and increased range, replacing wood-based static strength designs. These are generally regarded as typical representatives of the first-generation high-strength aluminum alloys [2]. The Aluminum Association, established in 1935, established the aluminum alloy designation registration system in 1954, with 2024 and 7075 among the earliest registered alloys still in use today [8], widely applied in aerospace, weapons, and high-end equipment manufacturing.

Notably, due to the development of supersonic aircraft, especially the continuous improvement of high-speed/high-acceleration performance in military aircraft, heat-resistant aluminum alloys have also been continuously developed. Representative alloys include 2618 (Al-Cu-Mg-Fe-Ni series) and 2219 developed by Alcoa in the late 1950s. The latter has been extensively used in aerospace, primarily for fuel tanks and rocket forging rings [9]. The 2618 alloy is still used in military aircraft today and was widely adopted by the European Concorde supersonic airliner, mainly for manufacturing aircraft skins and heat-resistant structural components to meet the aerodynamic heating requirements during Concorde’ s high-speed flight above Mach 2 (>2450 km/h). However, with the Concorde’ s withdrawal from commercial service, major aviation manufacturing nations have no immediate plans to develop new-generation supersonic passenger or transport aircraft, reducing civilian demand for Al-Cu-X series heat-resistant aluminum alloys, though military supersonic aircraft development still maintains some demand.

In the 1960s, based on the over-aging principle, T73 and T76 aging heat treatment technologies that caused discontinuous precipitation of grain boundary phases promoted the development of second-generation corrosion-resistant high-strength aluminum alloys. Aircraft crashes caused by fatigue and stress corrosion failures prompted aircraft designers to demand fatigue and corrosion resistance from high-strength aluminum alloys. The contradiction between high strength and poor stress corrosion resistance was particularly prominent in 7××× series alloys, which have higher strength levels than 2××× series. The key to improving stress corrosion resistance was the invention of over-aging heat treatment technology for 7××× series alloys, which made grain boundary precipitates discontinuously distributed, improving corrosion resistance at the expense of strength. The T73 condition enabled 7××× series alloys to meet not only static strength requirements but also corrosion resistance requirements for aircraft design. To reduce the significant strength loss from T73 treatment, the T76 heat treatment process was subsequently developed [10], better balancing the high strength and corrosion resistance of 7××× series alloys. The 7075-T73/T76 alloys became typical representatives of second-generation high-strength corrosion-resistant aluminum alloys.

In the 1970s, alloy purification and micro-alloying theories and technologies drove the development of third-generation high-strength, high-toughness aluminum alloys. Aircraft safe-life design imposed requirements for fracture toughness in aviation aluminum alloys. With deepening research on how Fe and Si impurities affect aluminum alloy toughness, the United States successfully developed the low-impurity 7475 alloy in the late 1960s. Compared with 7075 alloy, the main alloy compositions of Zn, Mg, and Cu differ only slightly, with the primary difference being significantly reduced Fe, Si, and other impurity contents, decreasing the number and size of coarse primary phases and excess phases, thereby providing both high strength and excellent fracture toughness [10]. In the early 1970s, with further research on the mechanisms of micro-alloying elements such as Cr, Mn, and Zr, Alcoa developed the low-impurity, Zr-microalloyed 7010 alloy [10] with support from the U.S. Navy and Air Force. These high-strength aluminum alloys basically adopted over-aging heat treatment technologies (such as T74 and T76), exhibiting high strength, high stress corrosion resistance, and fracture toughness. Notably, the quench sensitivity of 7050 aluminum alloy is lower than that of 7075, and when 7050-T74 plate thickness is increased to 150 mm, its strength can still reach approximately 500 MPa, demonstrating lower quench sensitivity than 7075-T74.

The classic 2024 aluminum alloy has also been improved by reducing Fe and Si impurity contents and increasing alloy purity and metallurgical quality, leading to a series of improved grades such as 2124, 2224, and 2324 [8]. Alloy purification and micro-alloying theories and technologies have driven the development of third-generation high-strength, high-toughness aluminum alloys.

In the mid-1980s, by adjusting the total Fe and Si impurity content and Fe/Si ratio, the 2219 alloy was developed into the 2519 alloy. Both 2219 and 2519 alloys have been used to manufacture various components, fasteners, and skins for supersonic aircraft, with 2519 alloy also widely used as armor for amphibious assault vehicles [11]. From the late 1970s to the late 1980s, the energy crisis drove aircraft design toward significant weight reduction, demanding increased range and payload for weapons and equipment. The need for high specific strength and high specific modulus materials promoted the research and application of Al-Li alloys [12]. Al-Li alloys have attracted great interest from materials researchers due to their low density and high specific modulus. With the development of Al-Li alloy melting and casting technologies, foreign countries developed Al-Li alloys for engineering applications. European and American countries developed Al-Li-Cu series alloys such as 2090, 2091, 8090, and 8091 [13–15], while Russia developed lower-density Al-Li-Mg series alloys such as 1420 and 1421 [16]. The 1420 and 1421 alloys have been widely applied in Russian military aircraft and spacecraft [17].

From the late 1980s to the late 1990s, the development of high-alloying composition and optimized design, along with precise microstructure control technology, drove the research and development of fourth-generation high-strength, high-toughness, corrosion-resistant, and high damage-tolerant aluminum alloy materials. The development of new-generation large aircraft imposed higher safety requirements, with damage tolerance design featuring "fail-safe" structural requirements that specify clear requirements for residual strength after structural damage and crack propagation life from initial to critical cracks. Consequently, higher comprehensive requirements were placed on fatigue crack growth rate, fracture toughness, and stress corrosion resistance of aluminum alloy materials. The primary challenge in developing new aluminum alloy materials was the contradiction between strength and fracture toughness, corrosion resistance, and fatigue crack growth rate. Although Alcoa, in collaboration with Boeing, developed the 7050-modified alloy 7150 in the late 1970s, it was not until the 1980s that Alcoa successfully developed the three-step aging precision heat treatment technology for 7150-T77 material, achieving for the first time the goal of meeting fracture toughness, corrosion resistance, and fatigue performance requirements without sacrificing alloy strength. Therefore, 7150-T77 material has been widely applied [3,18]. The subsequently developed 7055-T77 alloy has a strength about 30–50 MPa higher than 7150-T77, with comparable toughness and corrosion resistance, making it the highest-strength aviation aluminum alloy currently in use [19]. Concurrently developed with similar performance to Alcoa' s 7055 alloy is the 7449 aluminum alloy from Pechiney [20].

To meet the high damage tolerance requirements for aircraft skins, Alcoa successfully developed the high damage-tolerant 2524-T3 material through further reduction of Fe and Si impurity contents, addition of micro-alloying elements, optimization of main alloy compositions, and adoption of advanced heat treatment systems [21]. The ultra-high strength, high-toughness, corrosion-resistant 7055-T77 alloy and the high damage-tolerant 2524-T39 alloy have been successfully applied to the upper wing panels and fuselage skins of the B777, 被视为第四代航空铝合金材料的典型代表.

Micro-alloying of aluminum alloys attracted great interest after the 1990s, with micro-alloying elements expanding beyond Cr, Mn, Ti, and Zr to other elements (Sc, Er, Ag, etc.) [22-30]. In the mid-1990s, the discovery of the mechanism and effects of Ag micro-alloying in 2××× series aluminum alloys, which forms new atomic clusters or phases, led to the successful development of prototype alloys C415 and C417 [22,23]. These Ag-containing alloys exhibit good plasticity, toughness, and heat resistance, capable of long-term use at 200 °C. The high damage-tolerant 2139-T8× plate containing 0.15%–0.6% (mass fraction) Ag, with thickness up to 152 mm, demonstrates superior performance to 2$×24 − *T*3×$ and has been applied in supersonic military aircraft [29,30].

With deepening research on the micro-alloying mechanisms of Zr and Sc in aluminum alloys, Russia and the United States have developed a series of Zr- and Sc-containing 2×××, 7×××, and 5××× series aluminum alloys [31], which have been widely applied in fighter aircraft, carrier-based aircraft, and spacecraft.

During the same period, with research on Al-Li-Cu series alloys and micro-alloying technology development, the United States and Russia launched a new round of Al-Li alloy research. Russia mainly developed the 1460 alloy, while the United States primarily developed the Weldlite series alloys and Al-Li alloys such as 2097, 2197, and 2195 [32,33]. The 2097-T861 alloy has been applied to the rear fuselage bulkhead and mid-fuselage longeron of F-16 aircraft [21]. The 2198-T8× alloy features high strength, high damage tolerance, and high thermal stability, with good forming and welding properties [34]. In the early 21st century, new-generation Al-Li alloys such as 2098, 2198, 2099, and 2199 were developed.

Since the beginning of the 21st century, under the strong demand for large-size high-performance aluminum alloy materials and driven by in-depth research on the mechanisms of composition and multi-phase microstructure effects on properties, as well as multi-physical field control methods during material preparation, new-generation high-strength, high-toughness, low quench-sensitive aluminum alloys have emerged and developed.

The advanced, economical, and comfortable design of aircraft, along with pressure on airlines regarding environmental protection and operating cost reduction, have made aircraft weight reduction and fuel efficiency improvement urgent issues for the aviation industry. In addition to reducing alloy density, component design optimization is also an effective method for aircraft weight reduction and efficiency improvement. Integrated and large-scale component design can eliminate numerous traditional riveted joints, achieving both structural weight reduction and improved reliability. Integrated component manufacturing places higher demands on aluminum alloy material specifications/section thickness, comprehensive properties, and uniformity [4].

The primary challenge in preparing large-size, thick-section, uniformly performing aluminum alloy materials is that the quench sensitivity of high-strength aluminum alloys increases with strength. Using 7050 alloy' s composition-strength-quench sensitivity as a reference, by reducing Cu and Mg contents and increasing Zn content, developing advanced spray quenching and other controllable rapid cooling technologies, and establishing thermodynamic parameters and precipitation kinetics of the phase, new-generation low quench-sensitive aluminum alloys such as 7040, 7085, 7140, and 7081 have been developed [35-37]. As shown in Figure 2 [Figure 2: see original paper][36-38], the quench sensitivity of 7085 aluminum alloy is significantly lower than that of previously used high-strength 7075 and 7050 alloys [3-5,35]. Concurrently developed with similar performance to Alcoa' s 7085 alloy are Pechiney' s 7140 alloy and Aleris' s 7081 alloy.

Based on improving the damage tolerance of 2524 alloy materials and addressing its relatively low strength, Alcoa and Pechiney successively developed 2026 and 2027 alloys with high-strength and high damage-tolerant characteristics through optimized design of Cu and Mg main compositions and reduced Fe, Si, and Ti impurity contents. Their extrusions (12–82 mm thick) and plates (12–55 mm thick) show performance improvements of 20%–25% and 10%, respectively, compared to 2024 alloy.

To meet the advanced welding (such as laser welding and friction stir welding) and creep age forming manufacturing requirements for large aircraft fuselage skins and wing panels (skins), Pechiney developed Al-Mg-Si series alloys 6056/6156, 2022, and 2023 [39].

With continuous improvement in composite material properties, their application in aerospace structures has expanded from secondary load-bearing components to primary load-bearing components. The latest aircraft such as the B787 and A350 extensively use composite materials, posing unprecedented competitive pressure on aviation aluminum alloy development. Reducing the density of high-strength aluminum alloys and improving specific strength and specific modulus have once again become important directions for aluminum alloy research and development. At the beginning of this century, Alcoa-Boeing proposed the "Aviation 20/20 Initiative," and the European Union correspondingly launched the airframe integrated manufacturing program. These R&D programs propose integrating aluminum alloy composition design, material preparation, and large component manufacturing processes to carry out integrated material/structure innovation research and development, aiming to reduce existing aircraft structure weight by 20% and improve efficiency by 20%. Consequently, high-strength aluminum alloys have shown a flourishing development scenario. Recently developed low-Li-content Al-Cu-Li alloys 2050 and 2060 reflect the development trend of new-generation high-strength aluminum alloys toward reduced density. The 2050-T851 plate with thickness up to 152 mm not only outperforms 7050-T7451 but also has lower density, with improved strength, toughness, fatigue crack growth resistance, and heat resistance, achieving 5% weight reduction when replacing 7050 alloy [40].

Reviewing the development history of high-strength aluminum alloys reveals that aircraft and spacecraft structural design and high-strength aluminum alloy development have mutually promoted each other, enhancing both the fundamental and applied research levels of high-strength aluminum alloys while improving equipment structural efficiency, service life, and reliability.

2 Research Hotspots and Development Trends in High-Strength Aluminum Alloy Materials

"One generation of materials, one generation of equipment" —modern aluminum alloy materials are developing toward high comprehensive performance, low density, large specifications, high uniformity, and material/structure integration, providing support for high-performance manufacturing in aerospace, transportation, and high-end equipment. Large-size, high-performance aluminum alloy materials are fundamental for lightweight development in modern aviation, aerospace, and transportation, as well as a focus of research in high-strength aluminum alloy materials science and engineering.

As mentioned above, the research and development of new high-strength aluminum alloys and performance improvement of existing materials are related to innovative alloy compositions. However, once the composition is determined, obtaining high comprehensive performance characteristic microstructures requires complex preparation processes, during which metallurgical hereditary effects are significant. Each preparation stage affects microstructure formation and evolution, ultimately determining material comprehensive performance and uniformity.

Important characteristic microstructures of high-strength aluminum alloy materials can be summarized as: micron-sized crystalline phases formed during solidification, submicron or nano-scale dispersoids precipitated at high temperatures, and nano-scale metastable phases precipitated during aging, all dispersedly distributed in the Al matrix. The matrix microstructure can be summarized as: solid solution, grains, subgrains, grain/subgrain boundaries, cellular structures, textures, precipitation-free zones, vacancies, and dislocations. Multi-scale second phases and complex matrix structures determine aluminum alloy performance [41,42], as shown in Figure 3 [Figure 3: see original paper][42]. Notably, in addition to second phases and grain structures, macro/micro textures in aluminum alloy materials are also a focus of researchers [43–46].

Coarse primary phases dominate alloy fracture. Micron-sized primary phases (0.5–10 m) first form in the Al melt during solidification but cannot be eliminated during processing. Non-equilibrium crystalline phases form during non-equilibrium solidification, where main alloying elements (Zn, Mg, and Cu) fail to completely dissolve into the aluminum matrix solid solution and exist in the solidification structure as aluminides or eutectic phases [47,48]. Non-equilibrium crystalline phases can gradually dissolve into the Al matrix during homogenization, deformation, and solution treatment, with the remainder becoming residual crystalline phases. Fe and Si impurity elements in the Al melt can form various insoluble primary phases and difficult-to-dissolve non-equilibrium crystalline phases with Al and other alloying elements. Their phase boundaries easily form vacancies, voids, and cracks, reducing material plasticity, toughness, and fatigue resistance. However, appropriate Fe and Si contents and ratios can also improve material toughness and fatigue limits.

Dispersoids inhibit matrix recrystallization and thus dominate matrix microstructure, including grain/subgrain boundaries, producing synergistic effects on material toughness and stress corrosion resistance [49–53]. Dispersoids are submicron or nano-scale aluminide second phases (10–200 nm) formed by trace transition or rare earth elements that first dissolve in the Al matrix during ingot casting and then precipitate during homogenization heat treatment. As shown in Figure 4 [Figure 4: see original paper][50], introducing Zr, Cr, and Yb multi-element micro-alloying (individually or in combination) into Al-Zn-Mg-Cu alloys forms coherent or incoherent high-melting-point aluminides. These high-melting-point aluminides not only effectively pin grain boundaries and form curved subgrain boundaries but also improve alloy quench sensitivity. Therefore, such phases can dominate material toughness, corrosion resistance, and fatigue performance.

Intragranular aging precipitates (approximately 10 nm) dominate alloy strengthening and toughening, while grain boundary aging precipitates dominate localized (stress) corrosion cracking. Nano-scale metastable aging precipitates are second phases formed through precipitation after solution treatment and quenching. As aging temperature increases and time extends, the morphology, structure, and composition of precipitates undergo complex changes. As the number of aging precipitates increases, aluminum alloy strength improves, but corresponding enrichment of precipitates along grain boundaries into chain-like structures makes grain boundary fracture the dominant fracture mechanism, reducing alloy fracture toughness and corrosion resistance (stress corrosion resistance). Regulating intragranular and grain boundary aging precipitation states can identify optimal points among strength, toughness, and stress corrosion resistance [54–59].

The deformation temperature, degree, and speed of plastic processing for aluminum alloy materials determine matrix microstructure characteristics, texture, deformation stored energy, and specific process parameters for solid solution heat treatment. During hot processing, to achieve uniform plastic deformation of the alloy, dynamic recrystallization must generally be prevented, and recrystallization should also be avoided during solution treatment. Research has found that for high-strength 7××× aluminum alloys, methods such as stepwise heating solution treatment [46,59] and thermo-mechanical processing can both inhibit recrystallization and promote dissolution of the S phase (Al_2CuMg), thereby improving alloy strength, toughness, and corrosion resistance, as shown in Figure 5 [Figure 5: see original paper][60], while reducing quench sensitivity.

Large-size, high-performance aluminum alloy material preparation faces challenges requiring the development of series preparation technologies to achieve microstructure refinement, homogenization, metastabilization, and high comprehensive performance. In recent years, key preparation technologies have focused on high-purity melting and homogeneous casting of large ingots, uniform strong flow deformation processing of large-size materials, and fine regulation of homogeneous microstructure through heat treatment. Additionally, to reduce or avoid performance and material loss during manufacturing, integrated material/component forming/property development technologies that merge material preparation with component manufacturing have become an important development trend.

2.1 Design of High-Performance Aluminum Alloy Compositions and Microstructure Patterns

With the promotion of material calculation software such as phase diagrams and first-principles (e.g., Thermo-Calc, NAMD, Materials Studio), combined with advances in modern microstructure and property testing technologies, research on the effects of main alloying element contents and ratios, as well as micro-alloying elements, has become more convenient. Under theoretical calculation guidance, innovative design of aluminum alloy main compositions and micro-alloying compositions will eliminate traditional "trial-and-error" alloy design methods. Continuous improvement of aluminum alloy microstructure-property theories and characterization methods [44,61], development of new principles and characterization methods linking characteristic microstructures with comprehensive performance [62,63], and exploration of characteristic microstructure patterns for high strength, high toughness, high modulus, high corrosion resistance, high fatigue resistance, high damage tolerance, and high heat resistance have become research directions. Combining simulation of microstructure and internal stress evolution during casting, plastic processing, and heat treatment [64-66], forming finite element simulation and equipment adaptation [67-69], and performance evaluation systems has effectively promoted new principles and technologies for multi-scale microstructure fine regulation. In summary, combining theoretical calculation, simulation, and experimentation can significantly shorten the time and improve efficiency for new alloy development, performance improvement, and application.

The development of high-alloying 7××× series aluminum alloy materials explores the synergistic effects and mechanisms of composition and precipitates on strength, toughness, and hardenability while leveraging the high-strength characteristics of this series [70-75]. As shown in Figure 6 [Figure 6: see original paper][70], adjusting the Mg content in Al-8Zn-xMg-1.6Cu alloy (1#—1.0%, 2#—1.4%, 3#—2.0%) can regulate alloy hardness and quench sensitivity.

Adjusting the content and types of trace elements Cr, Mn, Ti, and Zr, Sc in high-strength 7××× aluminum alloys can effectively improve grain structure, toughness, stress corrosion resistance, and quench sensitivity. For example, alloys with Zr as the trace additive (such as 7050, 7055, 7085) have better stress corrosion resistance than alloys with Cr and Mn as trace additives (such as 7075, 7049) [71-73]. More importantly, Zr-containing high-strength aluminum alloys have lower quench sensitivity, enabling widespread application in large load-bearing components. Research [74-77] shows that Cr- and Mn-containing dispersoid particle interfaces are incoherent with the matrix, allowing equilibrium phases to preferentially precipitate at these particle interfaces during quenching.

In contrast, Zr-containing dispersoids (Al_3Zr) have interfaces coherent with the matrix, significantly reducing the possibility of equilibrium phase precipitation at Zr-containing dispersoid interfaces during quenching. Some studies [77] also indicate that some Al_3Zr dispersoids can induce equilibrium phase precipitation during quenching. This occurs because during recrystallization, grain boundary migration causes coherent-incoherent transitions in Al_3Zr dispersoids, as shown in Figure 7 [Figure 7: see original paper][77]. Incoherent Al_3Zr dispersoid interfaces induce quench precipitate formation, making the alloy quench-sensitive. Therefore, quench sensitivity control can be transformed into control of dispersoid types or recrystallization fraction.

In summary, to obtain uniformly distributed microstructures, technologies such as strong strain processing, graded solution and quenching, multi-stage aging, and integral aging heat treatment should be employed [78–81] to improve intrinsic properties such as toughness, corrosion resistance, and fatigue resistance, as well as processability such as hardenability, deep drawability, and weldability.

The development of 2××× series high-strength aluminum alloy materials, based on existing strength, toughness, and fatigue properties, requires continuous revelation of the effects and mechanisms of alloy composition and precipitate types on strength and toughness. As shown in Figure 8 [Figure 8: see original paper][82], when the Cu/Mg ratio reaches 4.9, both S phase and ω phase can precipitate simultaneously, which is beneficial for improving toughness. On the other hand, reducing and optimizing impurity contents, controlling plastic deformation and recrystallization, and developing new thermo-mechanical processing technologies can enhance the strength, toughness, and damage tolerance of these alloy materials [83–92].

After optimizing the composition of 2519 alloy, which possesses high strength, toughness, corrosion resistance, and weldability, the 2519A alloy was obtained [93–99]. Using thermo-mechanical processing and interrupted secondary aging technologies, second phases were refined and the distribution density of aging precipitates was increased, substantially improving mechanical properties and ballistic performance, as shown in Figure 9 [Figure 9: see original paper][100].

The development of Al-Li alloy materials, based on evaluating density-specific modulus-specific strength-anisotropy, further optimizes Li and Cu contents while developing vacuum melting and controlled rolling plastic deformation technologies for high-purity, large-size materials [34] to improve toughness, corrosion resistance, damage tolerance, superplastic forming performance, and reduce material anisotropy. In addition to using Li for density reduction, Al-Mg-Sc alloys have also been studied, but their low strength has limited their application as aviation materials.

2.2 Homogeneous Preparation of Large-Size/Thick-Section Aluminum Alloy Materials

The short-board effect of microstructural non-uniformity is the difficulty and key point in designing and preparing large-size/thick-section materials. High-strength aluminum alloy materials with large dimensions and high alloy element contents often exhibit significant macro/meso-scale non-uniformity in microstructure and properties. Non-uniform effects of flow field, temperature field, and stress field during solidification, processing, and heat treatment often cause macro-scale composition non-uniformity in large ingots and meso-scale non-uniformity of non-equilibrium crystalline phases and impurity phases; macro/meso-scale non-uniformity of deformation and recrystallization microstructures in thick-section materials; and macro/meso-scale non-uniformity of heat-treated microstructures and residual stresses. To investigate the effects and mechanisms of both material intrinsic characteristics caused by alloy composition and microstructure, and multi-field distribution non-uniformity caused by processing environments, key preparation technologies for macro/meso-scale microstructure homogenization, including melting and casting, plastic processing, and heat treatment, have been developed in recent years.

2.2.1 High-Purity Melting and Homogeneous Casting of High-Alloying Large Ingots Large-size/thick-section high-performance aluminum materials first require stable production of high-quality large ingots. Due to high alloying degrees, wide crystallization ranges, severe oxidation and gas absorption, and susceptibility to gas and inclusions, ultra-high-strength aluminum alloys for aviation applications have difficulty controlling macro/micro-scale composition distribution uniformity and are prone to cracking during casting, resulting in low yield. The melting and casting technology for wide thick-section, large flat ingots, and large-diameter homogeneous crack-free ingots has always been a hot issue that the global aluminum processing industry seeks to address.

High-purity ingots require minimal impurity and hydrogen contents—the higher the cleanliness, the better. Aviation materials have corresponding standards for gas and impurity contents, requiring no hot or cold cracking and high yield. Different width-to-thickness ratios and diameters of 7××× and 2××× series aluminum alloy large ingots have their own yield requirements depending on specifications at various processing plants.

Therefore, relatively in-depth research has been conducted on large ingot solidification theory and processes, such as melt solidification laws, ingot microstructures, surface characteristics, stress-strain distribution, and deformation patterns. Various advanced Al melt high-purification, grain refinement, and surface brightening melting and casting technologies have been developed, such as bottom electromagnetic stirring, multi-stage gas-slag combined removal, variable temperature melting and casting, electromagnetic-ultrasonic composite external field casting, oil-gas mixed lubrication casting, micro-vibration casting, and short mold casting technologies.

2.2.2 Uniform Flow Plastic Processing of Large-Size Ingots China has successively built large equipment for processing large-size materials and continuously developed plastic processing technologies for large-size alloy materials. For rolling mills with 600–850 mm opening and over 4000 mm width, 10000–12000 t pre-stretching machines, 12500 t extrusion presses, and 40000–80000 t forging presses, it is necessary not only to ensure geometric dimensional accuracy and surface quality of plates, profiles, and forgings but also to achieve deep and uniform plastic deformation, control dynamic recovery and dynamic recrystallization, and obtain expected microstructures and properties. Therefore, combining production, education, research, and application, research has been conducted on plastic processing technologies such as forging-rolling, angular rolling, and asymmetric rolling for aluminum alloy ultra-thick and medium-thick plates, isothermal extrusion of profiles, and isothermal forging of die forgings for different alloys and product specifications.

Low through-thickness performance of aluminum alloy thick plates has long been a difficult problem that the international aluminum processing community seeks to solve. Asymmetric internal shear rolling is a worthwhile technical approach [101–103]. The snake rolling technology developed by the Koblenz aluminum processing plant in Germany differs from flat rolling and traditional asymmetric rolling, enabling simultaneous shear deformation in both surface and interior layers of thick plates, eliminating the microstructure in the mid-layer of thick plates that cannot be penetrated by deformation, and substantially improving through-thickness microstructure and property uniformity. Additionally, the shear microstructure and texture state produced by snake rolling will cause a series of changes in plate strength, toughness, corrosion resistance, fatigue resistance, damage tolerance, and forming performance [104], with this technology currently under development.

2.2.3 Heat Treatment for Microstructure and Property Uniformity of Large-Size/Thick-Section Materials Heat treatment of these aluminum alloy materials mainly includes homogenization, solution quenching, and aging. Homogenization treatment requires not only dissolving non-equilibrium crystalline phases with large through-thickness differences but also regulating uniform precipitation of high-melting-point dispersoids of micro-alloying elements such as Cr, Mn, Ti, and Zr to obtain optimal recrystallization-controlled microstructures. Solution treatment requires dissolving precipitated solute atoms at high temperatures and eliminating excess phases or second phases generated during processing. Therefore, stepwise (multi-stage) homogenization and solution technologies have been developed [105–107]. Research [107] has found that the cooling rate after homogenization treatment of 7××× series aluminum alloy ingots not only affects deformation behavior and recrystallization fraction after solution treatment, as shown in Figure 10 [Figure 10: see original paper][107], but ultimately affects final strength and elongation.

During quenching, non-uniform precipitation of equilibrium phases at grain boundaries and phase boundaries in the center layer of thick plates leads to insufficient strengthening phases during aging, causing overall component performance degradation and creating a short-board effect. Quenching residual stresses are large and non-uniformly distributed, and even pre-stretching cannot eliminate residual stress and its non-uniform distribution [108-110]. Wide thin plates often have poor flatness and warping after quenching, large extruded profiles experience twisting deformation and non-uniform properties after quenching, and long hollow profiles have non-uniform vertical quenching performance. Therefore, research on medium-thick plate roller hearth solution quenching-pre-stretching, thin plate air cushion furnace solution-quenching, hollow profile horizontal continuous quenching, forging pre-compression, thin plate roller straightening for shape control and residual stress reduction has become a hotspot for high-end aluminum material preparation [69,106,109-125].

Aging is the key process determining final properties, and a series of aging technologies have been developed to improve material comprehensive performance. Alcoa developed the T77 retrogression and re-aging (RRA) technology, with its temperature-time relationship schematic shown in Figure 11 [Figure 11: see original paper]. This technology has achieved great success in regulating aluminum alloy strength, toughness, and corrosion resistance. As shown in Figure 12 [Figure 12: see original paper][126], through RRA treatment, toughness and corrosion resistance can be improved while strength can even exceed that of T6 temper materials. However, this technology has a narrow aging temperature window, making it difficult to solve the problem of macro/meso-scale microstructure and property non-uniformity in thick-section materials during multi-stage aging. Therefore, various medium-thick plate aging heat treatment technologies that integrate cumulative effects of temperature, time, external fields, and other factors have been developed, such as integral aging, high-temperature pre-precipitation, and multiple aging treatments [66,81,127]. As shown in Figure 13 [Figure 13: see original paper][127], the common feature of these aging methods is achieving discontinuous grain boundary phase precipitation and high-density intragranular phase precipitation in large-size materials, reducing precipitation-free zone width to ensure high comprehensive performance and uniformity.

2.3 Integrated Forming/Property Development for Materials/Components

Using large-size aluminum alloy materials to manufacture integrated components can achieve weight reduction and efficiency improvement, with significantly increased material utilization and a clear trend of integrating material and component manufacturing technologies. The manufacturing process for large integrated components is very complex and prone to large material consumption and performance loss during manufacturing. Therefore, integrated material/component forming/property development technologies have been developed, such as local selective enhancement of frame and beam primary load-bearing structural components, integrated panel component creep age forming [128,129], superplastic forming and solid-state diffusion bonding [130-132], laser welding [133,134], and friction stir welding [135,136] for large-size component manufacturing.

Currently, the world’ s largest passenger aircraft A380 uses ultra-high-strength 7055 aluminum alloy thick plates for its integrated upper wing panel (Figure 14 [Figure 14: see original paper][137]). The panel is first milled to create stiffeners in a flat state, then formed into final shape using creep age forming technology, measuring 33 m in length, 2.8 m at its widest point, with thickness varying from 3-28 mm and 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 [137].

However, modern aircraft extensively use 2××× series aluminum alloy panels and skins with aerodynamic curvature requirements, yet no reports on creep age forming technology application have been seen. One important reason is that 2××× series alloys exhibit so-called precipitate stress orientation effects during creep age forming [138,139], as shown in Figure 15 [Figure 15: see original paper][139]. In Al-4Cu alloy under stress aging, Al_2Cu (phase) does not precipitate in directions parallel to the effective compressive stress but precipitates extensively in perpendicular directions. The precipitate stress orientation effect causes material performance degradation, restricting the application of creep age forming in high-performance 2××× series aluminum alloy components.

3 Overview of High-Strength Aluminum Alloy Development and Application in China

The development of China’ s high-strength aluminum alloys has been primarily driven by domestic aerospace engineering needs and promoted by foreign high-strength aluminum alloy technology development. Over more than 60 years of development, China has roughly experienced five stages, gradually narrowing the gap with international levels. As shown in Table 2 , domestically developed and produced aluminum alloy materials have supported the development and batch production of various types of fighter aircraft, missiles, satellites, and spacecraft across different eras, accumulating rich production technology and processes for high-strength aluminum alloy materials and contributing to national security. With the launch of major projects such as large aircraft, manned spaceflight, lunar landing, and high-speed rail, China has basically established internationally advanced high-strength aluminum alloy material production equipment and processing bases through technology introduction, absorption, and domestic manufacturing integration.

However, China’ s overall foundation for aluminum alloy research and development remains relatively weak. China has developed very few aluminum alloy designations independently, with extremely limited specifications [140]. The quality of aluminum alloy material products needed for large aircraft design awaits stabilization, requiring gradual airworthiness certification and establishment of proprietary aviation material systems.

Over the decades, China’ s aluminum alloy material research and development have made significant progress, forming domestic first-generation, second-generation, and third-generation aluminum alloy materials and batch production capabilities. Series aluminum alloys such as LC4, LC9, LY12, 2A12, 2A16, 7A04, 7B04, 7A50, and 7B50 have been developed, along with their compositions and series heat treatment tempers [140]. Taking a certain fighter aircraft model as an example, the aluminum alloys used are mostly third-generation high-strength, high-toughness, corrosion-resistant aluminum alloy materials, all independently developed domestically, forming the supply capacity needed for batch fighter production. This marks the first batch application of domestic high-purity aluminum alloys in aircraft models, improving the overall level of domestic aviation aluminum alloy production and application, accelerating the upgrading of domestic aviation aluminum alloys, and enriching the advanced aluminum alloy material system for fighter aircraft.

The research and production of high-performance, large-size third-generation and fourth-generation aluminum alloy materials, as well as new-generation high-strength, high-toughness, low quench-sensitive aluminum alloy materials needed for large aircraft programs, are currently being organized for 攻关 and have achieved significant progress.

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4 Suggestions for Developing China’ s High-Strength Aluminum Alloy Materials

Large-size, high-performance aluminum alloy materials are a large-volume key structural material needed for China’ s national economic and defense industry development. Their development must follow the inherent laws of materials while combining with national engineering requirement objectives to determine development directions. China lacks specialized research institutions for aluminum alloy materials and needs to further strengthen the production-education-research-application cooperation model. Research must break through the tracking and imitation mode and properly handle the dialectical relationship between solving practical problems and innovative development.

On one hand, research on large-size, high-performance materials and their production process technologies and mechanisms must be strengthened to ensure product quality consistency and stability can meet national engineering requirements and large aircraft airworthiness certification requirements. On the other hand, forward-looking and fundamental research on new-generation aluminum alloys must be emphasized. Recent research [141] has discovered that during quenching of Al-Zn-Mg-Cu alloys, a strengthening phase similar to T1 (Al_2CuLi)

precipitates, providing new information for innovative design and material development of low quench-sensitive aluminum alloys. In summary, based on in-depth analysis of international high-strength aluminum alloy material development and intellectual property situations, clear objectives should be established to concentrate efforts on capturing several commanding heights in future basic and applied research. We firmly believe that in the near future, China will not only be a major producer of ordinary aluminum alloy materials but also a major developer and producer of high-end high-strength aluminum alloy materials.

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