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Material Innovations for Electric Aircraft: Progress in Battery Electrodes and Lightweight Fuselage Structure

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Abstract:

The rapid growth of the low-altitude economy has spurred the development of electric aircraft as a sustainable transportation solution. However, the heavy weight of traditional fuselage materials and limitations in battery energy density and safety pose significant challenges to enhancing aircraft performance. The purpose of this review is to examine how lightweight fuselage materials (such as carbon fiber composites and aluminum alloys) and advanced battery materials (including lithium-ion batteries and solid-state batteries) can be utilized in electric aircraft. Key findings indicate that while advanced lightweight materials, particularly carbon fiber composites, offer substantial gains in structural efficiency, significant challenges related to cost and manufacturing/recycling persist; Alternative materials present trade-offs in performance or environmental resistance. For power systems, lithium-ion batteries are prevalent but suffer from safety risks, while solid-state batteries show promise yet require breakthroughs in material stability and interfacial issues. The review identifies the most promising material combinations, underscores the decisive impact of material properties on aircraft range, payload, and safety, and outlines future research directions to overcome current barriers. This review provides insights into optimizing material selection and promoting the commercial viability of electric aircraft, thereby supporting the expansion of the low-altitude economy.

Keywords: Electric aircraft; lightweight fuselage materials; battery materials; energy density; low-altitude economy.

1. Introduction

The concept of the low-altitude economy, defined as an economic ecosystem centered on aviation activities below 1,000 meters altitude, has gained global attention owing to its potential for urban air mobility, cargo transport, and tourism. Emerging in the early 2010s, this sector includes aircraft manufacturing, air traffic management, and related infrastructure, with electric aircraft emerging as a key enabler due to their low emissions and operational efficiency. Currently, electric aircraft are required to have a minimum range of 500 kilometers to meet the needs of urban air mobility and short-haul transportation; The payload should reach at least 500 kilograms to ensure the transportation of passengers and cargo; In terms of safety, they must comply with strict aviation safety standards, such as avoiding thermal runaway of batteries and having reliable structural strength; And in terms of economy, the operating cost per kilometer should be reduced by more than 30% compared with traditional aircraft to promote commercialization. The performance of electric aircraft depends to a great extent on two critical components: the fuselage structure and the power system, which rely on lightweight materials and high-energy batteries, respectively.

Traditional fuselage materials like steel are too heavy, increasing energy consumption and limiting payload capacity. It was shown that a 10 % reduction in aircraft weight can improve fuel efficiency by 5-8 %. This has led to the creation of new types of lightweight and powerful materials, including carbon fiber-reinforced polymer composites, advanced aluminum alloys, and high-performance engineering plastic [1]. In addition, fast-charging capability and cycle life are critical for the operational efficiency and economy of electric aircraft, especially for electric vertical takeoff and landing (eVTOLs) aircraft with frequent takeoffs and landings. This statement sets higher requirements for the energy density and safety of battery materials. Solid-state batteries use solid electrolytes (like inorganic ceramics, polymers, or composite materials) to replace liquid or gel-state electrolyte. This structural feature not only enhances the safety performance by inhibiting thermal runaway caused by liquid electrolyte combustion, but also allows for a more compact cell design. It offers higher energy density and safety, making it a promising solution for addressing the energy and safety challenges in electric aircraft [2]. Despite systematic research on individual materials in the existing literature, there is a lack of comprehensive studies on how lightweight fuselage materials and advanced batteries interact to optimize aircraft performance. Gaps exist in understanding material compatibility, cost-effective manufacturing, and regulatory standards for electric aircraft materials.

The primary objective of this review is to bridge the gap between material science and aerospace engineering by evaluating how lightweight and battery materials can be integrated to enhance electric aircraft performance. This review addresses the application of two critical material categories in electric aircraft: Lightweight fuselage materials including carbon fiber composites, high-strength aluminum alloys, and high-performance engineering plastics, discussing their mechanical properties, manufacturing processes, and impact on aircraft efficiency; And power battery materials, including lithium-ion batteries (current industry standard) and solid-state batteries (emerging technology), focusing on energy density, safety, and operational challenges. Furthermore, the most promising materials for fuselage structures and power systems were identified. The effect of material properties on aircraft range, payload, and safety was analyzed. Finally, future research directions for overcoming technological challenges were proposed. This review is significant for guiding aircraft manufacturers in material selection, supporting policy makers in standard development, and accelerating the low-altitude economy by enabling sustainable, efficient air mobility.

2. Lightweight Fuselage Materials

2.1 Carbon Fiber Composites

Carbon fiber composites (CFCs) have emerged as a transformative force in aerospace engineering, reshaping aircraft design and performance through their remarkable properties. The composites are crafted by embedding carbon fibers within polymer matrices, such as epoxy, and their utilization spans critical aircraft components like fuselages, wings, and control surfaces. A prime example is the Boeing 787, where CFCs constitute 50 % of the structure, resulting in a 20 % weight reduction compared to traditional aluminum-based aircraft. At the core of their impact is an exceptional strength-to-weight ratio, with CFCs boasting a strength 5-10 times that of steel while weighing just one-fifth as much.

Their high strength and stiffness render them perfect for load-bearing parts, enhancing the overall structural efficiency of the aircraft. In the fuselage, this strength allows for a more robust yet lighter structure, enabling the aircraft to withstand the stresses of flight, thus allowing more cabin space and improving fuel efficiency. For wings, CFCs are used in wing skins and spars, which provide stiffness to help maintain aerodynamic shape under different flight conditions, contributing to improved fuel efficiency. The wing skin benefits from the composite‘s

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strength and stiffness to maintain its shape during flight, while the spar, a critical load-bearing component, relies on CFCs to support the wing's structure under various loads. Control surfaces, such as ailerons and rudder, also utilize CFCs. Their design flexibility enables the creation of aerodynamically efficient shapes that can precisely control the aircraft's movement [3]. For example, the complex curves of an aileron can be achieved with CFCs, allowing for smooth and responsive control during maneuvers [4].
Moreover, their corrosion resistance is a significant boon [5]. In the harsh environments that aircraft encounter, from high-humidity zones to areas with exposure to de-icing chemicals, CFCs do not corrode like traditional metals. This property directly translates to reduced maintenance costs over the aircraft's lifespan, as there is less need for repairs and replacements due to corrosion damage. Additionally, CFCs bring design flexibility to the table. Automated manufacturing techniques such as automated fiber placement (AFP) allow for the creation of complex aerodynamic shapes. This is particularly valuable in designing control surfaces, where intricate contours can be achieved to optimize airflow and control, ultimately enhancing the aircraft's maneuverability.
However, CFCs are not without their challenges. The production process is a major cost factor. Expensive autoclave curing and the need for precision control drive up the cost, with CFCs costing between $200-$300 per kilogram. This high cost can limit their widespread adoption, especially in smaller aircraft or for components where cost-effectiveness is a primary concern [6]. Recycling difficulties also pose a significant hurdle. Current methods, like pyrolysis, are energy-intensive and result in low-quality fibers [7]. As the aerospace industry increasingly focuses on sustainability, the inability to efficiently recycle CFCs becomes a more pressing issue, as discarded composites can contribute to waste management challenges.
Many efforts have been devoted to developing cost-effective manufacturing processes, such as out-of-autoclave curing. This technique aims to reduce the reliance on expensive autoclaves, thereby cutting production costs [8]. By optimizing curing processes at lower temperatures and pressures, it is possible to make CFCs production more accessible and affordable. Another exciting development is the use of 3D printing for CFCs. This technology has the potential to revolutionize the manufacturing of complex aerospace components, allowing for rapid prototyping and customized production. In terms of recyclability, solvent-based delamination techniques are being investigated. These methods could enable the recovery of high-quality carbon fibers from used composites, making the recycling process more efficient and environmentally friendly.

2.2 Aluminum Alloys

Aluminum alloys remain indispensable in aerospace lightweight applications, particularly for secondary components, due to their formability and cost-effectiveness. New-generation alloys like 7050-T7451 exemplify this trend, offering a yield strength of 480 MPa and enhanced fatigue resistance [9]. These properties make them ideal for wing spars and landing gear components, which endure cyclic loading during flight and ground operations.
Aluminum alloys excel in mature manufacturing processes, allowing for high-volume production with consistent quality. Their excellent thermal conductivity is critical for components near engines or heat-generating systems, as it enables efficient heat dissipation. Additionally, aluminum's recyclability aligns with the aerospace industry's growing sustainability demands, as recycled alloys can retain up to 95 % of their original properties. However, aluminum alloys face limitations: they are susceptible to corrosion in humid environments, requiring protective coatings, and their strength-to-weight ratio lags behind advanced composites, restricting their use in primary load-bearing structures [10].
Current research focuses on developing high-strength aluminum-lithium alloys to further reduce weight and improve corrosion resistance [11]. Aluminum-lithium alloys are advanced lightweight materials, with lithium typically accounting for 1.5-3 % of the composition, along with other elements like copper, magnesium, and zinc. Lithium, the lightest metal, lowers the alloy's density by 10-15 % compared to traditional aluminum alloys, directly enhancing the strength-to-weight ratio and thus fuel efficiency. Heat treatment of these alloys forms fine precipitates that strengthen the material by hindering dislocation movement, allowing them to achieve yield strengths of 500-600 MPa. Their uniform microstructure, along with a stable oxide film that forms on the surface, prevents the penetration of corrosive media, ensuring durability in harsh environments [12].

2.3 Special Engineering Plastics

Special engineering plastics are high-performance polymers characterized by superior mechanical, thermal, and chemical properties compared to traditional plastics. Unlike conventional plastics, which are mainly used for general-purpose applications like packaging and consumer goods, special engineering plastics can withstand extreme temperatures, high mechanical stresses, and harsh chemical environments. They typically have higher melting points, better dimensional stability, and enhanced resistance to wear and corrosion, making them suitable for demanding applications in the aerospace, automotive, and medical industries.

Common types of special engineering plastics include polyetheretherketone (PEEK), polyphenylene sulfide (PPS), polyimide (PI), and liquid crystal polymers (LCP). Each type offers unique properties: PPS has excellent chemical resistance and electrical insulation; PI can endure extremely high temperatures up to 400 ℃; LCP exhibits high strength, low moisture absorption, and good flowability for complex molding.

For electric aircraft, PEEK stands out as an ideal choice for non-load-bearing components, leveraging its low density (1.3 g/cm^3) and exceptional high-temperature resistance (up to 260 ℃) [13]. PEEK components, such as cable brackets and interior trim parts, offer significant weight savings compared to metal alternatives while withstanding the thermal stresses of engine bays or high-altitude environments. Additionally, PPS is also suitable due to its chemical resistance and ability to maintain structural integrity in high-humidity conditions often encountered in aircraft operation.

These plastics exhibit chemical inertness, resisting degradation from fuels, lubricants, and cleaning agents, which reduces maintenance needs. Their compatibility with 3D printing technologies allows for the rapid prototyping and on-demand production of complex parts, a key advantage in custom aerospace applications. However, engineering plastics have inherent limitations: their mechanical strength is lower than metals or composites, restricting them to non-structural roles. Prolonged exposure to sustained loads can also cause creep deformation, necessitating careful design considerations.

Nanofiller reinforcement is being used to enhance the mechanical properties of engineering plastics through ongoing developments, such as carbon nanotubes, to improve stiffness and load-bearing capacity. Researchers are also exploring hybrid designs that combine plastics with lightweight metals or composites to extend their application scope in semi-structural components [14].

2.4 Future Directions

The evolution of lightweight materials in aerospace is driven by three core objectives: reducing costs, improving sustainability, and establishing industry standards. For CFCs, out-of-autoclave curing and 3D printing technologies aim to lower production costs, while solvent-based recycling methods seek to address the energy-intensive nature of current composite disposal. Aluminum recycling efficiency is being enhanced through advanced sorting and remelting technologies, reducing the environmental footprint of material production.

Standardization remains a critical challenge, as diverse material types and manufacturing processes require unified testing and certification protocols [15]. Industry initiatives are underway to establish global standards for lightweight materials, ensuring consistent performance evaluation and regulatory compliance. By integrating material innovation with sustainable manufacturing and standardized practices, it is expected to release the full potential of lightweight solutions, driving more efficient, eco-friendly aircraft designs.

3. Power Battery Materials

3.1 Lithium-Ion Batteries

The cornerstone of electric aircraft power systems are lithium-ion batteries, which have energy densities in the range of 200-300 Wh/kg and cycle lives that range from 500-1,000 cycles [16]. These batteries employ liquid electrolytes, such as lithium hexafluorophosphate, and cathode materials like $LiNi_xMn_yCo_zO_2$ (NMC). In particular, nickel-rich formulations, such as NMC-811, have managed to achieve higher energy densities, although at the cost of reduced stability [17].

The maturity of lithium-ion battery technology represents a significant advantage. Well-established supply chains and manufacturing processes ensure consistent production quality and reliable availability. Moreover, their high power density makes them eminently suitable for eVTOL aircraft, which require substantial power for rapid acceleration during takeoff and maneuvering. For instance, in some eVTOL prototypes, lithium-ion batteries enable quick transitions between hovering and forward flight, contributing to the aircraft‘s agility.

However, lithium-ion batteries face dual challenges: struggling to meet the energy density requirements for long-range flights (targeting >400 Wh/kg) and the thermal runaway brings security risks [18]. The existing design of electrode materials for lithium-ion batteries is approaching its theoretical maximum energy density. To achieve significant improvements in energy density and, consequently, aircraft range, the exploration of new chemistries has become imperative. Additionally, safety risks pose a major concern, as the flammable nature of liquid electrolytes can lead to thermal runaway in the event of overcharging, short circuits, or mechanical damage.

The focus of efforts is to improve the performance of lithium-ion batteries for electric aircraft. For the cathode materials, researchers are exploring ways to increase the nickel content in NMC cathodes while maintaining stability, aiming to boost energy density further. On the anode side, silicon-carbon composite anodes are being investigated as they have the potential to store more lithium ions

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compared to traditional graphite anodes, thus increasing the overall capacity of the battery [19]. Lithium-ion batteries with slightly improved energy densities, which can reach up to 350 Wh/kg in experimental settings, have been demonstrated in recent developments, but there are still challenges in scaling up production while maintaining reliability.

3.2 Solid-State Batteries

Solid-state batteries have emerged as an extremely promising alternative to lithium-ion batteries, replacing the liquid electrolytes with solid conductors, such as sulfides, polymers, and oxides, enabling lithium ions to conduct through the solid electrolyte while significantly reducing the risk of electrolyte leakage. Several significant advantages are offered by this fundamental change, including higher energy densities that range from 400 to 1,000 Wh/kg and enhanced safety due to solid electrolytes being non-flammable.

3.2.1 Sulfide electrolytes

Sulfide electrolytes, exemplified by $Li_{10}GeP_2S_{12}$, exhibit remarkable ionic conductivities of up to 10^{-2} S/cm, facilitating fast ion transport within the battery [20]. Rapid charging and discharging are enabled by this property, which makes solid-state batteries based on sulfides appealing for electric aircraft applications. QuantumScape and other companies are leading the way in research and development, with the goal of commercializing sulfide-based cells that have 50 % higher energy densities than conventional lithium-ion batteries. In theory, such batteries could significantly extend the range of electric aircraft, potentially enabling long-haul electric flights.

However, sulfide electrolytes also present challenges. They are highly reactive with moisture in the air, which can lead to the degradation of the electrolyte and the formation of harmful byproducts. This reactivity necessitates strict manufacturing environments with low humidity, increasing production complexity and costs. Additionally, the long-term stability of the interface between sulfide electrolytes and electrodes remains a concern, as degradation at this interface can reduce battery performance over time [21].

3.2.2 Polymer electrolytes

Polymer electrolytes, such as polyethylene oxide, offer unique advantages due to their flexibility and compatibility with thin-film designs [22]. These characteristics make them well-suited for distributed propulsion systems in electric aircraft, where batteries need to be integrated into compact and irregularly shaped spaces. The flexibility of polymer electrolytes allows for better adaptation to the aircraft‘s structure, enabling more efficient use of available space.

Nevertheless, polymer electrolytes suffer from low ionic conductivity, typically around 10^{-6} S/cm, which severely limits their high-rate performance. As a result, batteries using polymer electrolytes may struggle to deliver the burst of power required for critical operations like takeoff or emergency maneuvers. Enhancing the ionic conductivity of polymer electrolytes is the focus of current research efforts, such as by incorporating additives (e.g., ceramic nanoparticles, ethylene carbonate and propylene carbonate) or modifying the polymer segments structure to create more efficient ion-conducting pathways.

In terms of modifying the polymer structure, one approach is to synthesize block copolymers. By combining different polymer segments with distinct properties, for example, linking a segment with high lithium-ion affinity to another segment with good mechanical strength, the resulting block copolymer can optimize both ion transport and structural stability. Another method involves cross-linking the polymer chains. Controlled cross-linking creates a three-dimensional network that can maintain the electrolyte‘s shape while providing continuous pathways [23].

3.2.3 Oxide electrolytes

Oxide electrolytes, like $Li_7La_3Zr_2O_{12}$, stand out for their excellent thermal stability, capable of withstanding temperatures up to 600 °C, and high chemical resistance [24]. These properties make them ideal for use in high-temperature environments within electric aircraft, such as near the engine or in regions with intense solar radiation.

However, oxide electrolytes have their own set of challenges. Their brittleness makes them prone to cracking during battery manufacturing and operation, which can disrupt ion transport and reduce battery performance. Moreover, achieving good contact between oxide electrolytes and electrodes is difficult, often requiring nanoscale engineering techniques. Researchers are exploring methods to improve the mechanical properties of oxide electrolytes, such as adding plasticizers or using composite materials, while also developing innovative electrode-electrolyte interface designs to enhance battery performance and longevity.

3.3 Challenges and Development Directions

The current electric aircraft market is still dominated by lithium-ion batteries, but solid-state batteries have exciting possibilities for the future. Through continuous research and innovation aimed at overcoming existing challenges, battery technology has the potential to revolutionize electric aviation, making longer flights, higher payloads, and greater energy efficiency a reality.

Across all battery types, several overarching challenges need to be addressed for wider adoption in electric aircraft. Electrolyte stability remains a key issue. For sulfide electrolytes, developing moisture-resistant coatings or manufacturing processes that eliminate exposure to humidity is crucial [25]. Oxide electrolytes require solutions to overcome brittleness and improve electrode contact.

Cost and scalability are also significant hurdles. Solid-state batteries are currently 3-5 times more expensive than lithium-ion batteries, mainly due to complex manufacturing processes and the use of specialized materials [26]. Reducing costs through economies of scale, process optimization, and the discovery of more abundant raw materials is essential for commercial viability.

Advanced battery management systems (BMS) are indispensable for monitoring the charging and discharging processes and the health status of batteries [27]. Future research will likely focus on developing intelligent BMS that can adapt to the changing conditions of different battery chemistries and predict potential failures, ensuring the safe and reliable operation of electric aircraft.

4. Conclusion

This review investigates the application of lightweight fuselage materials and advanced battery materials in electric aircraft, analyzing their mechanical properties, operational challenges, and technological advancements. Key findings reveal that CFCs significantly enhance structural efficiency with a strength-to-weight ratio 5-10 times that of steel, but face high production costs (US$200-300/kg vs. US$10/kg for aluminum) and energy-intensive recycling. Aluminum alloys (e.g., 7050-T7451) and engineering plastics (e.g., PEEK) serve as cost-effective alternatives for secondary components, though aluminum's corrosion susceptibility and plastics' low mechanical strength limit their scope. For power systems, lithium-ion batteries dominate but risk thermal runaway, while solid-state batteries address safety and energy density, yet sulfide electrolytes' moisture reactivity, polymer electrolytes' low conductivity, and oxide electrolytes' brittleness remain unsolved.

The review underscores the critical link between material science and aerospace engineering, which paves the way for commercial viability by reducing operational costs and enabling longer-range electric aircraft. Future efforts should prioritize three fronts: 1) Cost and scalability: develop out-of-autoclave CFC curing and 3D printing to cut production costs, and advance solvent-based recycling for composite materials. 2) Battery technology: engineer moisture-resistant sulfide electrolytes, enhance polymer electrolyte conductivity via nanocomposites, and mitigate oxide electrolyte brittleness through nano-engineering. 3) Industry standardization: establish unified protocols for functional material testing and intelligent BMS for batteries, which must monitor electrode-electrolyte degradation in real time. Integrating these directions will accelerate the transition to sustainable, high-performance electric aviation.

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