Advancements in Electric Motor Materials for Aviation Applications

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Abstract. As concerns about greenhouse gas emissions and noise pollution grow, the aviation industry is increasingly turning to electric propulsion for cleaner, quieter flight. Electric propulsion offers lower emissions and reduced noise, but significant challenges remain, particularly in materials science. This paper reviews key advancements in electric motor materials for aviation, focusing on high power density, efficient thermal management, mechanical strength, and electrical conductivity. Innovations such as high magnetic saturation materials, nanomaterials like graphene and carbon nanotubes, and advanced composites are explored for their potential to improve motor efficiency and durability. The role of additive manufacturing in producing lightweight, optimized components and the use of advanced coatings for enhanced performance are also discussed. Challenges such as reliance on rare earth materials and environmental sustainability are considered, emphasizing the need for alternative materials and improved recycling. Future research should focus on material innovations that enhance electric aviation's performance while aligning with environmental goals.

Keywords: Materials science, electric propulsion systems, environmental sustainability.

1. Introduction

As the increasing level of public awareness and concern about key environmental issues, greenhouse gas emissions, global warming and energy shortage for example, the aviation industry has witnessed a growing interest in electric propulsion systems. Although conventional fuel-based engines are more reliable, they contribute significantly to greenhouse gas emissions, global warming and noise pollution. Aviation is one of the most carbon-intensive activities, which contributes 2.4% of global carbon emission annually, and 4% of observed human-induced global warming to date was caused by aviation [1]. Beyond that, one of the most harmful effects of aviation is noise. It can cause community annoyance, disrupt sleep, adversely affect academic performance of children, and could increase the risk for cardiovascular disease of people living in the vicinity of airports [2]. Therefore, the aviation industry is pressed for improving propulsion system by adopting more environmentally friendly technologies.

Advancements in electric motors provide an opportunity to establish an alternative propulsion system that is cleaner and more sustainable. Electric propulsion systems offer several advantages over conventional propulsion systems, including mainly reduced emissions and lower noise level. Although the advent of small-scale electric airplane, NASA X-57 Maxwell for instance, has demonstrated the feasibility of electric propulsion system, commercialization of all-electric aircraft in scale is facing significant challenges in both technology and science aspects, such as materials science.

Addressing the limitations of present materials is the key to revolutionizing the propulsion system from fuel-based to electric. Materials designed for traditional internal combustion engines may not meet the demand for electric motors because electric motors have stringent requirements in performance, for example, high power density, efficient thermal management, mechanical strength, lightweight construction and electrical conductivity. Therefore, to realize scaling electric motors for aircraft, advancement in materials science is crucial because it can enhance the performance of electric motors and overcome many existent challenges.

The materials used to manufacture electric motors influence the performance of motors significantly since different types of materials have different properties. For the aviation industry, range and efficiency are very important because the main target is making profits. Also, weight reduction is essential for airplane production. Thus, electric motors have to be able to provide higher power while retaining or lowering their weight because batteries used to power them have much lower specific energy than gasoline, which means large mass of batteries is required to provide energy.

Innovations in materials are also essential for solving problems with thermal management. Electric motors generate massive amounts of heat during operation, which could negatively affect the performance of the motor. Hence, progress in materials is vital to guarantee reliable motor performance by avoiding overheating problems during operation. As well, materials have to be durable enough to work efficiently and safely under aviation conditions.

The scope of this essay is to review the latest advancements in electric motor materials, focusing on their potential effect on future aviation applications. By reviewing the most recent developments and providing possible areas for future research, this paper aims to provide a comprehensive understanding of how material innovations are shaping the future of electric aviation.

2. Key requirements and Core Innovations for Electric Motor Materials in Aviation

2.1. High Power Density

Power density, the critical factor of aviation, is defined as the amount of power generated per unit volume. Achieving high power density gives an opportunity for the design of more compact and lightweight motors because motors with high power density can generate sufficient thrust while retaining the total weight of aircraft to an acceptable value. Therefore, in other words, reaching high power density can simultaneously reduce the airplane weight and enhance efficiency.

The power density of electric motors can be affected by several properties of materials, such as magnetic properties and electrical conductivity. It is worth mentioning that magnetic properties of materials, magnetic saturation for example, are the key determinants because they can significantly influence the power density of electric motors. Materials with high magnetic saturation are crucial for increasing power density. Magnetic saturation is the state reached when an increase in applied external magnetic field cannot increase the magnetization of the material further, so the total magnetic flux density remains reasonably constant [3]. Magnetic saturation impacts power density by determining the maximum magnetic flux a material can handle before becoming saturated. Materials with higher saturation flux density, such as Iron-Cobalt Permendur, allow for smaller stator teeth and rotor yokes, reducing the motor's size and weight while maintaining high power output. This leads to higher power density and improved efficiency, especially in electric motor applications [4]. In addition to magnetic saturation, lowering core losses of electric motors is also vital for achieving high power density. Materials such as high silicon electrical steel, amorphous ferromagnetic metals, and soft magnetic composites (SMCs) have the potential to improve the performance of electric motors because they have high saturation flux density and low specific core loss, which allow motors to be more compact and efficient at high speeds while managing heat dissipation and magnetic properties [5].

Ceramic coatings can provide excellent thermal insulation, reducing heat loss and improving overall system efficiency [7].

2.2. Thermal Management and Heat Resistance

Effective thermal management is essential for maintaining the performance and reliability of electric motors, particularly in aviation where high power outputs and prolonged operation can generate significant heat. Inadequate cooling capacity relative to the motor's power rating can lead to insufficient heat dissipation and increases the motor operating temperature and thermal stress. The

high temperature inside a motor can also cause fatigue stress along the rotor bars, which can lead to thermo-mechanical failure [6].

Advancements in materials, nanomaterials for instance, provides a feasible solution to current challenges. The use of nanomaterials, such as graphene and carbon nanotubes, which possess exceptional thermal properties, allowing for more efficient heat transfer. As well, they can prevent scaling and degradation, hence, extending the lifespan of heat exchangers [7]. Additionally, coating is another development aspect which has the potential to improve the thermal properties of electric motors. Innovations in coatings have led to the creation of smart coatings that can optimize heat transfer efficiency in real time by adapting to changing conditions such as temperature variations and fluid compositions [7]. In addition, the use of nanomaterials in coating offers enhanced thermal conductivity. Some advanced coatings incorporate nanotechnology, utilizing nanocoatings to improve thermal contact between the heat exchanger surfaces and the fluids. These coatings reduce thermal resistance and enhance overall heat transfer rates [7]. Furthermore, Ceramic Matrix Composites (CMCs) are noted for their ability to withstand extremely high temperatures (up to 1400 degrees Celsius), making them ideal for electric motor applications [8]. Therefore, their ability to withstand extremely high temperatures makes them suitable for coating material. Ceramic coatings can provide excellent thermal insulation, reducing heat loss and improving overall system efficiency [7].

2.3. Mechanical Strength and Durability

In aviation, electric motors must endure significant mechanical stresses, including vibrations, shocks, and high-speed rotation. The materials used in these motors must be capable of withstanding these stresses without degrading over time. Mechanical strength and durability are crucial for ensuring the longevity and reliability of electric motors in the demanding environment of aviation.

Innovations in high-strength and lightweight materials have played a significant role in improving the mechanical properties of electric motors. Composite materials are worth mentioning because of their lightweight, high-strength properties. For example, carbon fiber composites, glass fiber composites, and aramid fiber composites (like Kevlar®), offer superior strength-to-weight ratios, making them suitable for motor design and manufacture [8]. Moreover, the use of magnesium and titanium alloys as alternatives to traditional materials like aluminum and steel can effectively improve the strength of motors while reducing the weight. Magnesium alloys, which are much lighter than steel, offer excellent damping and stiffness, making them suitable for reducing aircraft weight, and titanium alloys provide higher strength than aluminum [8]. Besides, using finite element analysis, particularly First-Order Shear Deformation Theory (FSDT), to simulate the behavior of laminated composite plates is very helpful for designing materials with better mechanical properties. This approach helps engineers optimize the ply orientation of composites to achieve maximum strength while minimizing weight [8].

2.4. Electrical Conductivity and Efficiency

Electrical conductivity is a critical factor in the efficiency of electric motors. Materials with high conductivity reduce resistive losses, which helps to minimize energy waste and improve overall motor performance. The selection of conductive materials plays a key role in optimizing motor efficiency and ensuring that the electric motor delivers the maximum possible power output.

The use of nanomaterials, specifically carbon nanotubes (CNTs) in electric motors can significantly enhance the electrical conductivity of motors. CNTs, particularly single-walled (SWCNTs) and multi-walled (MWCNTs), are highlighted for their remarkable electrical conductivity. Their unique structure, which allows electrons to flow with minimal resistance, makes them ideal for enhancing the electrical properties of other materials [9]. Moreover, synergistic effect of CNTs could improve the electrical conductivity of motor materials. To be more specific, when CNTs are added to materials like polymers or fibers, they form a continuous network within the matrix. This network facilitates better electron transport, thereby significantly improving the overall electrical conductivity

of the composite material [9]. There are several methods to incorporate CNTs into materials, including solution mixing, melt processing, and in situ polymerization. Advanced techniques, such as applying electric or magnetic fields during fabrication, help align the CNTs, further enhancing the material's electrical properties [9].

3. Advancements in Materials

3.1. Electrical Conductivity and Efficiency

Additive manufacturing (AM) and 3D printing technology have brought about significant changes in the designing and manufacturing process of aircraft's motor components. The process of combining materials via fusing, binding, or solidification is known as AM [10]. Conventional manufacturing techniques involve removing material from solid blocks or filling molds to finish shapes, and they have challenges when creating complex additive manufacturing (AM) or integrated systems. Using 3D CAD modeling, AM creates parts layer by layer as an alternative to traditional methods. This allows for the development of intricate inner structures, such as conformal cooling channels on combustion chamber or turbine blades, or such channels could be incorporated into stators, rotors, and impellers to lower heat gradients and increase overall efficiency [10]. This capability reduces thermal stress and enhances heat dissipation, which not only increases performance but also increases the lifespan of motor components.

AM processes can be referred to by terms like 3D printing (3DP), solid freeform fabrication (SFF), rapid prototyping (RP), direct digital manufacturing (DDM), and rapid manufacturing (RM). 3D printing applies various kinds of materials, including metal or alloys (the ones particularly used for AM are aluminum alloys, stainless steel, nickel-and-iron based superalloys, titanium alloys, copper alloys, cobalt alloys, refractory alloys, and steels, etc), ceramics, wooden or composite materials, plastics to construct prototypes or final buildings [10]. Many processes are included in 3D printing, such as material extrusion, powder bed fusion, binder jetting, directed energy deposition, material jetting, and sheet lamination. Selective laser melting (SLM), electron beam melting (EBM), fused filament fabrication (FFF), laminated object manufacture (LOM), and stereo-lithography (SLA), selective laser sintering (SLS) are the technologies that are most used [11].

The advantages of 3D printing and AM are not limited to simply creating complex geometries. One of the most crucial benefits is its influence on optimizing material use and reducing weight.

With metal additive manufacturing (AM), design freedom can be used to minimize volume and optimize material distribution without sacrificing the mechanical or other performance requirements of the component [12]. Moreover, it is possible to reduce cost and risk by combining components, which also reduces potential failure modes across joints. This is a particularly useful feature for high-performance applications where reliability and efficiency are necessary [12].

Furthermore, the process of part consolidation refers to the redesigning multiple interacting components integrated system, which enables improvements in technical performance and removal of mating structures and surfaces, enhancing structural efficiency. Moreover, the consolidation of various components could considerably reduce overall fabrication costs, which is enabled by the direct reduction of manufacturing lifecycle and subtraction in non-recurring costs related to design and risk-management of the failure modes associated with part interaction.

By utilizing computational design tools and advanced materials, 3D printing makes it possible to produce lightweight structures, without compromising strength or durability. Metal alloys, composite materials, and polymers can be used to produce parts with tailored properties, like high strength-to-weight ratios and enhanced thermal resistance. For instance, aluminum alloys used to be the most widespread material in aerospace because of their low cost, light weight, high strength-to-weight ratio and ease of manufacturing characteristics [12]. Also, stainless steels are frequently used in aircraft components due to the high strength-to-weight ratios, excellent durability, hardness and good mechanical properties. Stainless steels belonging to different classes, such as austenitic, precipitation hardened (PH), and maraging (aged and martensitic), are frequently utilized in combination with AM.

These types of stainless steel are utilized in structural joints, heat exchangers, landing gear systems, hydraulic parts, engine and exhaust system components, and heat exchangers [12].

The application of light-weighting also highly benefits the rotational components in aircraft engines. In addition to lowering the overall mass of aircraft and spacecraft, the mass reduction of these components also reduces rotational inertia, enhancing performance characteristics like braking and starting torque reduction as well as the interaction moment between the axle structures and the rotating components [12].

3.2. Advanced Coating and Surface Treatments

Materials used in engine or motor components and other crucial elements in the aircraft sector are always exposed to harsh circumstances, such as extreme temperatures, abrasive forces, and corrosive environments. In such severe conditions, improving the longevity and performance of these materials requires advanced coating processes.

To begin with, thermal barrier coatings (TBCs) are one of the key technologies to protect materials from high temperatures and thereby enhance the engine's efficiency and thrust [13]. The standard component of TBCs is YSZ-style ceramic topcoats—which has properties such as low thermal conductivity, high oxygen permeability, and a relatively high coefficient of thermal expansion—metallic bond coats, which are frequently composed of aluminum-rich materials to produce a protective oxide layer, and a substrate. TBC systems are currently capable of reducing the temperatures of metal materials up to about 140 ℃, with the potential estimated to be greater than 170 ℃ [13].

Also, manufacturing of high-temperature protective coatings plays an important part in preventing vital components from damage. Such coatings are made using technologies like APS, EB-PVD, and PS-PVD, which create different microstructures for various performance needs, such as APS's lamellar structure with low thermal conductivity and EB-PVD's columnar crystal structure for high strain resistance [14].

Anti-corrosion coatings are also crucial in protecting the materials. Corrosion protection coatings can be categorized based on composition into organic, inorganic, and metallic coatings, each of which has its own uniqueness:

Organic coatings: made up of polymeric binders, solvents, pigments, and additives. These coatings deposit a thin layer to work as a physical barrier on the surface, preventing the penetration of corrosive matters. New formulations have been developed, including coatings with nano fillers that enhance mechanical properties and barrier performances of coatings [15]. Also, self-healing coatings that can automatically repair damage or adjust properties due to environmental changes are under heated discussions and research.

Inorganic coatings: ceramic and glass coatings, for example, have great ability to withstand high temperatures, wear, and chemicals, providing long-term protection and stability. Recent advances in surface modification techniques like plasma treatment and chemical etching, and the development of new ceramic materials have greatly enhanced resistance under extreme conditions. Moreover, hybrid coatings, which can help combine the benefits are gaining attention [15].

Metallic coatings: Such coatings protect the substrate through sacrificial anode or barrier mechanisms. For example, preferentially corroding zinc coatings can shield the steel beneath from corrosion.

Wear-resistant coatings, including tungsten carbide and chromium-based compositions, are extensively employed to safeguard surfaces vulnerable to wear and erosion. These advanced coatings confer robust, long-lasting protection against mechanical wear, environmental degradation, and chemical corrosion, thereby ensuring components' sustained functionality and performance over extended periods [16]. Key coating deposition techniques, such as plasma spraying and chemical vapor deposition (CVD), significantly enhance component durability in demanding operational environments. To further augment material resilience, layers of hard chromium plating, physical vapor deposition (PVD), and diamond-like carbon (DLC) coatings are applied. These enhancements

prolong component lifespan and minimize friction, optimize operational efficiency, and decrease maintenance requirements, translating into substantial cost savings and operational benefits [16].

3.3. Nanotechnology and Composite Materials

Nanotechnology and composite materials represent cutting-edge advancements in material science. Because of their extraordinary electrical, thermal, and mechanical capabilities, nanomaterials are currently setting the standard for technological developments. Nanomaterials, such as carbon nanotubes and graphene, have special properties that could be applied to improve the performance of electric motors [17].

For electrical applications, incorporating conductive nanofillers, such as metal nanoparticles, conductive polymers, or carbon nanotubes (CNTs), can greatly increase the electrical conductivity of nanocomposites [17]. The way in which these nanofillers disperse and how networks are formed within the polymer matrix determine how electrically conductible the material is. For example, even at modest volume fractions, carbon nanotubes can significantly improve the electrical conductivity of the composite because of their high aspect ratio and outstanding electrical conductivity [18]. Furthermore, the material's electromagnetic shielding qualities can be enhanced by the inclusion of nanofillers, which is important for applications in electronic devices.

Thermal properties are also improved using nanomaterials. By choosing the right nanofillers and managing their matrix dispersion, it is possible to maximize the thermal properties of nanocomposites, such as thermal conductivity and thermal stability. Because of their high thermal conductivity, metal nanoparticles and carbon nanotubes, for instance, can function as efficient thermal conductors and improve the thermal performance of composite materials [18]. Furthermore, adding nanofillers can increase the material's thermal stability, which is important for motor components that operate under high thermal loads, since improved thermal management can enhance reliability and prevent overheating [18].

By using nanoscale reinforcement materials, nanocomposites' mechanical properties—such as strength, toughness, and hardness—can be greatly improved. For instance, MXene and graphene are great for improving the mechanical performance of composite materials because of their high strength and flexibility [19]. The material's ability to withstand loads is enhanced by the strong interfacial contacts and high specific surface area of nanofillers, which promote stress transmission. For instance, adding carbon nanotubes and nanoclay can significantly improve the modulus and strength of composites made of polymers [18]. Controlling the distribution and form of nanofillers can also improve the toughness of nanocomposites by improving energy absorption and crack propagation resistance.

4. Challenges and Opportunities in Electric Motor Material Development

Developing advanced materials for electric motors often involves the use of rare earth elements and other key materials, which poses a major challenge to the supply chain. Rare earth elements, such as neodymium, dysprosium and terbium, are essential to produce high-performance magnets used in electric motors. However, these elements are scarce, expensive, and subject to geopolitical and environmental uncertainty.

The price and accessibility of rare earth elements can restrict the scalability of innovative technologies and have an impact on the overall cost of motor components. Concerns of resource management and sustainability are also brought up by the effects of these components' mining and processing on the environment. A multifaceted strategy is needed to address these issues, including the creation of substitute materials, enhanced recycling techniques, and initiatives to lessen reliance on vital resources.

To deal with the material sustainability challenges, Inter-industry collaboration holds significant value. By fostering knowledge exchange, resource sharing, and technology transfer across sectors, collaborative efforts can catalyze advancements in material science and promote sustainable practices

[20]. Such collective endeavors can lead to mutually beneficial innovations and more effective material management strategies.

In the context of electric motor material development, it is imperative to address the substantial environmental implications associated with material extraction, processing, and disposal. Mining operations, for instance, can lead to substantial ecological disruption, including habitat loss and water contamination. When the ore is dug up and put into a large leaching pool, chemicals are put in to separate the different elements, but these pools can release dangerous chemicals into the air, such as poor seals. They can also seep into the ground, into the groundwater, including radioactive elements mixed with rare earths. Therefore, some environmentalists say that this act, which was originally intended to protect the environment, will eventually pollute or even destroy the earth. Manufacturing processes contribute to environmental concerns through energy consumption, emissions, and waste production. To mitigate these impacts, integrating sustainable methodologies across the material's life cycle is essential. This entails fostering energy-efficient procedures, maximizing waste reduction through recycling and repurposing, and ensuring responsible disposal or recycling of abandoned components [19]. For instance, Zero Waste Program in San Francisco, which is a case of implementing an enhanced waste management program that demonstrates how to drive a shift in waste management to resource and material systems thinking through policy innovation and governance structures. San Francisco passed the Comprehensive Waste Management Act (Assembly Bill 939), which sets waste diversion goals and pushes the city to go beyond state legislative requirements to reduce landfill and increase recycling rates [20]. Furthermore, promoting the utilization of eco-friendly materials and technologies serves to minimize the overall environmental footprint of material sourcing and utilization.

In the aviation sector, strict adherence to material usage and performance regulations is paramount for ensuring safety, reliability, and environmental stewardship. Regulatory bodies establish rigorous standards for material characteristics, performance metrics, and ecological footprint, aligning with operational and safety benchmarks. Manufacturers must seamlessly integrate these regulations into their material R&D processes, encompassing comprehensive testing, securing certifications, and furnishing documentary evidence to validate compliance with regulatory benchmarks. For instance, Advanced Research Projects Agency - Energy (ARPA-E) received $30 million in funding for the Rare Earth Alternatives in Critical Technologies (REACT) program, aimed at developing technologies that reduce dependence on rare earth elements [20]. Upholding industry norms safeguards the integrity of aviation materials and bolsters overall performance and safety. Looking ahead, the evolution of electric motor materials centers on the investigation of novel materials and their prospective applications in the realm of sustainable aviation. Advanced ceramics, innovative composites, and bio-based alternatives are under scrutiny for their potential to enhance thermal stability, electrical efficacy, and eco-friendliness in motor systems. The only other commercially available high-performance magnetic material options for electric motors are samarium-cobalt compounds ($SmCo_5$ and Sm_2Co_{17}), with $Nd_2Fe_{14}B$ currently being the most popular choice. Emerging materials including $Sm_2Fe_{17}N_3$, $Fe_{16}N_2$, and the FeNi L_{10} structure are being studied to overcome criticality concerns. These materials can provide similar magnetic characteristics since they use less expensive elements. The pursuit of cross-industry collaboration offers fertile ground for accelerating material innovation. Collaborative efforts among aerospace, automotive, and materials science sectors can catalyze shared knowledge, resources, and technological advancements. Such alliances can lead to the creation of novel materials, streamlined processes, and tailored solutions, propelling forward the frontiers of electric motor technology. In conclusion, the convergence of material engineering advancements and the exploration of cutting-edge materials signifies a pivotal moment for enhancing electric motor performance. Navigating these advancements and leveraging collaborative opportunities will be instrumental in ushering in a new era of high-performance, environmentally conscious electric motors.

5. Conclusion

A pivotal shift towards sustainable aviation solutions is underway, propelled by the industry's commitment to mitigate environmental challenges. This transition relies heavily on material innovations that enhance power density, thermal management, mechanical robustness, and electrical conductivity. High-performance materials like iron-cobalt permanent magnet composites and soft magnetic composites (SMCs) have demonstrated their capacity to boost efficiency and power output. Nanomaterials, such as graphene and carbon nanotubes, exhibit exceptional thermal properties, optimizing heat exchange and extending the lifespan of heat exchangers. Advanced composites and alloys fortify mechanical integrity while maintaining lightweight structures. Furthermore, the integration of nanomaterials like carbon nanotubes seamlessly enhances electrical conductivity through the creation of efficient conductive pathways within the material.

The advent of advanced materials portends a transformative era for electric aviation. These materials, characterized by their high-power density, hold the key to designing sleeker and lighter electric motors, pivotal for enhancing aircraft performance and extending operational ranges. Enhanced thermal management systems ensure robust engine functionality and mitigate overheating risks, thereby bolstering aviation safety. Advances in mechanical resilience and longevity contribute to the development of more dependable and enduring electric motor technology. Optimized conductivity optimizes motor efficiency and output, collectively paving the way for a future where electric aviation offers cleaner, quieter, and more sustainable air travel.

Future research endeavors in electric aviation necessitate concentrated efforts in several pivotal domains. The exploration of alternative materials to rare earth elements, vital for high-performance magnet technology, demands attention due to supply chain concerns regarding sustainability. Efficient and eco-friendly extraction and processing methodologies must be advanced. Additionally, substantial advancements in thermal management materials are crucial for effectively managing the heat output of high-powered electric motors. The pursuit of lightweight yet High-intensity materials will significantly contribute to weight reduction and enhanced operational efficiency. Lastly, fostering cross-disciplinary collaboration between materials scientists, engineers, and environmental specialists is imperative to ensure that material innovations harmoniously align with the dual objectives of electric aviation's performance and environmental stewardship.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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