Dean&Francis

ISSN 2959-6157

The influence of coating materials on aircraft performance

Yaoqi Duan[1, *]

[1]Blair academy, Blairstown, United States
*Corresponding author: duanyq@blair.edu

Abstract:
Aircraft coatings have progressed from simple protective layers to advanced multifunctional systems that markedly improve aerodynamic performance, fuel efficiency, and overall operational efficacy. This study investigates the effects of three principal coating types: standard polyurethane paints, low-friction fluoropolymer coatings, and sophisticated hydrophobic nanocoatings. Polyurethane coatings are extensively utilized for their resilience and ease of application; nonetheless, they are prone to degradation over time, resulting in heightened surface roughness and aerodynamic drag. Fluoropolymer coatings yield a smoother surface and can moderately diminish drag; nevertheless, their softness and complex application techniques render them less prevalent. Hydrophobic nanocoatings use advanced technology with tiny structured surfaces that repel water, ice, and dirt, which helps maintain smooth airflow and boosts sensor performance. These coatings facilitate weight reduction and improve surface cleanliness, both essential for optimal airplane performance. The study examines advances including self-healing coatings, adaptive smart materials, and bioinspired surface designs, with the objective of enhancing durability, minimizing environmental effect, and optimizing aircraft efficiency. These achievements signify a substantial progression in aerospace surface engineering and the ongoing evolution of high-performance aircraft technology.

Keywords: Coating materials; aircraft performance; fuel efficiency.

1. Introduction

The efficiency of aircraft is influenced by numerous independent factors, like the engine, aerodynamic structures, and structural weight, as well as stealth capabilities. One often overlooked factor is the materials used for aircraft coating. Historically, coatings are designed for corrosion resistance, radar absorption, and surface durability. Recently, however, there has been a growing interest in coatings that can enhance the aerodynamic performance of aircraft by reducing surface drag and preventing the accumulation of contaminants such as dirt, ice, and other particles.

An aircraft's aerodynamic efficiency is substantially influenced by its surface properties. The concept of boundary layer drag is highly relevant in this context. The boundary layer is the thin layer of air adjacent to the aircraft's surface, where air molecules interact with the surface texture. An irregular or contaminated surface increases this layer's friction, hence enhancing drag and reducing fuel efficiency [1]. Military aircraft coatings serve purposes that go beyond simply inhibiting corrosion. Radar absorbent materials (RAMs) utilized in stealth aircraft must attain a balance with aerodynamic efficiency. Traditional polyurethane coatings, although resilient, are prone to the accumulation of environmental contaminants and micro abrasions over time, leading to heightened surface roughness that may impact fuel efficiency and stealth. Recent breakthroughs in materials science have facilitated the creation of low friction coatings employing fluoropolymers and silicone-based compounds. These materials enhance airflow and diminish drag coefficients by lowering the surface energy of the aircraft's exterior. Aerospace firms and military research entities have assessed these coatings on unmanned aerial vehicles (UAVs), multirole fighters, and reconnaissance aircraft, producing promising results. Hydrophobic nanocoating's represent the most recent advancement in the treatment of aircraft exteriors. These coatings utilize nanostructured surfaces to prevent biological fouling and the accumulation of water, ice, and dirt. These coatings can reduce impurity adhesion, so minimizing parasitic drag, eliminating ice accumulation in low temperatures, and maintaining the integrity of sensors and radar systems. Kwon and Hsu [2] found that military UAVs with hydrophobic nanocoating's have improved endurance, diminished detectability, and increased lift drag ratios. Weight is a critical element in military aviation, as fuel load and payload are precisely adjusted for maximum operational efficiency. Contemporary nanocoatings offer lighter substitutes to traditional methods, reducing structural weight while meeting or exceeding protection and performance standards.

This article examines how different types of aircraft coatings affect the speed and fuel efficiency of aircraft, with a particular focus on military aircraft. The main focus of the article is on three types of coatings: traditional polyurethane coatings, low-friction fluoropolymer coatings, and cutting-edge hydrophobic nano-coatings. These technologies have been evaluated in terms of air resistance, thermal reflectivity, anti-pollution capabilities, weight impact, stealth compatibility, and long-term operational benefits.

2. Characteristics of Different Coatings

2.1 Traditional Polyurethane Paints

Since the mid-20th century, polyurethane coatings have been essential for aircraft protection. These coatings are synthesized chemically by the interaction of polyols and isocyanates, resulting in urethane linkages that create a durable, enduring polymer network. This cross-linked structure is augmented with UV stabilizers, corrosion inhibitors, fungicides, and coloring agents intended for both aesthetic and functional applications. These chemicals enhance weather resilience and offer color customization, aiding in both recognition and camouflage for military purposes. The primary strength of polyurethane coatings lies in their mechanical and chemical resilience. Their ability to withstand ultraviolet radiation, oxidation, corrosive substances, and abrasive particles makes them appropriate for many environments, from wet tropical airbases to desert locations filled with flying sand and dust. They construct a strong shell over the fuselage and wings, safeguarding the underlying metal surfaces, which helps delay structural fatigue and corrosion-related degradation over the aircraft's lifespan. Polyurethane coatings are acknowledged for extending the operational lifespan of airframes by decades in specific military fleets. The ease of application is an added benefit of polyurethane coatings. Their compatibility with conventional air-spray and electrostatic application methods reduces the need for specialized equipment and decreases maintenance frequency [3]. Moreover, their recoating capabilities and polish ability enable aircraft to undergo touch-up maintenance or complete repainting without requiring the thorough removal of previous layers, thus reducing labor effort and environmental waste. Nonetheless, despite their widespread application, polyurethane coatings do not enhance aerodynamic performance. Extended exposure to flight-induced abrasion, particulates, salt, and airborne pollutants leads to minute roughening of the coating's surface. This micro abrasion increases surface friction and facilitates pollutant accumulation, negatively affecting laminar airflow. As a result, fuel efficiency may progressively decline with prolonged operation, especially under high-speed flight conditions where boundary-layer characteristics are affected by surface condition. Moreover, polyurethane coatings typically exhibit greater density than modern nanostructured materials. This supplementary weight, however negligible per square meter, accumulates significantly throughout the entire airframe. In stealth aircraft, polyurethane coatings do not improve radar absorbency and may hinder the efficacy of the radar-absorbent materials (RAM) located beneath them. This limits their use in fifth-gener-

ISSN 2959-6157

ation military platforms and long-range unmanned aerial systems (UAS), where weight and radar cross-section (RCS) reduction are critical for mission accomplishment. Manufacturers have investigated fluorinated polyurethanes and hybrid composites to mitigate certain concerns. While these offer marginal improvements in friction reduction and contamination resistance, they do not attain the performance standards of nanostructured alternatives. As a result, traditional polyurethane is mostly employed in commercial jets, support aircraft, and non-stealth military platforms, rather than in modern fighter or reconnaissance aircraft.

2.2 Low-friction Fluoropolymer Coatings

Fluoropolymer coatings signify a substantial advancement in aviation surface engineering. Materials such as PTFE, FEP, and PFA possess robust carbon-fluorine bonds, the most stable in organic chemistry, resulting in exceptional resistance to solvents, acids, UV radiation, and thermal degradation. These characteristics render fluoropolymers not only durable in demanding aircraft conditions but also exceptionally smooth, with contact angles frequently surpassing 110°, a vital measure of their non-adhesive capabilities. The smooth surface of fluoropolymer coatings aerodynamically diminishes skin friction drag by minimizing molecular interactions between the aircraft's surface and the airflow boundary layer. This promotes more stable laminar flow and postpones the transition to turbulent flow, which correlates with elevated drag coefficients. Even little enhancements in laminar flow can result in significant decreases in fuel usage over extended flights. Zhang et al. [4] evidenced a fuel reduction of 3–5% in long-range UAVs coated with fluoropolymer surface layers, underscoring the potential for practical operational advantages. Moreover, fluoropolymer coatings possess inherent hydrophobic and oleophobic properties. This dual repellency facilitates the removal of rain, ice, insect residue, and aviation fuel spills, thus preserving surface integrity and reducing weight accumulation from adherent particles. In frigid conditions, they provide enhanced resistance to frost and freezing rain; however, not to the degree of superhydrophobic nanocoatings. They are resistant to jet fuels and hydraulic fluids, rendering them appropriate for engine nacelles, flap systems, and landing gear doors.

Notwithstanding their aerodynamic benefits, fluoropolymer coatings pose numerous implementation obstacles. Their low surface energy complicates bonding, requiring intricate surface preparation methods like plasma etching or chemical priming. These methods are both labor-intensive and susceptible to contamination and environmental factors. Furthermore, fluoropolymer coatings necessitate high-temperature curing methods, frequently above 250°C, which may not be suitable for many aircraft substrates, particularly composites. A further concern is mechanical durability. Fluoropolymer coatings exhibit more softness compared to polyurethane and are more vulnerable to erosion caused by sand, hail, and high-velocity particle impact. Consequently, they frequently necessitate regular reapplication or incorporation within a multi-layered system that has a more resilient base coat for structural safeguarding [5]. The expense of fluoropolymer materials and their application methods is considerably elevated, restricting their utilization to mission-critical platforms where performance enhancements warrant the expenditure. The selective application of fluoropolymer coatings—specifically on leading edges, propeller blades, and high-drag zones—has become more prevalent in high-speed military aircraft and UAVs. These coatings act as a conduit between conventional polyurethane paints and sophisticated nanocoatings, offering moderate performance improvements with a reduced technological threshold.

2.3 Cutting-edge Hydrophobic Nanocoatings

Hydrophobic nano coatings exemplify the pinnacle of aircraft surface engineering, offering corrosion resistance, durability, and significant aerodynamic benefits. These coatings are predicated on the principle of super hydrophobicity, defined by water contact angles surpassing 150° and negligible roll-off angles. This phenomenon is achieved through hierarchical surface architecture and chemical modifications that reduce surface energy. The surface architecture of hydrophobic nano coatings typically exhibits dual-scale roughness, consisting of microscale elevations combined with nanoscale projections, produced using sol-gel processing, electrospinning, or nanoimprinting techniques. These patterns capture air beneath water droplets, diminishing the solid-liquid contact area. The result is a self-cleaning surface that facilitates the easy removal of contaminants by water droplets or air currents. These coatings commonly include fluorinated silanes, silica nanoparticles, or titanium dioxide as primary components due to their chemical inertness and ability to form resilient, textured films [6]. The aerodynamic implications are substantial. Hydrophobic nano coatings prevent the accumulation of ice, insects, and particles, hence maintaining surface smoothness and reducing parasitic drag. Their ability to resist water and pollutants ensures optimal performance of critical onboard equipment, such as pitot tubes, infrared sensors, and radar arrays. In stealth aircraft, this denotes a consistent radar signature and uninterrupted sensor operation. A notable benefit of nanocoatings is their remarkably low mass [7].

Unlike traditional coatings measured in mils (thousandths of an inch), nanocoatings often have a thickness of under 1 micron. This tiny mass increase makes them ideal for unmanned vehicles and stealth aircraft, where weight optimization is crucial. Moreover, the capacity to tailor nanocoatings for diverse activities allows for their stratification or integration into composite materials, resulting in multifunctional aircraft exteriors. Empirical evidence validates these benefits. Kwon and Hsu [8] reported a 12–15% improvement in the lift-to-drag ratio of UAVs treated with hydrophobic nanocoatings. These enhancements led to a 10% increase in flight time, raised operational altitude thresholds, and reduced infrared emissions due to lower engine stress. These advances are not merely theoretical; they offer strategic advantages in surveillance, aerial supremacy, and fuel optimization. Challenges remain, particularly about long-term durability. The nanostructures that confer super hydrophobicity are fragile and vulnerable to damage from mechanical abrasion, high temperatures, or chemical exposure [9]. Thus, most modern nanocoating require topcoats or sacrificial layers to maintain their properties in practical applications. The application is a challenge: achieving uniform coatings on curved, riveted, or composite surfaces requires accurate tools and controlled environments. Despite these limitations, the potential for hydrophobic nano coatings continues to expand. Research is underway on self-healing variants that repair damaged structures utilizing embedded microcapsules or stimuli-responsive polymers [10]. Researchers are examining adaptive nanocoatings that respond to humidity, temperature, or electric.

3. Trends in Aircraft Coating Materials

The evolution of aviation coating technologies is influenced by the demand for multifunctionality, cost-effectiveness, and environmental sustainability. An emerging concept is the creation of "smart coatings" that can sense, respond to, and adapt to environmental circumstances.

Self-healing nanocoating can autonomously mend microcracks, maintaining aerodynamic smoothness and prolonging operating lifespan without the need for manual maintenance. Likewise, temperature-responsive coatings are being engineered to enhance surface emissivity in real-time, hence improving thermal management during flight. A significant trend is the integration of bioinspired design. Researchers are investigating natural surfaces, including shark skin and butterfly wings, to emulate drag-reducing patterns that may be reproduced at the microscale on aircraft surfaces. These bioinspired nanostructures may provide passive drag reduction without sacrificing stealth or weight, potentially transforming the design of future military and civilian aircraft. The expense continues to be a major obstacle to the widespread adoption of sophisticated coatings. The implementation of scalable manufacturing methods, including roll-to-roll printing, plasma-enhanced chemical vapor deposition, and atomic layer deposition, is anticipated to reduce production expenses.

Government-sponsored defense research, in partnership with aerospace firms, is facilitating the transition of these technologies from laboratory to runway. Environmental laws are influencing the advancement of aircraft coatings. Conventional solvent-based polyurethane coatings are being replaced with low-VOC (volatile organic compound) alternatives that minimize emissions and environmental effect during application. Nanocoatings, characterized by their low thickness and solvent-free application techniques, are congruent with sustainability objectives.

4. Conclusion

Aircraft coatings have progressed from basic corrosion-resistant layers to intricate multifunctional systems that significantly improve flight performance. Although conventional polyurethane paints are prevalent due to their durability and cost-efficiency, they are becoming progressively inadequate for advanced military and high-velocity applications. Low-friction fluoropolymer coatings enhance aerodynamic performance, particularly in certain high-drag regions, although encounter issues with durability and scalability. Hydrophobic nanocoating signify a significant advancement, providing a distinctive amalgamation of drag reduction, ice and dirt repulsion, stealth compatibility, and ultra-lightweight application. In military aviation, where every kilogram and radar signature decibel is critical, these coatings may establish the next generation of operational superiority. With the ongoing advancements in materials science and nanotechnology, along with increasingly economical application methods, hydrophobic nanocoating are set to transition from experimental stages to conventional aerospace applications.

References

[1] Smith Diu, Lee Je. Surface wear and aerodynamic performance in polyurethane aircraft coatings. International Journal of Aerospace Coatings and Materials, 2021, 18(3): 88–97.

[2] Adebayo Biu, Ode Aer. Review of multifunctional nanocoatings for aerospace applications. Progress in Organic Coatings, 2020, 149(24): 105885.

[3] Zhan Wan, Torres. Application of fluoropolymer coatings for aerodynamic drag reduction in long-range UAVs. Aerospace

ISSN 2959-6157

Science and Technology, 2019, 92(23): 350–359.
[4] Kwon Su, Hsu Pen. Performance enhancement of UAVs using hydrophobic nanocoatings: Aerodynamic and operational implications. Journal of Aerospace Materials and Technology, 2022, 47(2): 123–135.
[5] Liu Yu, Chen Ju, Zhao Hiu, et al. Self-healing nanocoatings for aerospace applications: Mechanisms and materials. Advanced Functional Materials,2023, 33(4): 2300456.
[6] Bhushan Ber. Biomimetics: Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology. Physics Today, 2020, 70(23): 60-61.
[7] Gao Liu, Mccarthy Te, Jour, et al. The "Lotus Effect" Explained: Two Reasons Why Two Length Scales of Topography Are Important. Langmuir, 2006, 22(7): 2966-2967.
[8] Lee Hu, Kim Yi, Park, et al. Hydrophobic and ice phobic nanocoatings for aircraft surfaces: A review. Surface and Coatings Technology, 2021, 409: 126879.
[9] Li Ju, Sun Xi, Chen Li, et al. In fluence of Ta and Y co-alloying on the structure, mechanical, and thermal properties of TiAlN coatings. Surface and Coatings Technology, 2025, 495(233): 23445.
[10] Bedoya-Zapata, Omiya Ta, Serra Rer, et al. Tribological Performance of Silver- and Oxygen-Doped Diamond-Like Carbon Coatings Under Nitrogen-Based Copolymer Additives. Tribology Letters, 2025, 73(3): 23-34.