Plasmonic paints in aviation*

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Abstract

Plasmonic paints, rooted in the interaction between light and nanostructured metallic surfaces, have emerged as a revolutionary alternative to conventional pigment-based coatings, particularly in the demanding field of aerospace. This review synthesizes recent advancements in plasmonic coloration, nanostructure design, and material engineering, with a focus on their application in aviation. We begin by elucidating the physical principles behind plasmonic color generation and their superior optical characteristics, such as angle independence, high chromaticity, and environmental stability. Methodologically, we examine the fabrication approaches ranging from self-assembly and nanoimprint lithography to atomic layer deposition and additive manufacturing, all of which facilitate scalable and precise production of functional nanostructures. The comparative performance of plasmonic paints against traditional coatings in terms of weight reduction, durability, resistance to environmental degradation, and non-toxic composition is assessed. Findings highlight the significant optical and mechanical enhancements provided by these coatings, including their integration into multifunctional roles such as anti-corrosion, electromagnetic shielding, passive radiative cooling, and even colorimetric sensing. Furthermore, how these materials contribute to aircraft efficiency by reducing coating mass, improving surface properties, and enabling novel aerodynamic applications is analyzed. In conclusion, plasmonic paints stand at the intersection of photonic innovation and sustainable aviation technology. Their ability to deliver vibrant, tunable, and robust colors without the ecological drawbacks of conventional pigments positions them as key contributors to the future of aerospace coatings. As fabrication techniques mature, the transition from laboratory prototypes to industrial-scale deployment appears both feasible and imminent.

Keywords

Plasmonic colors, nanostructured coatings, aerospace surface engineering, metamaterials, eco-friendly aviation paints.

1. Introduction

Since the early days of aviation, the coating of aircraft surfaces has been regarded not merely as a matter of aesthetics, but as a functional necessity rooted in long-standing engineering practice. Paint, in the conventional sense, has played a crucial role in protecting the structural integrity of aircraft by shielding metal surfaces from corrosion, reducing the impact of ultraviolet radiation, and providing a certain degree of thermal insulation. Furthermore, it has long been used for identification, visibility, and branding purposes, fulfilling both regulatory and commercial requirements. For decades, the materials and techniques used in aircraft painting followed well-established norms, grounded in proven methods and time-tested materials, reflective of a discipline that places great value on reliability, safety, and continuity.

Traditional aircraft paints typically consist of organic binders, synthetic pigments, and solvent-based carriers. The application processes— whether by spray, dip, or brush— are standardized, meticulous, and carefully regulated. These systems, despite their complexity, have been refined over generations and have served the industry faithfully. However, even the most established traditions must adapt in the face of mounting pressures and evolving demands. In recent years, the

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aerospace sector has encountered an intensifying imperative to reduce environmental impact, increase fuel efficiency, and enhance the functional lifespan of every component, including the aircraft's exterior coating.

The limitations of conventional paints are becoming increasingly apparent in this context. The mass of paint applied to a commercial airliner can add several hundred kilograms to the aircraft's weight, thereby increasing fuel consumption. In addition, organic pigments tend to fade under prolonged exposure to sunlight and extreme environmental conditions, necessitating periodic repainting— a costly and time-consuming process. Moreover, many traditional paints contain volatile organic compounds and other environmentally harmful substances that pose challenges in manufacturing, application, and disposal.

In parallel with these challenges, technological advancements in nanoscience and materials engineering have opened new avenues for innovation. Among the most promising developments is the emergence of plasmonic paint—a fundamentally different approach to coloration that does not rely on chemical pigments, but instead on nanostructured surfaces that manipulate light at the sub-wavelength scale. Drawing inspiration from natural phenomena— such as the vibrant wings of butterflies or the shimmering scales of certain beetles— plasmonic color arises from the precise arrangement of nanoscale metallic structures that resonate with specific wavelengths of light. In this way, color is not applied but engineered, and the result is a coating that maintains its vibrancy over time without the degradation associated with traditional pigment-based systems.

The implications of this shift are significant, particularly in the field of aviation, where every gram of weight matters, and every improvement in durability and performance has cascading benefits. Plasmonic coatings, by virtue of their physical rather than chemical origin, can be extraordinarily thin—often just a few hundred nanometers thick—resulting in a drastic reduction in overall paint weight. Their structural nature makes them highly resistant to fading, peeling, or chemical breakdown, even under harsh atmospheric conditions. Additionally, the tunable optical properties of plasmonic materials open the door to new functionalities, such as adaptive thermal control, radar absorption, or even sensor integration—features that are of increasing interest in both civil and military aviation sectors.

Despite the promise of plasmonic coatings, their implementation in large-scale industrial contexts such as aircraft manufacturing requires careful consideration. Production methods must be compatible with the rigorous standards of aerospace engineering. Materials must be not only effective but also safe, durable, and economically viable. Integration into existing maintenance, repair, and overhaul (MRO) processes is essential. These are not minor hurdles, but the history of aviation is a testament to the industry's capacity to gradually and methodically incorporate innovation—provided that the new respects the wisdom of the old.

This paper aims to provide a thorough exploration of plasmonic paint in the context of aviation. It begins by examining the physical principles that underlie plasmonic coloration, highlighting the interaction of light with metallic nanostructures and the resulting optical effects. It then discusses the technical methods by which these coatings are fabricated and applied, evaluating their suitability for aerospace applications. A comparison with traditional paint systems will be offered, focusing on weight, durability, environmental impact, and long-term maintenance requirements. Finally, the challenges of industrial adoption and the potential roadmap for future implementation will be considered, with an emphasis on harmonizing innovation with the conservative and safety-driven nature of the aviation industry.

At its core, the question is not whether the past should be abandoned in favor of the new, but rather how the lessons of tradition can inform and strengthen the application of emerging technologies. Plasmonic paint represents not a rejection of conventional wisdom, but its logical evolution— a refined tool, shaped by deeper understanding, to meet the enduring challenges of flight.

2. Plasmonic colors explained

Plasmonic colors arise from the interaction of light with nanostructured metallic surfaces, offering an alternative to traditional pigments.[1] They can be generated through through various designs, including hole arrays, rods, and metal-insulator-metal structures[2] and various methods, including laser-induced nanoparticle formation on bulk metals[3] , silver-based reflective metal-insulator-nanodisk plasmonic cavities[4], metal-coated microsphere lattices[1], metal nanopillar arrays fabricated using moth-eye films (angular independence and potential for colorimetric sensing applications)[5] and refractory hafnium nitride plasmonic crystals.[6]

The resulting colors are tunable by adjusting parameters such as nanoparticle size, metal type, and coating thickness.[1],[5],[7] Functional materials like magnesium, liquid crystals, and phase-change materials enable active control of plasmonic colors.[8-9] Scalable fabrication methods, such as colloidal lithography, have been developed to produce bright, reflective plasmonic colors using silver-based metal-insulator-nanodisk cavities.[4] Plasmonic colors have attracted interest due to their durability, potential for high-resolution rendering, and environmental benefits.[3][9]

Plasmonic superstructures created through physical triple co-deposition offer dichroic color engineering, enabling a wide range of colors in both reflection and transmission modes.[10] These advancements in plasmonic colors have potential applications in displays, sensors, and data storage.[5][10]

Plasmonic colors offer high resolution, with some systems achieving up to 63,500 dpi.[6] They also demonstrate potential for various applications, including reflective displays, solar energy harvesting, and colorimetric sensing, with some designs showing high refractive index sensitivity and resolution.[5-6] These advancements pave the way for practical applications of plasmonic structural coloring in various fields.

3. Plasmonic nanostructures in light-matter dynamics

Plasmonic nanostructures have emerged as powerful tools for manipulating light-matter interactions at the nanoscale. Plasmonic nanostructures enable manipulation of light-matter interactions at the nanoscale through surface plasmon resonances.[11] These structures can enhance decay rates and quantum efficiency of light emitters placed near metals.[11] Mode engineering in plasmonic nanoantenna arrays, combining lattice plasmon modes with local surface plasmon polaritons, creates Fano-type resonances that further enhance light-matter interactions.[12] Surface wave holography can be used to design plasmonic lenses and shape wavefronts.[13]. Amplification of surface plasmons in metal nanoparticles with gain media can lead to reduced resonance linewidth and enhanced local electric field intensity.[13] Plasmonic resonators, acting as nanosized metallic antennas, convert optical electromagnetic waves into localized fields, enabling the study and manipulation of light-matter interactions in nanoscale volumes.[14]

Plasmonic nanogaps, particularly in nanoparticle-on-mirror (NPoM) configurations, offer extreme field enhancement and controllable optical responses.[15] When integrated with two-dimensional materials, NPoM structures provide a platform for studying quantum plasmonics and enhancing interactions with excitons and phonons.[15] Experimental studies have demonstrated vertical distribution of light-matter interactions at ~1 nm spatial resolution, with photoluminescence enhancement factors up to 2800 times due to the Purcell effect and large local density of states in gap-mode plasmonic nanocavities.[16] These advances pave the way for novel applications in nonlinear optics, optoelectronic devices, and molecular optomechanics.[15] Recent advancements in plasmonic nanostructures have revolutionized light-matter interactions at the nanoscale. These structures can confine light into intense local electromagnetic fields, enabling applications in spectroscopy, energy harvesting, and chemical sensing.[17]

4. Plasmonic paint vs. traditional coatings

Innovative coatings were explored to improve aircraft efficiency and reduce environmental impact. Plasmonic structural color paints offer significant advantages. These ultralight coatings, weighing only 0.4 g/m2, provide vivid, angle-independent colors while being non-toxic and fade-resistant.[18-19] Additionally, novel Cirrus HybridTM coatings offer excellent protection for light metal alloys used in aerospace applications. These thin-film, inorganic coatings are up to 5 times thinner than traditional coatings, energy-efficient, and provide superior anti-corrosion, scratch resistance, and tribological properties.[20] These advancements in coating technology promise to enhance aircraft performance by reducing weight and drag while improving durability and environmental sustainability.

Superhydrophobic coatings have been developed as passive anti-icing systems for small aircraft, significantly reducing surface free energy and work of adhesion.[21] Ultralight plasmonic structural color paint has emerged as a revolutionary alternative to traditional pigment-based colorants, offering vivid, angle-independent colors with minimal weight.[22] Additionally, advanced electromagnetic shielding coatings, such as ZrB2 composites and metal-doped films, are being developed to enhance aircraft safety and reliability.[24] Plasmonic nanostructures with geometric disorder can exhibit an optical response that is insensitive to the choice of plasmonic material.[25] These innovations in coating technology contribute to reducing drag, improving overall aircraft efficiency, and addressing specific challenges in aerospace applications.

5. Plasmonic materials and their optical properties

Plasmonic materials and nanostructures offer unique optical properties and applications in nanophotonics. The arrangement and disorder of plasmonic nanoparticles can significantly influence their far-field optical properties and color appearance.[26] Interestingly, geometric disorder in plasmonic nanostructures can lead to material-insensitive optical responses, providing flexibility in material selection for various applications.[25] However, current plasmonic devices face challenges due to losses in constituent materials, prompting research into alternative plasmonic materials with improved performance.[27] These materials enable a wide range of applications, including optical nanoantennas, ultra-compact detectors, sensors, and energy harvesting designs. The field of plasmonics continues to advance, with developments in field enhancement, collective effects in nanostructures, and alternative plasmonic materials contributing to the transformation of nanoscale photonics and optical metamaterials.[28]

These materials can be used to create unique visual appearances through disordered resonant metasurfaces, combining plasmonic and Fabry-Perot resonances to produce uncommon iridescent effects.[29] Plasmonics enables the confinement of light energy to nanoscale oscillations, facilitating advancements in various photonic designs and applications, including nanoantennas, sensors, and energy harvesting.[28] Integration of plasmonic nanostructures with two-dimensional materials enhances light absorption efficiency and influences electronic properties, addressing the limitations of poor light absorption and restricted spectral responsivity in 2D materials.[30] These developments in plasmonic materials and their integration with other nanostructures are driving innovations in optoelectronic devices and expanding the possibilities for tailoring optical appearances.

6. Plasmonic paints: Optical innovations

Potential of plasmonic nanostructures for creating structural color paints were explored in recent research. These paints offer advantages over traditional pigment-based colorants, including stability, reduced toxicity, and vivid colors.[22] Self-assembled plasmonic nanoparticles near a mirror can produce angle-independent structural colors, providing a versatile and cost-effective coloration solution.[23] Plasmonic layers covering nanoparticles can be tailored to control scattering features, enabling complex optical effects such as Fano resonances and electromagnetic induced transparency.[31] These nanostructures have potential applications in biosensing, displays, and optical tagging.[31] Advancements in quantum plasmonics and optical-frequency magnetism have led to the development of "metamaterial paints" with unique optical properties, including the potential for negative refractive indices.[32]

Cencillo-Abad and colleagues developed angle-independent[33] and ultralight[22][33] plasmonic paints using self-assembled nanoparticles, offering vivid colors without the environmental toxicity of traditional pigments. These paints are scalable for industrial applications and achieve full coloration with minimal material. An optical Janus effect was demonstrated in multilayer plasmonic films, where reflected color varies depending on viewing direction, while transmitted color remains constant.[34] This effect has potential applications in architecture and security features. Polarization-controlled chromo-encryption using plasmonic nanorods was explored, producing a wide range of colors controllable by light polarization.[35] This technique allows for the creation of encrypted images and artworks with rich optical effects. These innovations demonstrate the growing potential of plasmonic materials for creating novel optical effects in paints and coatings.

7. Durability of plasmonic coatings

Recent research has focused on improving the durability and environmental stability of plasmonic coatings. Artificial antibody-based plasmonic biosensors have shown superior thermal, chemical, and environmental stability compared to natural antibody-based sensors, making them suitable for point-of-care applications.[36] Ultrathin protective coatings, such as aluminum oxide (Al2O3), have been found to significantly enhance the stability of plasmonic structures without altering their optical properties .[37] Atomic layer deposition (ALD) has emerged as a promising technique for creating shell-isolated silver nanostructures with long-term stability in various environments.[38] Furthermore, sub-10 nm nanolaminated Al2O3/HfO2 coatings have demonstrated remarkable effectiveness in extending the lifetime of copper plasmonic nanodisks in physiological environments, with a linear relationship observed between coating thickness and device longevity.[39] These advancements contribute to the development of more robust and stable plasmonic devices for diverse applications.

Molybdenum oxide coatings on aluminum nanostructures have demonstrated enhanced optical-field and long-term stability.[40] Atomic layer deposition (ALD) has been used to create ultrathin oxide coatings on silver nanostructures, providing long-term stability in various environments while preserving plasmonic properties.[38] For copper plasmonic nanodisks, sub-10 nm nanolaminated Al2O3/HfO2 coatings deposited by ALD have significantly extended their lifetime in physiological environments from ~5 hours to ~180 days.[39] Plasmonic nanoparticles offer unique reaction pathways for breaking down persistent pollutants in air, water, and soil, though further research is needed to overcome barriers to scalable implementation.[41] These advancements in protective coatings are crucial for expanding the applications of plasmonic materials in challenging environments and resource-limited settings.

8. Plasmonic coatings and paints for aircraft efficiency

Ultralight, non-toxic plasmonic structural color paints as develped as an alternative to traditional pigment-based colorants. These innovative paints exploit plasmonic resonances in self-assembled subwavelength cavities to produce vivid, angle-independent colors across the visible spectrum.[18][22] The paints are remarkably lightweight, with a surface density of only 0.4 g/m2, making them the lightest in the world.[19][22] Unlike conventional pigments, these structural colors offer improved environmental stability, fade resistance, and reduced toxicity.[18] The fabrication process utilizes large-scale techniques, bridging the gap between laboratory demonstrations and real-world industrial applications.[23] This versatile coloration solution can be applied to various substrates and has potential applications in biosensing, displays, and as stand-alone paints.[22][24]

9. Appearance of plasmonic paints in aviation

Plasmonic paints are emerging as a promising alternative to traditional pigment-based paints in aviation. While conventional paints offer angle insensitivity and large-volume production, they face challenges such as environmental toxicity and color fading.[42] Recent advancements in plasmonic structural color paints address these issues. These innovative paints utilize self-assembled subwavelength plasmonic cavities to create vivid, angle-independent colors while addressing issues of instability, toxicity, and environmental concerns associated with conventional pigments.[19][22] These ultralight paints, weighing only 0.4 g/m2, are non-toxic, fade-resistant, and environmentally friendly.[18] They can be fabricated using large-scale techniques, making them suitable for industrial applications. In aviation, surface treatments like plasma activation can enhance the wettability and surface properties of metal alloys used in aircraft construction.[43] The plasmonic paint technology offers a versatile platform for large-scale, low-cost applications, bridging the gap between proof-of-concept science and real-world industrial use.[33] Additionally, researchers have explored the potential of disordered resonant metasurfaces to create unique iridescent visual appearances by combining plasmonic and Fabry-Perot resonances. This approach offers uncommon iridescent effects and resilience to fabrication imperfections, making it suitable for innovative coatings and fine-art applications.[29] These advancements in plasmonic paint technology show promise for various industries, including aviation, where lightweight and durable coatings are highly desirable.

10. Fabrication techniques of plasmonic paints for aeronautical surfaces

Recent advancements in nanofabrication techniques have enabled the creation of plasmonic nanostructures with tailored optical properties for various applications, including aerospace engineering.[44-45] Fabrication methods such as electron-beam lithography, focused-ion lithography, and nanoimprint lithography allow for precise control over nanostructure size, shape, and periodicity.[45] These techniques can produce 2D and 3D plasmonic array patterns with tailored optical properties, enabling light management and electromagnetic field enhancement.[45] For aerospace applications, hierarchical structured surfaces fabricated by drag reduction from shark skin have shown promise in airfoil design, self-cleaning paints, and anti-corrosion coatings.[44]

Ion beam etching and lift-off processes are two common approaches for fabricating metallic nanostructures, with ion beam etching providing more precise control over smaller features.[46] These fabrication methods allow for the creation of plasmonic structural color paints, which offer advantages over traditional pigment-based colorants, such as improved stability and reduced environmental toxicity.[22] Additionally, an additive printing technology enables direct fabrication of gold/silver nanostructure patterns for plasmonic devices and sensors, allowing one-step production of large-area plasmonic substrates with size-controlled nanoparticles.[47] Plasmonic nanostructures can be designed to produce specific optical effects, including localized surface plasmon resonance and surface lattice resonance, making them suitable for applications in sensing and light management.[45] Another method combines solvent-assisted soft lithography with in situ nanoparticle growth to create large-scale arrays with precise control over particle characteristics, achieving ultranarrow surface lattice resonances.[48] These techniques offer potential for creating advanced plasmonic paints and surfaces for aeronautical applications, combining improved optical properties with practical fabrication methods. Plasmonic metasurfaces for coloration have been demonstrated using scalable techniques like embossing, injection molding, and roll-to-roll printing, with aluminum-coated polymer-based surfaces showing potential for mass production.[49]

11. Functional advantages of plasmonic paints in aviation

Plasmonic structural color paints are developed as an eco-friendly alternative to traditional pigment-based colorants. The self-assembled subwavelength plasmonic cavities overcome challenges of previous nanostructured materials, offering tailorable platforms for rendering structural colors.[19] [22]

These paints can be tailored for specific applications across the electromagnetic spectrum, enhancing sensing, energy, and optical communications capabilities.[50] Plasmonic structures can also be integrated into passive radiative cooling coatings, allowing for colorization while maintaining adequate cooling power of around 60 W/m^2.[51] Furthermore, colorful low-emissivity paints have been developed, exhibiting high reflectance in infrared wavelengths while displaying various colors. These paints enhance radiative heat insulation and reduce solar heat gain, leading to significant energy savings in space heating and cooling applications.[52]

12.Conclusion

In conclusion, plasmonic paints represent a transformative innovation in the field of aerospace coatings, reconciling the traditional demands of durability, safety, and performance with the modern imperatives of efficiency, sustainability, and functional versatility. Unlike conventional pigment-based coatings, which rely on chemically bound colorants and thick polymeric layers, plasmonic coatings derive their chromatic effects from engineered nanoscale metal-dielectric architectures. These structures enable vibrant, angle-insensitive colors in ultrathin films, reducing both the mass and the environmental impact of aircraft paint systems.

Throughout this review, the foundational physics of plasmonic coloration is explored —how nanostructures manipulate light through localized surface plasmon resonances— and the advancements in plasmonic nanostructures that underpin such optical control are examined. Careful comparisons to traditional coatings, highlighting the superior resistance of plasmonic paints to UV degradation, mechanical wear, and chemical exposure. Importantly, these materials also facilitate emergent functionalities such as passive thermal management, electromagnetic compatibility, and embedded sensing are drawn—each of which holds immediate relevance for current and future aircraft designs.

Innovations in fabrication are reviewed, also, ranging from self-assembly and scalable nanoimprint techniques to atomic layer deposition and additive nanoparticle printing. These methods pave the way toward industrial-scale application, ensuring that the promise of plasmonic paint can be realized without compromising aerospace standards. Still, challenges remain, including the integration of these coatings into existing maintenance frameworks and ensuring long-term reliability under the extreme environments of flight.

Looking forward, plasmonic paints offer a unique opportunity to modernize aircraft coatings in a way that honours the traditional values of aviation—safety, resilience, and craftsmanship—while embracing the benefits of nanoscale engineering. Their adoption could yield lighter, longer-lasting, and more sustainable paint systems, unlocking new performance margins in fuel efficiency and operational overhead. As fabrication techniques mature and interdisciplinary collaboration strengthens, plasmonic paints have the potential to shift from laboratory validation to mainstream aerospace practice.

In essence, plasmonic coatings do not aim to discard the traditions of aircraft paint—they seek to elevate them. Through a judicious blend of nanophotonic insight and material science, they offer a future where the aesthetics, function, and longevity of surface treatments meet the rigorous demands of flight. This synergy between legacy and innovation may well define the next generation of material appearance in aviation.

Declaration on generative AI

The author have not employed any generative AI tools.

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