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Review

Intelligent nanocomposite coatings for stratospheric airships: Materials, functions, challenges, and future directions

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Abstract: Due to their broad coverage and long operational duration, as well as their ability to be used as quasi-stationary platforms, stratospheric airships have gained increasing popularity for persistent near-space communication relay, Earth observation, environmental monitoring, and military reconnaissance. Nevertheless, their operational stability is severely threatened by the harsh conditions of the stratosphere, including intense ultraviolet light, ozone exposure, low pressure, extreme temperature variations, and periodic mechanical strain. The envelope coating, as the primary discontinuity between the lifting gas and the external environment, is a determinant of structural integrity, gas retention, thermal control, and operational reliability. This review is a systematic summary of recent developments in intelligent nanocomposite coating materials for airships operating in stratospheric airspace. The practical needs of these coatings, such as mechanical strength, environmental stability, gas protection properties, light structures, and multifunctionality, are initially discussed. Next, representative polymer matrices, multifunctional nanofillers, and new fabrication technologies are presented, with a focus on interface engineering and hierarchical structure design. The smart capabilities of self-healing, self-sensing, stimuli-responsive adaptation, and synergistic performance improvement mechanisms have been extensively examined. Existing uses in envelope protection, thermal control, anti-icing, anti-static dissipation, and structural health monitoring are outlined, and issues related to scalability, durability, cost, and system integration are noted. Lastly, future development trends, including AI-aided materials design, digital twins, self-powered sensing systems, and sustainable multifunctional coatings, are suggested. The intelligent nanocomposite coating is anticipated to transform the development of stratospheric airships by enabling the creation of lightweight, adaptive, and autonomous near-space systems.

Keywords: stratospheric airships; intelligent nanocomposite coatings; self-healing; structural health monitoring; multifunctional materials

1. Introduction

Stratospheric airships, or high-altitude platform stations (HAPS), are lighter-than-air aircraft meant to be flown continuously in the stratosphere, usually at altitudes of 18–25 km. Over the past few years, these platforms have gained increasing attention due to their ability to combine large-scale satellite coverage with the flexibility and recoverability of traditional aircraft. Stratospheric airships have the potential to offer lower-latency communications, simpler deployment, and lower operational costs compared to low Earth orbit satellites. They have much greater endurance, payload capacity, and the ability to remain stationary for extended periods than fixed-wing aircraft or unmanned aerial vehicles. These strengths enable stratospheric airships to serve a range of applications, including broadband communications relay, Earth surveillance, meteorological surveillance, disaster warning, environmental surveillance, border surveillance, and military reconnaissance [1–4].

Although potentially very promising, the harsh, highly unpredictable near-space environment limits the practical application of stratospheric airships. The stratosphere is subjected to severe service conditions, including intense ultraviolet (UV) radiation, high ozone concentrations, large diurnal temperature variations (between about −70 °C at night and over 50 °C during periods of solar radiation), and high wind shear. These environmental stressors can accelerate the deterioration of structural materials, leading to polymer embrittlement, microcracking, gas leakage, and mechanical fatigue. **Table 1** summarises the key environmental features of the stratosphere along with their effects on the performance of coating materials. Because the envelope itself constitutes most of the airship's structural surface area and is the primary point of contact between the interior lifting gas and the exterior environment, its long-term reliability directly affects the operational endurance, energy efficiency, and safety of the entire system [5–7]. A stratospheric airships envelope material is usually a multilayer composite system (layer) consisting of a structural substrate, a gas barrier layer, and a protective coating layer. One of these, the coating layer, is especially important, as it is responsible for protecting the airship against solar radiation, oxidative corrosion, moisture vapour penetration, electrostatic deposition, and mechanical erosion. Some of the commonly studied conventional coating materials include polyurethane, fluoropolymers, and silicon-based coatings, as these have relatively low density and are resistant to weathering. Nevertheless, such conventional coatings are typically optimized towards one particular task and cannot meet the challenging multifunctional needs of the next-generation stratospheric missions. As an example, a coating which is optimized to be very UV resistant can be very stiff at low temperatures, and a material with a good gas barrier can be very brittle or have a weight penalty. The issue of lightweight construction, mechanical toughness, environmental resilience, and functional integration at the same time has been a significant bottleneck [8–10].

Table 1. Environmental characteristics of the stratosphere and their effects on airship coating materials.

Environmental factor	Typical conditions in the stratosphere	Impact on coating materials	Required material response	References
Ultraviolet radiation	High UV-A/UV-B intensity	Polymer chain scission, photoaging, embrittlement	UV shielding, photostability	Chouhan et al. [11]
Ozone concentration	Elevated O_3 levels	Oxidative degradation, surface cracking	Ozone/oxidation resistance	Chouhan et al. [11]
Temperature fluctuation	−70 °C to +50 °C	Thermal stress, brittleness, softening	Thermal adaptability, flexibility	Chouhan et al. [11]
Low atmospheric pressure	1–10 kPa	Gas expansion, structural stress	Pressure resistance, dimensional stability	Huang et al. [12]
Wind shear/mechanical cycling	Continuous cyclic loading	Fatigue, crack propagation, delamination	Fatigue resistance, toughness	Hussain et al. [13]
Moisture/condensation	Temporary during ascent/descent	Adhesion loss, icing risk	Hydrophobicity, anti-icing	Xiang et al. [14]
Electrostatic charging	Friction/solar-induced	Electrical discharge, sensor interference	Conductivity, anti-static behavior	Bera et al. [15]

Recent developments in nanotechnology and smart materials have opened new possibilities for overcoming these limitations. Intelligent nanocomposite coating materials (polymer matrices containing a combination of nanoscale fillers and stimuli-responsive functional components) are a new class of advanced materials with the potential to offer synergistic properties. Mechanical strengthening, thermal stability, UV shielding, gas protection, and electrical conductivity can be significantly enhanced through nanoscale reinforcement and interface engineering by incorporating nanomaterials such as graphene, carbon nanotubes (CNTs), MXenes, nanosilica, titanium dioxide, and zinc oxide. More to the point, smart functionalities, such as self-healing, self-sensing, adaptive thermal control, anti-icing, and self-cleaning, enable coatings to respond to environmental conditions or structural damage, thereby improving service life and minimizing maintenance requirements [16].

Self-healing coatings, such as those that can automatically repair microcracks with intrinsic reversible chemical bonds or extrinsic healing factors trapped in microcapsules or vascular networks. This is especially significant for averting crack propagation and gas leaks during long-duration missions. Conductive piezoresistive or capacitive nanofiller networks, known as self-sensing coatings, can identify strain, temperature changes, or impact damage in real time, facilitating structural health monitoring and predictive maintenance. Also, tunable solar-reflectance or infrared-emissivity adaptive thermal-management coatings can be dynamically used to control the thermal balance of the airship envelope, reducing the effects of extreme temperature changes. These smart features herald a transition from passively protecting to actively perceiving, adapting, and repairing [17].

Despite considerable advances in nanocomposite and smart coating development across the aerospace, marine, automotive, and wearable electronics industries, research on their use in stratospheric airships remains comparatively limited. Most previous review articles have focused on general envelope materials or traditional aerospace-coated materials, or individual smart capabilities such as self-healing or anti-icing. There is no systematic review of intelligent nanocomposite coating materials for stratospheric airships in particular. Specifically, bridging the gap between material design, functional mechanisms, fabrication technologies, and the exceptional operational needs of near-space platforms is needed.

Thus, the main objective of this review is to present an extensive, futuristic overview of intelligent nanocomposite coating materials, a revolutionary technology driving the next generation of stratospheric airships. This is a new review in several ways. First, it systematically summarizes the functional needs of coating materials in stratospheric environmental conditions, such as mechanical, thermal, optical, and gas barrier requirements. Second, it categorizes and contrasts the most recent material systems, such as polymer matrices, nanofillers, and new two-dimensional materials, with a focus on interface engineering and hierarchical structural design. Third, it brings to light the intelligent features of self-healing, self-sensing, and stimuli-response adaptation and clarifies the mechanisms of their implementation towards better performance. Fourth, it discusses fabrication and scale-out problems, such as process scalability, long-term reliability, and multifunction trade-offs. Lastly, suggested future development trends include AI-aided materials discovery, AI-enabled health monitoring, and sustainable multifunctional coating systems [18].

By incorporating insights from materials science, nanotechnology, aerospace engineering, and intelligent systems, this review aims to develop a holistic model for the rational design of next-generation coating materials for use in stratospheric airships. It is hoped that smart nanocomposite coating will not only overcome existing shortcomings in endurance and reliability but also enable new capabilities that broaden the mission of near-space platforms. These materials can thus form a pivotal technological breakthrough in the creation of durable, robust, and self-sustaining stratospheric airships [19,20].

This article adopts a narrative critical-review approach to evaluate polymer–carbon nanocomposite coatings relevant to Vectran-based stratospheric airship envelopes. Relevant publications were identified from Scopus, Web of Science, and Google Scholar using combinations of the terms “Vectran coating,” “airship envelope,” “helium-barrier coating,” “polymer nanocomposite coating,” “carbon nanotube coating,” “graphene gas barrier,” “ultraviolet-resistant aerospace fabric,” and related keywords. Studies were considered when they addressed at least one of the following topics: helium or gas permeability, mechanical reinforcement, ultraviolet durability, coating–substrate adhesion, nanofiller dispersion, large-area coating fabrication, or environmental reliability. Publications dealing with unrelated substrate systems were used only when they provided transferable mechanistic or processing insights. Because the reviewed studies differ in substrate architecture, coating composition, nanofiller concentration, coating thickness, processing conditions, and test methodology, their numerical results are treated as literature-derived benchmarks rather than as directly comparable experimental data. The review therefore emphasizes mechanistic interpretation, cross-study limitations, engineering trade-offs, and research priorities rather than statistical meta-analysis.

2. Functional requirements and design principles of coating materials for stratospheric airships

The stratospheric airship envelope coating is not just a passive protective layer but a multifunctional engineering interface that directly controls aerodynamic stability, structural integrity, energy efficiency, and mission endurance. The airship is exposed to a mixture of environmental extremes that are not usually experienced together in other aerospace systems, such as high levels of ultraviolet radiation, high concentrations of ozone, low pressure, extremes in temperature, and cyclic mechanical loads due to wind shear and day-night thermal expansion when operating in the stratosphere. Such conditions impose very strict requirements on coating materials that are sometimes in conflict. The perfect coating system should hence offer lightweight protection at the expense of mechanical strength, environmental resistance, gas barrier properties, and smart responsiveness. The design philosophy has been transformed toward the maximization of individual properties, toward a multifunctional synergy with materials selection, structural engineering, and interface control [10,21,22].

2.1. Mechanical performance requirements

One of the most basic requirements for coating materials to be used in stratospheric airships is mechanical reliability. Even though the coating layer is not very thick compared with the structural substrate, it helps with resistance to abrasion, inhibition of crack initiation, and redistribution of local stress. The envelope undergoes numerous cycles of tensile, compressive, and flexural deformations during operation due to inflation-deflation cycles, aerodynamic forces, and dimensional changes from temperature variations. The cumulative effect of these cyclic stresses over time may lead to fatigue damage, interfacial delamination, and the propagation of microcracks.

A high-performance coating should thus have sufficient tensile strength, elongation at break, tear resistance, and fatigue resistance. This is, though, at the cost of flexibility when building strength. For example, highly crosslinked polymers or rigid inorganic fillers can enhance stiffness and puncture resistance but also decrease strain tolerance under dynamic loading. On the other hand, elastomeric materials are highly flexible and can have low creep and long-term deformation resistance. This trade-off underscores the need to balance stiffness and ductility through rational composite design [23,24].

To address this shortcoming, nanocomposite reinforcement has emerged as a viable approach. Nanoscale fillers such as graphene, carbon nanotubes, or nanosilica can greatly enhance load transfer efficiency and crack-deflection behaviour due to their high aspect ratio and high specific surface area. However, filler dispersion and interfacial compatibility are highly influential in the mechanical improvement. Agglomeration of nanofillers can lead to a concentration of stress sites, which will hasten, rather than inhibit, failure. Thus, interface engineering and hierarchical reinforcement architectures play an essential role in attaining a reliable mechanical performance [25].

2.2. Environmental resistance requirements

Polymer-based coatings are severely degraded in the stratospheric environment due to physicochemical processes. One of the most destructive of these factors is ultraviolet radiation. At altitudes in excess of 20 km, the lower atmospheric shielding leads to a large increase in UV intensity, which may cause chain scission, oxidation, discoloration, and embrittlement in polymer matrices. At the same time, high ozone levels enhance oxidative degeneration, which destroys unsaturated chemical bonds, further weakening the structure.

Another problematic issue is temperature fluctuation. Temperatures on the envelope surface can drop below −70 °C at night and rise to more than 50 °C when it is directly exposed to the sun. Thermal cycling may cause internal stresses due to incompatible thermal expansion coefficients between coating layers and substrate materials, thereby facilitating crack propagation and delamination. Various polymers are brittle at low temperatures and may soften or undergo accelerated ageing at high temperatures [26–28].

Coating materials used to resist these conditions should have superior photo-stability, resistance to oxidation, and thermal flexibility. Fluoropolymers and silicone are commonly used due to their high chemical bonds and low surface energy, which provide excellent weatherability. Inorganic nanoparticles (TiO_2, ZnO, and SiO_2) can enhance UV protection and thermal stability in light of their ability to reflect or absorb harmful radiation. Nevertheless, photocatalytic nanoparticles, including TiO_2, can unintentionally accelerate polymer degradation unless surface-modified. This shows that environmental resistance arises not only from the intrinsic properties of individual components but also from their interactions within the composite system [29–32].

Besides, the anti-condensation behaviour and moisture resistance cannot be ignored. Though the stratosphere is considered mostly dry, condensation can occur during descent or under transient atmospheric variations, potentially affecting adhesion and electrical performance. The hydrophobic or superhydrophobic surface of a multifunctional coating can reduce the presence of water and contaminants and provide self-cleaning properties [33–37].

2.3. Gas barrier and lightweight requirements

Reducing the permeation of lifting gases, e.g., helium or hydrogen, is one of the characteristic purposes of the envelope coating. The buoyancy can be greatly impaired by even small amounts of gas leakage during long-duration missions, resulting in higher energy consumption to maintain altitude or a reduced work life. The polymers permeate gases by solution diffusion mechanism, which is highly dependent on free volume, mobility of the molecular chains, as well as microstructural defects.

A good coating should then provide a dense, tortuous path for gas molecules to diffuse. Platelet-like nanofillers like graphene oxide, montmorillonite, and MXenes have shown to be particularly useful, as they enhance diffusion path length and decrease permeability. The impermeability of multilayer barrier architectures comprising inorganic and organic layers can be further enhanced by reducing defects and leveraging synergistic effects. Nevertheless, overloading filler can make it denser, less flexible, and cause processing issues [32].

Lightweight construction is also critical. Because the payload-carrying capacity and energy efficiency of stratospheric airships are highly sensitive to structural mass, the coatings need to be multifunctional with minimal weight penalty. This need is what makes airship coatings a lot different from much of the terrestrial protective coating, which do not have a mass-constrained need. The most significant issue is the maximisation of specific performance, which is the functional output per unit mass. Potential solutions include ultrathin coatings, porous nanostructures, and multifunctional fillers with the potential to simultaneously improve mechanical, barrier, and optical properties.

The problem of balancing barrier performance and lightweight design is more a matter of optimisation than maximisation. For example, a thicker coating decreases gas permeability and increases mass, which can limit flexibility. Further developments in material systems should target high-efficiency nanostructured barriers that deliver high performance at ultralow thicknesses [38–40].

2.4. Multifunctional integration and intelligent design principles

Conventional coating design tends to use a one-function optimization strategy, like maximizing UV resistance or reducing gas permeability. But the next generation of stratospheric airships must have coating systems capable of performing multiple functions simultaneously, such as protection, sensing, self-repair, thermal control, and electrostatic dissipation. Multifunctional integration has so become one of the key design principles.

Multifunctionality is difficult to achieve, due to the possible conflicts between various functional requirements. Indicatively, conductive networks employed in self-sensing or anti-static operation can affect optical reflectivity or rise in thermal absorption. Likewise, self-healing agents might reduce mechanical strength or create defects affecting barrier performance. The intelligent nanocomposite coating design should thus rely on integrating synergistically rather than additively.

One of the promising strategies entails hierarchical and multilayer architectures wherein the various layers have different but complementary functions. An outer layer could be an example of this, providing UV protection and the ability to clean itself; an intermediate layer could be a gas barrier and thermal insulation; and an inner layer could be a sensing or self-healing layer. This kind of structural decoupling minimizes functional interference without affecting the system performance [41].

Another principle that is vital is interface engineering. The interactions between the polymer matrices, nanofillers, and functional additives are critical to the performance of nanocomposite coatings. Dispersions can be enhanced through surface functionalization, coupling reagents, and covalent or noncovalent bonding to enhance dispersion, stress transfer, and environmental stability. Interfaces optimization in most instances provides more performance improvements than the filler content increment.

Moreover, computational methods, including molecular dynamics simulation, machine learning-aided materials screening, and performance prediction with the use of digital twins, are becoming increasingly important in intelligent design. These methods can help to speed up the process of finding optimal material combinations and forecasting the long-term behaviour under the complex conditions of the stratosphere. Instead of data-driven and application-oriented, the future of coating development is likely to be based on evidence-based on trial and error and research.

3. Material systems and fabrication technologies of intelligent nanocomposite coatings

The constituent materials and fabrication technologies of intelligent nanocomposite coatings for stratospheric airships determine the performance of these coatings. In contrast to traditional protective coatings, these systems need to combine various functionalities in an ultrathin and lightweight architecture and have the ability to remain stable under near-space conditions over time. The selection of the polymer matrix, type of nanofiller, and structural design has a direct impact on mechanical integrity, gas barrier, thermal, and intelligent responsiveness. Similarly, fabrication technologies affect microstructural uniformity, interfacial adhesion, defect density, and scalability. Thus, the creation of high-performance coatings is not merely a question of material choice but is a complex issue that necessitates a comprehensive view of composition-structure-property correlation as well as manufacturing limitations [42,43].

3.1. Polymer matrix materials

The coating is a continuous phase that is made of the polymer matrix and defines flexibility, adhesion, processability, and environmental stability. To be used in the stratospheric environment, the matrix should be mechanically stable at low pressure and at extremes of temperature and be compatible with active nanofillers and additives.

Polyurethane (PU) is one of the most frequently researched matrix materials due to its high flexibility, wear resistance, and adjustable mechanical characteristics. Elasticity and strength can be designed by the molecular structure, using soft and hard domains, which are segmented, enabling the mechanical properties of the structure to be altered. PU coatings have high adhesion to textile and film substrates that are typically used as airship envelopes. Conventional PU is, however, vulnerable to degradation by UV light and hydrolytic effects, leading to poor long-term performance unless stabilized with additives or fillers that shield against UV light. Waterborne PU systems have environmental benefits and simpler processing, although they could have worse barrier properties than solvent-based systems [44,45].

Polyimide (PI) has received growing attention due to its excellent thermal stability, chemical resistance, and mechanical strength. PI-based coatings are capable of sustaining structure at high temperatures and at high radiation levels. They have great resistance to oxidation and ozone attack due to their aromatic imide backbone. Nevertheless, the rigidity of PI itself tends to cause brittle behavior particularly at low temperatures and may require large-area coating fabrication to be done at the cost of poor processability. To overcome these limitations, flexible PI derivatives or PI-based hybrid composites have been created [46].

Polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), and fluorinated ethylene propylene (FEP) are some of the most appealing fluoropolymers because of their outstanding weather resistance, low surface energy, and lack of chemical reactivity. These materials are very UV stable and hydrophobic and can be used in outer protective layers. Their weak sticking to surfaces and lack of mechanical toughness, however, frequently require treatment on the surface or intertwining with other polymers. Also, fluoropolymers typically offer minimal self-healing or sensing and do not offer further functionalization [47].

Silicone polymers such as polydimethyl siloxane (PDMS) have a high level of flexibility, thermal stability, and low temperatures because of the high flexibility of the SiO backbone. They have a low glass transition temperature, which enables them to be used in adverse thermal cycling conditions. Moreover, silicone coating can be used to give anti-icing and self-cleaning features. However, their sufficiently high gas permeability and low mechanical strength limit their use as standalone products in applications with barrier critical requirements.

There is no one polymer matrix that can meet all the requirements at once. Consequently, blending and interpenetrating polymer networks have gained more significance in terms of combining complementary properties. The move is on hybrid polymer structures that can balance flexibility, durability, and multifunctionality in comparison to single-matrix systems [48].

3.2. Nanofillers and functional additives

The intelligent nanocomposite coatings are based on nanofillers, as nanoscale reinforcement and functionalization are both capable of improving several qualities at the same time. They are not only effective based on their intrinsic properties but also their morphology, dispersion state, and interfacial interaction with the matrix.

One of the most versatile fillers is carbon-based nanomaterials. Graphene and graphene oxide have high aspect ratios, mechanical strength, and very strong barrier properties. They have a tortuous diffusion pathway due to their two-dimensional structure, which renders them less permeable to gases. Secondly, graphene-based networks can be used to provide electrical conductivity, enabling self-sensing and anti-static properties. Poor compatibility with nonpolar polymers and aggregation are, however, the biggest challenges. Surface modification and covalent functionalization can be required to enhance dispersion [49].

CNTs offer high tensile strength, electrical conductivity, and thermal conductivity. Low CNT loading can also create percolation networks that enable strain or damage sensing. Their one-dimensional geometry is especially useful in bridging a crack and transferring stress. CNT dispersion is, however, hard to control and anisotropic alignment can result in unbalanced properties unless it is carefully engineered [50].

SiO_2, TiO_2, Al_2O_3, and ZnO are inorganic nanoparticles that are commonly used to enhance mechanical stability, UV protection, and thermal stability. SiO_2 nanoparticles increase hardness and abrasion resistance and decrease surface contamination. TiO_2 and ZnO are good UV absorbers and photocatalysts, but uncontrolled photocatalysis can be used to speed up the breakdown of the matrix. Al_2O_3 provides thermal insulation and wear resistance. The success of these nanoparticles is usually determined by the particle size and the treatment of the surface in order to limit agglomeration.

New two-dimensional materials, particularly MXenes, have attracted interest due to their distinct properties, including metallic conductivity, barrier properties, and electromagnetic shielding. Their stratified structure is capable of decreasing gas permeation and offering electrical pathways for sensing applications. Oxidation sensitivity and processing stability are, however, unresolved problems.

Another significant type is functional additives that heal themselves. Microcapsules containing therapeutic molecules can break when cracks form, releasing reactive molecules to mend the rupture. Alternatively, dynamic bonds that are reversible (such as hydrogen bonding, exchange disulphide, or Diels-Alder chemistry) can enable intrinsic self-healing in systems without external intervention. Although these systems enhance durability, they could undermine strength or complicate it [51].

On the whole, nanofiller systems are transitioning toward multifunctional, synergistic systems. The barrier, mechanical, and sensing functions of graphene and CNT fillers can be combined into hybrid fillers, including graphene-SiO_2 or CNT-MXene composites, to be more efficient than single-component fillers. **Table 2** provides a comparative overview of typical polymer matrices and nanofillers, their benefits, limitations, and common applications [52].

Table 2. Comparison of representative polymer matrices and nanofillers for intelligent nanocomposite coatings.

Material category	Representative materials	Main advantages	Main limitations	Typical functions	References
Polymer matrix	Polyurethane (PU)	Flexible, good adhesion, abrasion resistance	UV degradation, hydrolysis	Structural protection	Du et al. [53]
Polymer matrix	Polyimide (PI)	High thermal stability, chemical resistance	Brittle, difficult processing	Thermal protection	Daghigh et al. [54]
Polymer matrix	Fluoropolymers (PTFE, PVDF, FEP)	UV/weather resistance, hydrophobicity	Poor adhesion, low toughness	Outer protective layer	Ameduri [55]
Polymer matrix	Silicone (PDMS)	Flexibility, low-temperature stability	High gas permeability	Anti-icing/self-cleaning	Xun and Li [56]
Carbon nanofiller	Graphene/GO	Barrier property, strength, conductivity	Aggregation	Barrier, sensing	Lawal [57]
Carbon nanofillers	CNTs	High conductivity, crack bridging	Dispersion difficulty	Self-sensing, anti-static	Shchegolkov et al. [58]
Inorganic nanofillers	SiO_2	Hardness, abrasion resistance	Agglomeration	Wear resistance	Shchegolkov et al. [58]
Inorganic nanofiller	TiO_2/ZnO	UV shielding, photocatalysis	Photo-induced degradation	UV protection/self-cleaning	Baysal [59]
2D nanofiller	MXenes	Conductivity, EMI shielding, barrier	Oxidation instability	Sensing, anti-static	Baysal [59]

3.3. Fabrication and deposition methods

The fabrication techniques have a significant impact on the coating microstructure, thickness uniformity, and scalability. Even the most sophisticated formulation of materials may fail in case of defects, bad adhesion, or non-uniform dispersion during processing. Some of the most common methods include solution casting and spray coating because they are simple to use and can be utilized on large areas and flexible substrates. Solution casting can produce smooth films with controlled thickness, although solvent evaporation can cause defects such as voids or stress. Spray coating is scalable and flexible for complex surfaces, but it can be difficult to control uniformity and thickness.

The LbL assembly enables the formation of multilayer structures with nanoscale precision based on the alternating deposition of oppositely charged or interacting materials. One application of this method is the creation of gas barrier films and multifunctional hierarchical structures. LbL assembly is, however, currently quite slow, and not yet applicable to large-scale production.

CVD and atomic layer deposition (ALD) offer extremely uniform, conformal layers and fine control over thickness. CVD is widely used for depositing graphene or an inorganic barrier layer, and ALD can produce defect-free, ultrathin oxide layers that are more impermeable. However, such techniques tend to be costly and not easy to apply to large airship envelope surfaces. Electrospinning also enables the creation of nanofibrous interlayers with lightweight, multifunctional properties, e.g., thermal insulation or sensing. Together with coating technologies, hierarchical structures can be produced via electrospinning processes, yielding improved performance.

New techniques in additive manufacturing, such as 3D printing and emerging 4D printing, are also of interest for creating complex adaptive structures and surfaces that respond to stimuli. These technologies are in their infancy in large-scale aerospace coatings, though they could allow programmable morphologies and on-demand functional integration in the future.

The choice of fabrication technology must be based on performance as well as feasibility of the industry. Scalable, cost-effective, and reliable manufacturing processes are needed to work out the practical usage of airships [60]. The relationships among material systems, fabrication technologies, and resulting functions are summarized in **Figure 1**.

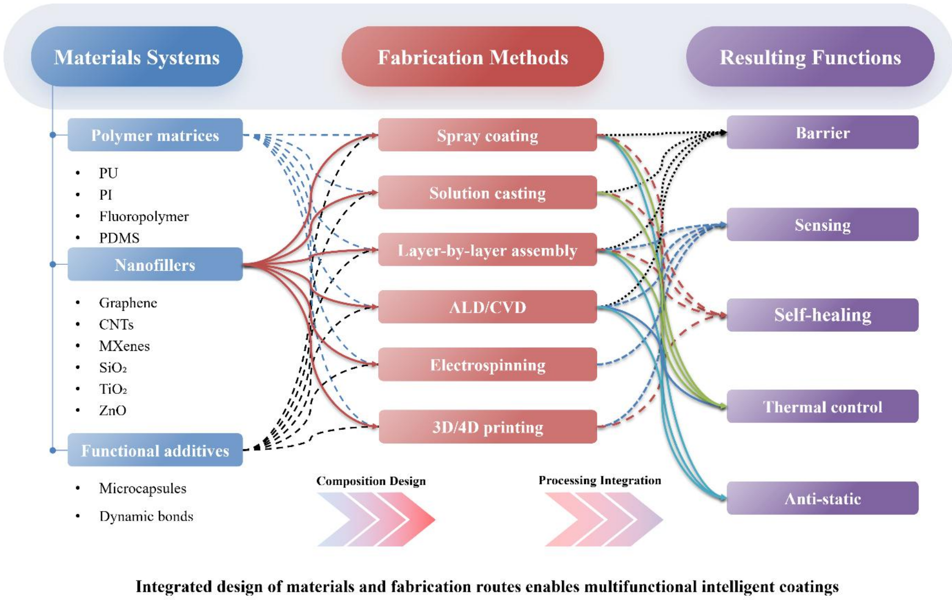

Figure 1. Classification of material systems and fabrication technologies for intelligent nanocomposite coatings.

3.4. Interface regulation and hierarchical structure design

The interaction between the polymer matrices and the nanofillers is usually the most critical aspect that can determine the performance of the composite. Inadequate interfacial adhesion may cause filler pull-out, stress concentration, and microvoids, compromising mechanical and barrier properties. On the other hand, good interfacial interactions enhance stress transfer, hinder crack propagation, and stabilize conductive networks.

A typical approach to interface regulation is surface modification of nanofillers. The compatibility and dispersion can be enhanced by the use of silane coupling agents, polymer grafting, and plasma treatment. Strong bonding is offered through covalent functionalization, but at the cost of filler structure, whereas covalent methods offer preservation of intrinsic properties at the cost of weaker bonds. The best solution is based on the desired function.

Multifunctionality is also increased with the hierarchical structural design, which organizes materials at various length scales. Toughness and barrier performance can be provided by bio-inspired architectures like nacre-like layered structures that are able to deflect cracks and dissipate energy in a controlled manner. Multilayer coatings have the potential to spatially isolate functions, minimising the interference of sensing, barrier, and protective elements.

An example is an outer layer rich in fluoropolymers can offer UV protection and be hydrophobic, a middle barrier layer of nanocomposites can offer lower gas permeability, and an inner conductive layer can offer structure health indicators. This type of architecture enables individual functions to be optimally tuned and at the same time, overall lightweight functionality to be maintained [61].

The design of the interface in the future is likely to be more data-driven. Machine learning and molecular simulations are able to make predictions of interface interaction and optimized formulations prior to experimental confirmation. This change of empirical optimization to rational design will speed up the creation of the next generation intelligent coatings.

In short, the overall performance of intelligent nanocomposite coatings of airships in the stratosphere is a joint decision of material systems and fabrication technologies. The development of polymer matrices, multifunctional nanofillers, scalable processing methods, and interface engineering has facilitated significant developments to lightweight, robust, and intelligent coating systems. But there are still problems to balance multifunctionality, processability and large-scale manufacturability. It is probable that future breakthroughs will be based on integrated design approaches based on new materials, hierarchical designs, and smart manufacturing technology [62].

4. Intelligent functions and performance enhancement mechanisms

The major difference between the traditional protective coatings and the intelligent nanocomposite coatings is the latter can sense, react, and recuperate to environmental or structural alterations. In the case of stratospheric airships, this intelligence cannot be described as a feature but as a technology that allows the airships to operate long distances with minimal maintenance. Cumulative damage, sudden thermal imbalance, electrostatic build-up, and performance decay are caused by the severe near-space environment, which is challenging to predict or correct in real time by external intervention. Intelligent coating is a solution to these problems, which employs the self-healing, self-sensing, adaptive response, and multifunctional reinforcement properties to lightweight material systems. These functions are realized with the help of complex physicochemical processes that act at the molecular, nanoscale, and macroscale. These mechanisms are critical concepts that must be understood in the rational design and optimization [43].

4.1. Self-healing mechanisms

One of the most appealing intelligent capabilities of stratospheric airships is self-healing, since even tiny cracks can spread due to cyclic loading and ultimately cause leakage of gases, delamination, or disastrous structural failures. Independent repair of damage may extend service life and reduce maintenance costs.

There are mostly two classes of self-healing mechanisms: intrinsic and extrinsic. Intrinsic self-healing is based upon reversible polymer network interactions or dynamic covalent chemistry. Common mechanisms include hydrogen bonding, metal-ligand coordination, disulfide exchange, imine bond exchange, and Diels-Alder reactions. On the event of an injury, these reversible bonds are capable of forming back under external factors like heat, light, or pressure to restore structural continuity. Intrinsic systems have the merits of being able to heal repeatedly without running out of healing agents. Nevertheless, the effectiveness of healing usually depends on molecular mobility, which can be restricted in low-temperature stratospheric conditions. Secondly, mechanical stiffness or thermal stability can be decreased by increasing dynamic bond density.

In extrinsic self-healing systems, the coating includes encapsulated networks of healing agents or vascular networks. As cracks spread, microcapsules are torn open, releasing monomers, catalysts, or reactive resins that polymerize and close the damaged area. The presence of multiple channels of supply of healing agents by the vascular systems allows many healing cycles. Such systems tend to provide fast and effective recovery of localized injuries. Microcapsules, however, could also be a source of defects that can weaken the matrix and once ingested, the body is no longer able to heal, unless it can be replenished [63,64].

In the case of stratospheric purposes, the greatest difficulty is to meet the requirements of healing capacity and lightweight manufacturing and environmental sustainability. The healing responses should be effective under low pressure, high temperature variations, and minimal external energy input. The systems in the future will have the capability of integrating both intrinsic and extrinsic strategies to attain repeatability as well as high healing efficiency.

4.2. Self-sensing and structural health monitoring

Stratospheric airships require structural health monitoring since it is hard to perform manual inspection and repair when the aircraft is on a long-duration mission. Self-sensing coatings offer distributed and lightweight strain, deformation, temperature, crack initiation, or impact damage detection in real time.

Changes in electrical properties are the most frequently used self-sensing mechanism in nanocomposite coatings. The percolative networks are created by conductive nanofillers like carbon nanotubes, graphene, MXenes, or metallic nanowires in the polymer matrix. Mechanical deformation changes the contact resistance or tunneling distance between conductive pathways, which leads to piezoresistive responses that are measurable. These systems are sensitive to tensile strain or bending or localized damage.

Capacitive sensing is also a common phenomenon investigated. In such systems, the geometries or dielectric constant of the coating are modified during deformation, which changes capacitance. Capacitive sensors tend to have more stability and reduced hysteresis compared to piezoresistive systems, but have more complicated signal processing.

Thermosensitive or thermoelectric effects can be used to sense temperature. This is especially useful for observing thermal gradients throughout the airship envelope and avoiding the build-up of thermal stresses. Multifunctional systems are able to monitor strain and temperature signals simultaneously, but signal decoupling is difficult [65].

Self-sensing coatings have some shortcomings, even though they have the potential. Conductive networks can corrode during repeated mechanical cycling or oxidation, causing signal drift. Increased filler loading enhances conductivity, but can reduce flex, transparency, or barrier. Moreover, the interpretation of data in large-area distributed sensing systems may be complicated. In the future, smarter and more autonomous structural-health monitoring of airships can be achieved through integration with wireless communication and AI-based anomaly detection.

4.3. Stimuli-responsive and adaptive functions

The stimuli-responsive coating is able to change its properties dynamically based on external stimuli like temperature, light, humidity, electric fields, or mechanical stress. In the case of stratospheric airships, adaptive behavior can be especially useful for thermal regulation, aerodynamic optimization, and environmental protection.

Thermo-responsive coatings can switch the solar reflectance or infrared emissivity in response to temperature. Variable emissivity material can release any unwanted heat during the day and store the heat during the night, hence balancing thermal conditions and lowering the amount of energy used to control active thermal regulation. This is commonly studied using phase-change and thermochromic materials such as vanadium dioxide (VO_2). VO_2 has a reversible metal-insulator transition that varies infrared transmittance. Nevertheless, it might need optimization in its transition temperature and durability to be used in the aerospace.

When it comes to solar irradiation, it is possible to vary optical properties by using photo-responsive coatings. Photochromic materials are materials that switch color or reflectance in the presence of UV, which could be used to control solar absorption. Likewise, photocatalytic surfaces have the potential to decontaminate and have self-cleaning characteristics. But there are also long-term photo-fatigue and undesired photocatalytic degradation of the matrix of concern [66].

Shape-memory materials have the ability to revert to pre-programmed shapes when exposed to thermal or electrical stimuli. As part of adaptive surfaces, they can facilitate morphing aerodynamic surfaces or functions of closing cracks. Despite this potential, in practice, it is difficult to apply in ultrathin coatings. Adaptive responses may also include the use of anti-icing and de-icing. Superhydrophobic surfaces reduce ice nucleation, and networks of electrothermal conductors can actively melt ice. As icing can happen in an ascent, descent, or transitional condition, adaptive anti-icing capability increases the reliability of operations. The primary weakness of stimuli-responsive systems is their stability in terms of functionality during repeated environmental cycling. Adaptive materials are usually fatigued, slow responding, or less effective with time. Consequently, the focus of future research must be on the reversibility over time, and efficient response mechanisms that are energy efficient [67].

4.4. Synergistic enhancement mechanisms

Multifunctional performance of intelligent nanocomposite coatings is often not due to the single components but due to the synergies between the matrix materials, nanofillers, and structural architectures. It is due to these synergistic processes that mechanical, thermal, electrical, and barrier properties can be enhanced simultaneously. The effects of nanoconfinement are important in polymer nanocomposites. Polymer chains at the nanoscale are close enough to filler surfaces, and this behavior results in enhanced mobility and orientation, which can enhance stiffness, thermal stability, and impermeability. Nanoconfinement is determined by the size of fillers, aspect ratio, and surface chemistry.

Interfaces interactions are also significant. Covalent or noncovalent bonding between fillers and the matrix is strong and enhances stress transfer and inhibits crack propagation. In conductive composites, stable interfaces ensure that electrical pathways are preserved through deformation, and it improves the reliability of sensing. Dielectric or electromagnetic shielding properties can also be enhanced by interfacial polarization [68].

Another important mechanism is multiscale reinforcement. Interconnected networks can be achieved by combining fillers of various dimensions, including zero-dimensional nanoparticles, one-dimensional nanotubes, two-dimensional nanosheets, and others, with a better distribution of loads and multifunctionality. As an illustration, graphene sheets can be used to provide barrier performance, and CNTs can be used to bridge cracks and be conductive.

The hierarchical architectures also enhance the synergistic effects through spatial organization of functions on different levels or scales. A layered design is capable of incorporating UV protection, gas barrier properties, and self-sensing without extreme functional interference. Bio-inspired structures like nacre-like lamellae enhance toughness by deflection of cracks and dissipation of energy. Nevertheless, this does not necessarily mean synergy. The lack of dispersion or incompatible interfaces or over-loading of fillers may have antagonistic effects, e.g., brittle behavior, agglomeration, and low processability. Thus, it is necessary to maximize cooperative interactions and minimize trade-offs by means of optimization. **Table 3** summarizes the smart functions, mechanisms, representative material systems, and their challenges surrounding nanocomposite coatings [69].

Table 3. Intelligent functions, underlying mechanisms, and representative material systems in nanocomposite coatings.

Intelligent function	Mechanism	Representative materials/systems	Advantages	Challenges	References
Self-healing	Reversible bonds	PU with hydrogen bonding/Diels–Alder polymers	Repeatable healing	Lower strength	An et al. [70]
Self-healing	Microcapsule release	Epoxy + healing microcapsules	High healing efficiency	Limited healing cycles	An et al. [70]
Self-sensing	Piezoresistive response	CNT/PU, Graphene/PI	Real-time strain monitoring	Signal drift	Zhang et al. [71]
Self-sensing	Capacitive response	Layered dielectric composites	Stable response	Complex electronics	Zhang et al. [71]
Thermal adaptation	Variable emissivity	VO_2-based composites	Thermal regulation	Transition temperature issue	Hu et al. [72]
Anti-icing	Superhydrophobicity/electrothermal	PDMS + CNT/graphene	Reduced ice adhesion	Durability concern	Peng et al. [73]
Anti-static	Conductive network	MXene/CNT composites	Charge dissipation	Conductivity stability	Peng et al. [73]

5. Applications, current challenges, and future perspectives

A key step toward making the next generation of stratospheric airships possible is the transition of intelligent nanocomposite coatings based on materials at the laboratory scale to viable systems in the realm of engineering. Although important advancements have occurred in the study of material systems, fabrication technologies and intelligent mechanisms, practical applications demand that these coatings operate accurately and predictably in the complicated conditions of operation over a long-term basis. Practically, coating materials should not only have multifunctional protection but should also be able to merge with airship structures, power systems, sensing networks, and mission-specific subsystems. Meanwhile, the issues of manufacturability, cost, durability and performance trade-offs remain in the way of large-scale adoption. In this section, the existing application scenarios are discussed critically, the key obstacles to implementation are outlined, and future research and development directions are outlined [8].

5.1. Current applications in stratospheric airships

Envelope protection is the closest use of intelligent nanocomposite coating in stratospheric airships. The envelope is subjected to constant UV radiation, ozone, thermal cyclic stress, and aerodynamic abrasion. Fluoropolymers, polyurethane hybrids, and silicone composites nanocomposite protective coatings have been explored to increase weather performance, mechanical stability, and gas retention. Barrier properties and crack resistance can be enhanced by the addition of nanoscale fillers (graphene oxide or nanosilica) to enhance the service life and decrease the leakage of helium. These coatings are used as passive protective barriers in current systems, although this is changing, and the additions of self-healing and sensing capabilities are starting to make these coatings an active structural interface.

Other significant applications include solar-reflective and infrared-control coating. Stratospheric airships face a significant problem in thermal management as overheating during daylight hours can lead to an increase in internal air pressure and structural forces, whereas cooling during the night can lead to a loss of buoyancy and impact onboard electronics. High solar reflectance and controlled infrared emissivity coatings can control surface temperature and minimize energy requirements of active thermal control systems. Compounds that use TiO_2, or Al_2O_3 or other thermochromic materials like vanadium dioxide have been promising in the dynamical regulation of heat and radiation. Despite these technologies being long-established in building materials and thermal control of spacecraft, their development to flexible, lightweight airship envelopes is still in its infancy [74].

Anti-icing and anti-static finishes become also more applicable. Icing is not as serious in the stratosphere because of the altitude at which the aircraft is based, but it may also be experienced during ascent or descent or during transient weather conditions. Nanostructured coatings that are superhydrophobic can slow the formation of ice and decrease the sticking of ice, whereas electrothermal de-icing can be offered by conductive nanocomposite coatings. On the same note, friction, atmospheric particulates, or sun radiation may result in the accumulation of electrostatic charges that could disrupt onboard electronics and pose discharge dangers. Charge dissipation pathways can be offered by conductive fillers (CNTs, graphene, or MXenes) without adding much weight.

One of the most promising applications is self-sensing coatings for structural health monitoring. The envelope can be equipped with distributed sensing layers that track strain distribution, crack formation, and temperature changes in real time. These systems can minimise the cost of maintenance and enhance the safety of operations through predictive diagnostics. Most of the reported systems are however at the prototype phase and are yet to be proven to work in the large-area near-space applications [75].

In general, existing applications are still disjointed, and most of the coatings are aimed at one or two particular functions. Multifunctional intelligent coatings that are truly integrated are still in their infancy.

5.2. Challenges in practical deployment

Although there are encouraging developments, there are several significant obstacles to implementing intelligent nanocomposite coatings on stratospheric airships in practice. The first one is scalability and consistency of manufacturing. Most high-performance coatings are designed in a controlled laboratory setting using small-scale fabrication tools such as layer-by-layer assembly, solution casting, or precision deposition techniques. It is still hard to scale these techniques to make defect-free layers on hundreds or thousands of square meters of flexible envelope material. Even small defects such as pinholes, agglomerates, or thickness variations can significantly reduce barrier performance and mechanical reliability.

Long-term durability and reliability are the second challenge. Laboratory tests are frequently concerned with short-term property improvement under controlled conditions, but the reality of airships is that the coating needs to last months or years of being exposed to UV radiation, thermal changes, mechanical wear, and oxidizing environments. The interaction effects among various degradation mechanisms are not yet well understood. For example, repeated mechanical deformation can hasten the disruption of nanofiller networks, reducing sensing performance and electrical conductivity. In the same manner, UV can compromise interfaces and decrease the ability to self-heal with time.

The complexity of one more challenge lies in its multifunctional, lightweight design. It is possible to add several functional fillers or multilayer structures to enhance performance, but it may make a filler more dense, complicated, and more difficult to process. In the case of stratospheric airships, the increase in envelope mass can dramatically impact the payload and energy usage. Thus, the coatings should be used to maximize specific performance more than absolute performance. This poses a challenging optimization problem in which increases in one property can come at the expense of others [75].

There are also cost and maintenance factors that restrict adoption. State-of-the-art nanomaterials like MXenes, high-quality graphene, or functionalized CNTs are costly and challenging to make on a large scale. In addition, certain intelligent functions, like extrinsic self-healing, can be necessitated by periodic replenishment, or can add complexity to maintenance. These materials have to be evaluated based on their economic viability in terms of mission duration, performance gains, and lifecycle costs.

Lastly, system-level integration is an under-researched area. Smart coatings would have to connect to airship control systems, wireless communication networks, power supplies, and data processing platforms. An example is that self-sensing systems must be able to obtain and process robust signal acquisition and interpretation in changing environmental conditions. Even the most useful materials will not provide practical value without proper integration [76].

5.3. Future development trends

The intelligent nanocomposite coating in the future is likely to shift towards increased autonomy, multifunctionality, and sustainability. Artificially intelligent material design and artificial intelligence are likely to be transformative. To find the best polymer-filler combinations, machine learning algorithms are capable of predicting the structure-property relationships and long-term degradation behavior. In combination with high-throughput experimentation and molecular simulation, AI-assisted design can considerably reduce development times.

Another potential direction is digital twin technology. Digital twins may be used to predict damage evolution, optimize maintenance schedules, and enhance mission planning by combining real-time sensor data of self-sensing coatings with virtual models of the airship structure. These systems may turn passive coatings into active components of an intelligent aerospace ecosystem [77].

Self-powered and autonomous sensing coatings are also bound to come into being. The energy-harvesting technology, including triboelectric, piezoelectric, or photovoltaic nanocomposites, could potentially be used to put coating on the armature that also provides sensing and communication capabilities. This would minimize reliance on onboard power systems and enhance operational independence in the long term.

Environmental regulations will increase in importance, and recyclable and sustainable materials will become more and more popular with the large-scale deployment. Recyclable thermoplastic polymers, bio-based polymers, and environmentally benign nanofillers have the potential to decrease the environmental impact of the lifecycle. Sustainability should, however, not be at the expense of durability or performance. The other important trend is the creation of multifunctional architectures that are fully developed. Instead of introducing separate functionalities, future coating systems will probably introduce gas barrier capabilities, thermal management, self-healing, sensing, anti-icing, and anti-static operations in hierarchical or gradient systems. This will require developments in interface engineering and smart manufacturing. **Figure 2** shows a potential future development path of intelligent nanocomposite coatings [2].

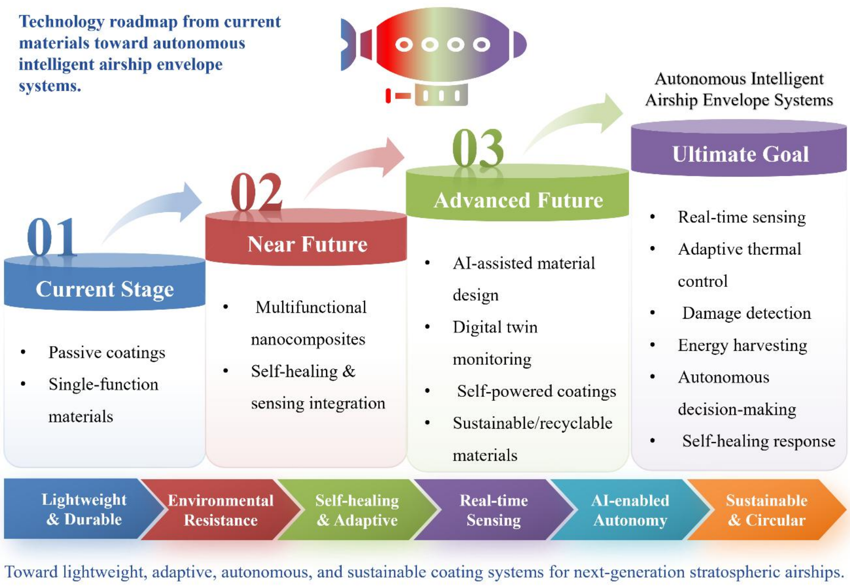

Figure 2. Future development roadmap of intelligent nanocomposite coatings for stratospheric airships.

Finally, standardization and realistic testing protocols are urgently needed. Current evaluation methods often fail to replicate the coupled environmental stresses of near-space operation. Accelerated aging tests combining UV radiation, ozone exposure, pressure variation, and mechanical cycling would provide more realistic performance assessment and facilitate industrial adoption. The major challenges, current limitations, and possible future development directions are summarised in **Table 4**.

Table 4. Current challenges, limitations, and future directions for the development of intelligent nanocomposite coatings.

Challenge	Current limitation	Potential solution	Future trend	References
Scalability	Small-scale fabrication methods	Roll-to-roll coating, automated deposition	Industrial mass production	Park et al. [78]
Durability	Limited long-term validation	Accelerated aging protocols	Standardized reliability testing	Cha et al. [79]
Multifunctionality trade-off	One property compromises another	Hierarchical/multilayer design	Fully integrated smart coatings	Tao et al. [80]
High cost	Expensive nanomaterials	Low-cost synthesis, hybrid fillers	Commercial viability	Homocianu [81]
System integration	Difficult sensor/data integration	Wireless sensing + AI analytics	Digital twin-enabled monitoring	Mihai [82]
Energy dependence	External power needed	Energy harvesting/self-powered systems	Autonomous coatings	Muthalif et al. [83]
Sustainability	Non-recyclable polymers	Bio-based/recyclable matrices	Green aerospace materials	Saitta et al. [84]

6. Conclusion

Stratospheric airships have become a very promising near-space platform for persistent communications, Earth observations, environmental monitoring, and defense-related services with long endurance, wide-area coverage, and quasi-stationary operation. But in practice, their operation in the harsh stratospheric environment and their long-term durability are essentially limited by the severe nature of the environment: extreme ultraviolet irradiation, exposure to ozone, extreme diurnal temperature variations, low pressure, and periodic mechanical stressing. In that case, envelope coating is no longer a mere protective coating but a multifunctional interface that is critical and directly defines structural integrity, gas retention, thermal balance, and mission endurance.

The review has summarized systematically the recent advancement in intelligent nanocomposite coating materials as a revolutionary technology of next-generation stratospheric airships. The first step was the critical analysis of the functional requirements of the coating materials in near-space conditions, which highlighted the necessity of mechanical robustness, environmental resistance, gas barrier performance, lightweight design, and multifunctional integration. Airship coatings are not limited to conventional aerospace-grade finishes; multifunctionality per unit mass is an important design parameter because of the very strict mass limits, especially where mass is a significant concern.

Second, this review also analyzed the important material systems and fabrication technologies employed in intelligent nanocomposite coatings. The different polymer matrices, such as polyurethane, polyimide, fluoropolymers, and silicone-based materials, have different benefits in terms of flexibility, durability, and environmental stability, and none of these can meet all the performance demands singly. Nano-scale reinforcement and interface engineering have greatly improved mechanical, thermal, electrical, and barrier properties by incorporating multifunctional nanofillers graphene, carbon nanotubes, MXenes, and inorganic nanoparticles. In the meantime, various fabrication technologies have developed, like layer-by-layer assembly, chemical vapor deposition, atomic layer deposition, electrospinning, and additive manufacturing, and have facilitated more complex hierarchical and multifunctional architectures.

Third, the smart functions and performance improvement systems of these coatings were explained. Microcracks may be autonomously repaired by self-healing systems, strain, damage, and temperature can be monitored in real-time by self-sensing coatings, stimuli-responsive materials can be able to change thermal, optical, or aerodynamic properties under changing environmental conditions. These smart features change the purpose of coatings to be not mere protection, but dynamic adaptation, senses, and healing. Dynamic molecular networks, conductive nanostructures, and multiscale hierarchical designs are the main factors that govern their effectiveness through synergistic interactions.

Lastly, the existing applications, key issues, and future perspectives were critically evaluated. Despite the promise of intelligent nanocomposite coatings in envelope protection, thermal management, anti-icing, anti-static control, and structural health monitoring, large-scale applications have yet to be realized due to manufacturability, long-term stability, cost, and system integration issues. The development in the future is probably AI-assisted materials discovery, predictive maintenance using digital twins, self-powered sensing, and sustainable multifunctional materials. Moreover, standardized testing procedures in near-space conditions will be necessary to hasten the industrial adoption.

In general, intelligent nanocomposite coating materials are a paradigm shift in materials that are transforming the design philosophy of stratospheric airships. These coatings will enhance the endurance, reliability, and the mission capability of near-space systems significantly by incorporating lightweight protection, autonomous functionality, and adaptive intelligence into one material platform. As new interdisciplinary materials science, nanotechnology, aerospace engineering, and artificial intelligence converge, intelligent coatings will play an inseparable role in the future design and evolution of resilient, autonomous, and high-performance stratospheric airships.

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