Corrosion in Military Aircraft: A Survey

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Abstract

This survey paper explores the pervasive issue of corrosion in military aircraft, with a particular emphasis on galvanic corrosion and its implications for structural integrity and operational reliability. It highlights the criticality of understanding corrosion mechanisms, especially in the presence of dissimilar metals and electrolytes, which form galvanic cells and accelerate material degradation. The paper underscores the economic and safety impacts of corrosion, which cost the U.S. over
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1 Introduction

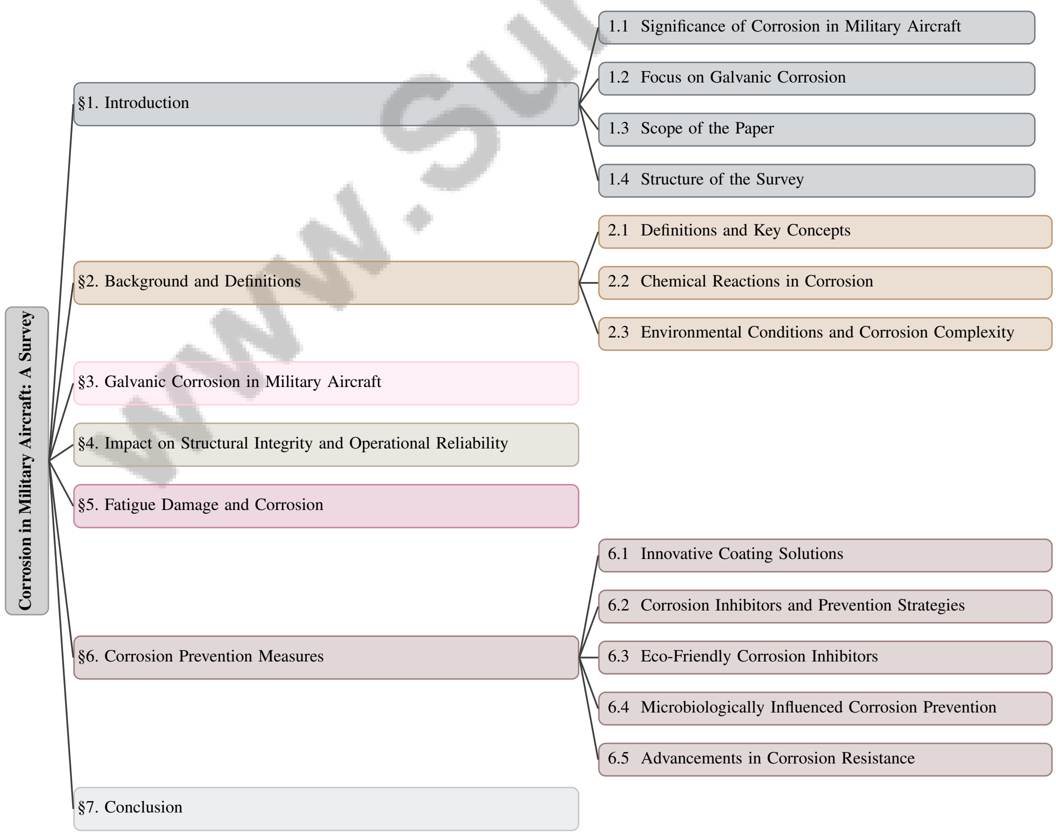

Figure 1: chapter structure

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1.1 Significance of Corrosion in Military Aircraft

Corrosion in military aircraft significantly impacts safety, performance, and economic viability. It threatens structural integrity, leading to the deterioration of critical components and compromising operational reliability [1]. The economic burden of corrosion is considerable, with estimates exceeding $300 billion annually in the United States alone [2]. This highlights the urgent need for advanced corrosion resistance model.$

The degradation of passive films on materials like 316L stainless steel, commonly used in military applications, underscores the importance of understanding corrosion mechanisms to maintain safety and performance standards [3]. The economic ramifications extend beyond maintenance costs to include potential safety hazards and impacts on the aircraft's operational lifecycle. Developing environmentally friendly corrosion inhibitors and advanced materials, such as hexagonal boron nitride, is crucial for effective long-term corrosion protection [4]. The economic implications of corrosion in military aviation mirror those in other industries, emphasizing the need for comprehensive understanding and mitigation strategies [5].

1.2 Focus on Galvanic Corrosion

Galvanic corrosion is a critical concern in military aircraft due to its widespread occurrence and significant impact on material degradation. This type of corrosion occurs when dissimilar metals are coupled in corrosive environments, a frequent scenario in military settings. The high chemical activity of binary magnesium (Mg) alloys, commonly used in military applications, makes them particularly susceptible to galvanic corrosion [6]. Additionally, interactions between graphene and metal substrates can form galvanic cells, further complicating the corrosion process [2].

Mathematical modeling of galvanic corrosion phenomena in electrochemical systems is essential for understanding and predicting these processes in the complex environments faced by military aircraft [7]. The inhibition of hydrogen evolution during corrosion, particularly in magnesium alloys, highlights the complexity of galvanic corrosion [8]. Addressing the environmental threats posed by corrosion through the development of eco-friendly inhibitors is imperative, given the operational challenges associated with galvanic corrosion in military contexts.

A deeper understanding and management of corrosion processes in aircraft structures, rooted in electrochemical and chemical interactions, is essential [9]. The mechanisms of corrosion inhibition are closely tied to galvanic corrosion, necessitating advanced mitigation strategies to protect military assets [5]. Consequently, this survey prioritizes galvanic corrosion due to its critical threat to the structural integrity and operational reliability of military aircraft.

1.3 Scope of the Paper

This survey delineates the parameters of corrosion research in military aircraft, focusing on aspects with significant implications for structural integrity and operational reliability. It emphasizes advancements and challenges related to hexagonal boron nitride (h-BN) based anticorrosion coatings, including protection mechanisms, functionalization strategies, and scalable synthesis methods, while excluding materials that do not utilize h-BN's unique properties [10]. The survey also covers corrosion testing methodologies relevant to aerospace coatings, including both chromate and non-chromate systems, ensuring applicability to military aircraft and excluding unrelated materials or methods [11].

Additionally, phase-field models of corrosion, especially their interaction with mechanical fields and multi-physics modeling, are explored while excluding non-mechanistic approaches to maintain a focus on scientifically grounded methodologies [12]. The survey addresses corrosion modeling for steels in marine environments, incorporating empirical models and acknowledging their limitations, while excluding unrelated corrosion types [13]. Furthermore, it systematically screens and ranks magnesium corrosion inhibitors, evaluating the effectiveness of various compounds in preventing corrosion [8].

The mechanisms, classifications, and active functional groups of organic green corrosion inhibitors (OGCIs) derived from plant extracts are also examined, deliberately excluding synthetic and traditional inorganic inhibitors to focus on environmentally friendly alternatives [4]. Lastly, the survey considers the surface properties of carbon steels relevant to corrosion processes, providing foundational insights that inform the broader scope of corrosion in military aircraft [5]. Through these focused examinations, the survey aims to deliver a comprehensive overview of corrosion-related challenges and solutions pertinent to military aviation.

1.4 Structure of the Survey

This survey is systematically organized to provide a thorough analysis of corrosion in military aircraft, with a focus on galvanic corrosion and its implications. It is divided into key sections that address specific aspects of the topic to ensure a holistic understanding.

The introduction highlights the significance of corrosion in military aircraft, emphasizing the critical role of galvanic corrosion in compromising structural integrity and operational reliability. Following this, a detailed background section defines essential terms and concepts related to corrosion, elucidating the chemical reactions and environmental conditions that exacerbate corrosion complexities.

The survey explores the mechanisms of galvanic corrosion, detailing how dissimilar metals and electrolytes contribute to this phenomenon and identifying material vulnerabilities specific to military aircraft. It also examines the influence of tensile stress on corrosion severity.

Subsequent sections analyze the impact of corrosion on structural integrity and operational reliability, discussing the economic implications and practical challenges of managing corrosion in military contexts. The relationship between corrosion and fatigue damage is scrutinized, particularly focusing on hydrogen embrittlement and its role in material degradation.

A comprehensive review of current corrosion prevention measures assesses innovative coating solutions, the effectiveness of corrosion inhibitors, and advancements in corrosion resistance technologies. The survey investigates the application of eco-friendly corrosion inhibitors, specifically OGCIs derived from plant extracts, and highlights innovative methods for preventing microbiologically influenced corrosion (MIC), emphasizing their biodegradable and non-toxic properties, along with their effectiveness in protecting metal surfaces against corrosion [5, 14, 4, 15, 16].

The conclusion synthesizes key findings from the research, underscoring the critical need to comprehend and mitigate corrosion processes that significantly affect the structural integrity and longevity of military aircraft. By addressing various types of corrosion and their effects on aircraft materials, the study emphasizes that improved testing methodologies and realistic corrosion models are vital for enhancing aircraft performance and safety throughout their operational lifespan [9, 11, 13]. This survey aims to inform future research and development efforts in corrosion management, contributing to advancements in military aviation technology.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Definitions and Key Concepts

Corrosion in military aircraft is primarily the degradation of metal substrates through oxidation and electrochemical processes, leading to material loss and structural failures. This is critical in military contexts where structural integrity is paramount. The electrochemical nature involves complex interactions between metal surfaces and environmental components, resulting in significant economic losses, particularly in aviation [17]. Galvanic corrosion, prevalent in military aircraft, occurs when dissimilar metals contact an electrolyte, forming galvanic cells that accelerate degradation [18]. Magnesium alloys, commonly used in military applications, are especially vulnerable due to anodic dissolution and hydrogen evolution reactions [6]. The degradation of passive films on materials like stainless steel, often exacerbated by chloride ions, further complicates corrosion mechanisms [3].

Corrosion inhibitors are vital for mitigating these effects, particularly in magnesium alloys, by slowing corrosive processes [8]. Organic green corrosion inhibitors (OGCIs) offer biodegradable and non-toxic alternatives to traditional inhibitors, aligning with environmental sustainability [4]. Their effectiveness is crucial for maintaining the structural integrity of military aircraft [5]. Advanced mathematical modeling, including the non-local sinh-Poisson equation, is essential for predicting corrosion behaviors and designing effective prevention strategies [7]. However, challenges remain in accurately predicting corrosion inhibition performance, especially with small datasets prone to overfitting in machine learning models [17]. Addressing these challenges is critical for developing robust corrosion management strategies in military aviation.

2.2 Chemical Reactions in Corrosion

The chemical processes underlying corrosion in military aircraft involve complex electrochemical interactions and environmental influences. Stress corrosion cracking (SCC) occurs when materials under tensile stress in corrosive environments experience crack initiation and propagation. High-temperature SCC (HSSCC) is particularly concerning for titanium alloys exposed to halides at 200-500°C, where crack propagation accelerates [19]. Understanding the electrochemical response of materials under tensile stress is crucial for elucidating accelerated corrosion mechanisms, revealing the interplay between mechanical stress and corrosion kinetics [20]. This interplay is complicated by the spontaneous nature of metal corrosion, driven by chemical thermodynamics and environmental factors, including electrolytes and microbiological activity.

Magnesium alloys, widely used in military applications, exhibit hydrogen evolution during corrosion, complicating prevention strategies [8]. The corrosion of carbon steels, influenced by surface characteristics and galvanic interactions, is critical for understanding aircraft component degradation [5]. Current protective coatings, such as those with graphene, can inadvertently promote corrosion through galvanic interactions with underlying metal substrates, highlighting the complexity of corrosion chemistry [2]. Existing testing methods often fail to replicate the diverse environmental conditions faced by military aircraft, necessitating advanced research methodologies to accurately capture corrosion dynamics [11].

A thorough understanding of the complex chemical reactions involved in corrosion is essential for maintaining structural integrity and operational reliability in aircraft, given the diverse materials used in construction, varying environmental conditions, and the types of corrosion that can develop with aging. Advancements in corrosion modeling and testing methodologies are critical for predicting the service life of materials and coatings under real-world operational conditions, ensuring the longevity and safety of military aircraft [5, 11, 9, 13, 12].

2.3 Environmental Conditions and Corrosion Complexity

Environmental conditions significantly influence the corrosion processes affecting military aircraft, contributing to the complexity and variability of corrosion phenomena. Factors such as humidity, temperature fluctuations, and exposure to marine environments are particularly influential in accelerating corrosion rates and determining corrosion types [9]. High humidity levels, common in tropical and coastal regions, increase moisture accumulation on aircraft surfaces, promoting electrochemical reactions and the formation of corrosive electrolytes.

Marine environments, characterized by high salinity and chloride concentrations, exacerbate corrosion potential, especially for aluminum and its alloys used in aircraft structures. Chloride ions in marine atmospheres can compromise protective oxide layers on metal surfaces, facilitating localized pitting and crevice corrosion. Research employing advanced surface analysis techniques, such as Time of Flight Secondary Ion Mass Spectroscopy (ToF-SIMS) and X-Ray Photoelectron Spectroscopy (XPS), has shown that chloride ions can infiltrate the bilayer structure of the passive film on 316L stainless steel, particularly within the hydroxide outer layer, even at concentrations below XPS detection limits. This infiltration disrupts the passive state by inhibiting the beneficial enrichment of protective elements like chromium and molybdenum, ultimately increasing susceptibility to corrosion. Pre-passivation treatments in chloride-free electrolytes effectively block chloride entry into the passive film, preserving its protective qualities and mitigating localized corrosion risks in chloride-rich environments [5, 3]. This is particularly concerning for aircraft operating in naval and coastal regions, where prolonged exposure to salt-laden air can lead to significant material degradation.

Temperature variations substantially affect corrosion dynamics by influencing the kinetics of electrochemical reactions and the solubility of corrosive agents. Elevated temperatures can accelerate reaction rates and alter ion solubility, including chlorides that may penetrate protective oxide layers. This interaction is critical for understanding corrosion mechanisms, particularly for materials like carbon steel and stainless steel, where surface properties and environmental conditions significantly impact degradation and failure mechanisms [5, 9, 13, 3, 12]. Elevated temperatures can not only accelerate chemical reactions but also lead to moisture accumulation in confined spaces, further promoting corrosion.

The accumulation of pollutants and industrial emissions introduces corrosive agents, such as sulfur dioxide and nitrogen oxides, which can react with moisture to form acidic compounds that significantly accelerate corrosion processes in materials, particularly in aviation. Understanding the chemical interactions and environmental conditions contributing to these corrosion mechanisms is crucial for developing effective protective measures and improving material durability [5, 11, 9, 4, 13]. These acidic environments can lead to accelerated corrosion rates, increasing the complexity of managing corrosion in military aircraft. Thus, comprehending these environmental interactions is essential for developing effective corrosion prevention strategies and ensuring the structural integrity and operational reliability of military aircraft in diverse operational settings.

3 Galvanic Corrosion in Military Aircraft

Understanding the mechanisms of galvanic corrosion in military aircraft is crucial for addressing the challenges posed by this electrochemical phenomenon. The interaction of dissimilar metals in corrosive environments accelerates degradation, compromising material integrity. This section explores these mechanisms, highlighting their implications for military applications.

Figure 2 illustrates the hierarchical structure of galvanic corrosion mechanisms in military aircraft, categorized into electrochemical interactions, material vulnerabilities, and the impact of tensile stress. The figure emphasizes the susceptibility of materials such as magnesium and titanium alloys, the role of advanced modeling techniques, and the significance of protective measures in mitigating corrosion effects. By integrating this visual representation, we can better understand the complexities of galvanic corrosion and the critical factors influencing material performance in military contexts.

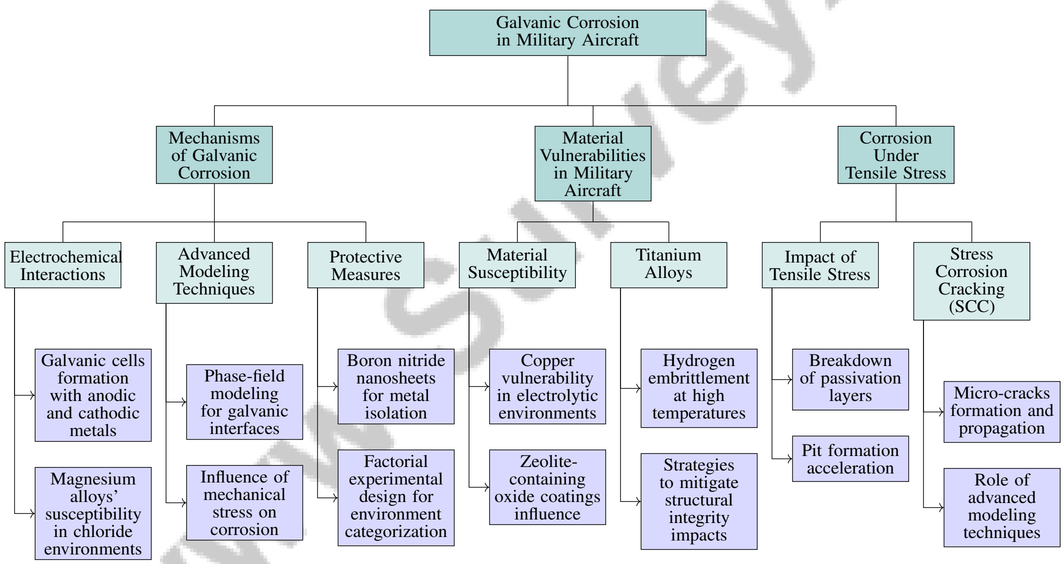

Figure 2: This figure illustrates the hierarchical structure of galvanic corrosion mechanisms in military aircraft, categorized into electrochemical interactions, material vulnerabilities, and the impact of tensile stress. It highlights the susceptibility of materials like magnesium and titanium alloys, the role of advanced modeling techniques, and the significance of protective measures in mitigating corrosion effects.

3.1 Mechanisms of Galvanic Corrosion

Galvanic corrosion in military aircraft is driven by electrochemical interactions between dissimilar metals and electrolytes, forming galvanic cells where the metal with lower potential becomes the anode, undergoing accelerated corrosion, while the cathodic metal remains protected [2]. Magnesium alloys, due to their anodic activity, are particularly susceptible, especially in chloride-rich environments where protective oxide layers are compromised [3]. In binary Mg alloys, the presence of dissimilar metals exacerbates corrosion rates [6].

Advanced modeling techniques, such as phase-field modeling, simulate galvanic interfaces without explicit interface tracking, providing insights into dynamic electrochemical interactions and the influence of mechanical stress on corrosion dynamics [18, 12]. The role of surface properties in corrosion resistance is further explored through frameworks categorizing research based on these characteristics [5]. Protective measures, including boron nitride nanosheets, aim to mitigate galvanic effects by isolating metals from corrosive environments [2].

Factorial experimental design links laboratory tests with real-world exposure, categorizing testing environments to develop effective strategies against galvanic corrosion [11, 9].

As illustrated in Figure 3, this figure encapsulates the mechanisms of galvanic corrosion, highlighting key areas such as electrochemical interactions, modeling techniques, and experimental design. The "Electrolyte and Electrode Configuration" image shows a model of cathodic and anodic regions, essential for understanding galvanic cell operation, while the "EIS Analysis of Copper" image offers insights into material behavior under various conditions, crucial for evaluating aircraft material durability [18, 15]. Together, these components emphasize the complex interplay between dissimilar metals, the role of advanced modeling like phase-field methods, and the importance of experimental frameworks to simulate real-world conditions.

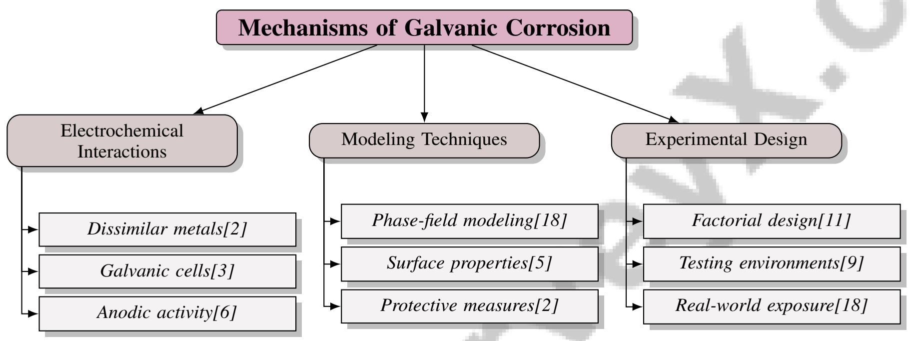

Figure 3: This figure illustrates the mechanisms of galvanic corrosion, highlighting key areas such as electrochemical interactions, modeling techniques, and experimental design. It emphasizes the complex interplay between dissimilar metals, the role of advanced modeling like phase-field methods, and the importance of experimental frameworks to simulate real-world conditions.

3.2 Material Vulnerabilities in Military Aircraft

Material susceptibility to galvanic corrosion in military aircraft is critical, impacting system durability and reliability. Copper is notably vulnerable when paired with noble metals in electrolytic environments [2]. Zeolite-containing oxide coatings enhance corrosion resistance but may influence galvanic interactions, necessitating careful material management [1]. Titanium alloys, while strong and corrosion-resistant, are prone to hydrogen embrittlement at high temperatures, requiring strategies to mitigate structural integrity impacts [19].

3.3 Corrosion Under Tensile Stress

Tensile stress significantly impacts galvanic corrosion rates and severity in military aircraft by breaking down passivation layers and exposing metals to corrosive environments, accelerating pit formation [20]. High entropy alloys, valued for aerospace applications, exhibit rapid corrosion under tensile stress, necessitating understanding of these mechanisms for structural integrity [9, 20]. Stress corrosion cracking (SCC) is heightened under tensile stress, with micro-cracks forming and propagating rapidly in corrosive environments. Advanced modeling techniques, like phase-field simulations, are essential for understanding mechanical stress and corrosion interplay, aiding in developing effective resistance strategies [20, 11, 12, 19]. Magnesium alloys, due to their reactivity, face rapid degradation under combined tensile stress and galvanic corrosion, requiring comprehensive mitigation strategies to ensure military aircraft structure durability and reliability.

4 Impact on Structural Integrity and Operational Reliability

4.1 Corrosion and Structural Integrity

Corrosion poses a significant threat to the structural integrity of military aircraft, with galvanic and crevice corrosion being particularly detrimental in operational environments. The use of boron nitride (BN) nanosheets is effective in inhibiting copper substrate oxidation, crucial for maintaining aircraft component integrity [2]. Advanced mathematical models, such as those developed by De la Torre et al., enhance the understanding of corrosion dynamics and degradation mechanisms [7].

Magnesium alloys, favored for their lightweight properties, are especially susceptible to galvanic corrosion, necessitating robust management strategies [8]. Severe corrosion-related aircraft failures documented by Czaban et al. underscore the critical need for effective interventions [9]. Surface properties play a pivotal role in corrosion resistance, as highlighted by Dwivedi et al., emphasizing the importance of understanding the relationship between surface characteristics and corrosion resistance for assessing impacts on structural components [5].

To visualize the complexities involved in addressing these challenges, Figure 4 illustrates the hierarchical structure of corrosion threats, management strategies, and testing methodologies relevant to maintaining the structural integrity of military aircraft in corrosive environments. Addressing corrosion's impact on structural integrity involves integrating advanced materials, predictive modeling, and comprehensive management strategies. These efforts are vital for prolonging operational reliability, especially in corrosive environments that can compromise structural components over time. Improved testing methodologies for corrosion resistance can predict in-service performance, mitigating premature failures and enhancing military aviation's safety and effectiveness [9, 11].

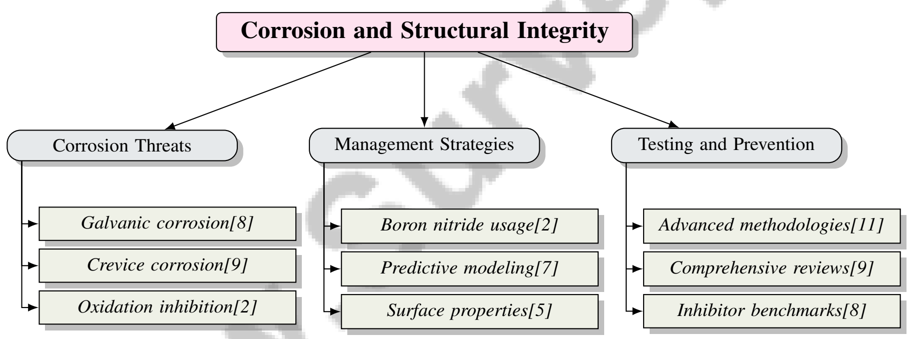

Figure 4: This figure illustrates the hierarchical structure of corrosion threats, management strategies, and testing methodologies relevant to maintaining the structural integrity of military aircraft in corrosive environments.

4.2 Operational Reliability and Economic Implications

Corrosion significantly affects the operational reliability and economic aspects of military aircraft, necessitating comprehensive management strategies. It compromises structural integrity, leading to increased maintenance demands and potential downtime. The U.S. aircraft industry faces an annual cost of approximately $2.2billionduetocorrosion, highlightingthesubstantialeconomicburden$[9].

Corrosion-induced failures critically impact operational reliability, resulting in unexpected maintenance needs and reduced aircraft availability. These failures necessitate extensive inspections and repairs, affecting mission readiness and increasing lifecycle costs. Corrosion incurs direct repair costs and necessitates premature component replacements, escalating labor expenses. This degradation, exacerbated by environmental conditions and aging materials, can lead to unexpected failures, straining military budgets. Enhanced understanding of corrosion processes and improved predictive models are essential for managing costs and ensuring aircraft longevity and safety [11, 9, 20, 13, 12].

Effective corrosion management is crucial for enhancing operational reliability and minimizing economic impacts. This involves implementing advanced monitoring technologies, predictive maintenance strategies, and developing corrosion-resistant materials. Addressing corrosion's root causes through proactive measures can improve operational efficiency, ensuring military aircraft remain mission-capable and cost-effective throughout their service life [9, 11, 13, 4].

4.3 Economic and Practical Considerations

Managing corrosion in military aircraft involves complex economic implications and practical challenges, requiring strategic resource optimization to ensure operational efficiency. The substantial economic burden of corrosion, encompassing maintenance, repairs, and replacements, significantly impacts military budgets. Effective management strategies must integrate comprehensive analyses of these economic implications, as they critically affect structural component integrity and can lead to costly failures if not addressed [9, 11, 13].

To illustrate these complexities, Figure 5 presents a hierarchical structure of corrosion management in military aircraft, highlighting key economic considerations, data and methodological challenges, and innovative solutions. The figure emphasizes the significant maintenance costs and budget impacts associated with corrosion, as well as the necessity for standardized data collection and advanced analytical tools to address data inconsistency.

A major challenge is the reliance on inconsistent data sets that fail to capture corrosion processes' complexity across varying environmental conditions. This inconsistency can result in suboptimal decision-making and resource allocation, underscoring the need for standardized data collection and analysis methodologies [13]. By improving data consistency and leveraging advanced analytical tools, military organizations can better predict corrosion risks and implement targeted interventions.

Innovative corrosion inhibitors, such as arginine, present promising economic benefits by reducing maintenance costs and extending component service life [21]. Such advancements yield economic savings and align with sustainability objectives, minimizing the environmental impact of corrosion management practices.

Practical challenges in corrosion management include integrating new technologies and materials into existing systems. Ensuring compatibility and effectiveness requires rigorous testing and validation, which can be resource-intensive. However, the long-term advantages of enhanced corrosion resistance and reduced maintenance requirements justify the financial investments, ultimately improving operational reliability and fiscal sustainability. By investing in advanced materials and coatings that provide superior corrosion resistance, military aviation programs can ensure longer service lives for aircraft, lower maintenance costs, and enhance mission readiness and operational effectiveness [9, 20, 11, 13]. Addressing these economic and practical considerations is essential for developing comprehensive corrosion management strategies that protect military assets and optimize resource utilization.

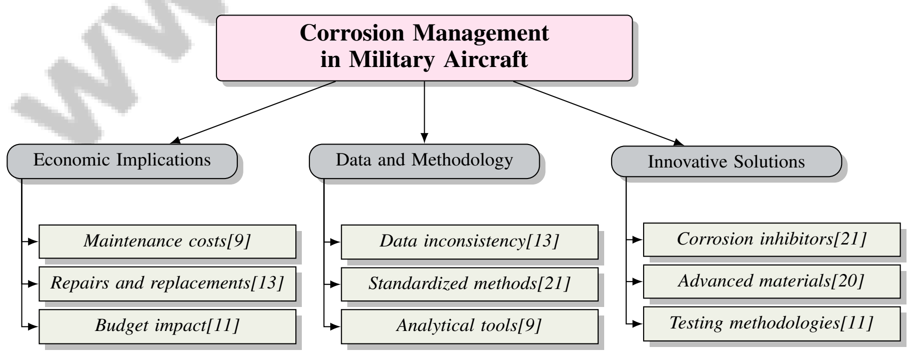

Figure 5: This figure illustrates the hierarchical structure of corrosion management in military aircraft, emphasizing economic implications, data and methodological challenges, and innovative solutions. Key economic considerations include maintenance costs and budget impacts. The need for standardized data collection and advanced analytical tools addresses data inconsistency. Innovative solutions involve corrosion inhibitors, advanced materials, and improved testing methodologies.

5 Fatigue Damage and Corrosion

5.1 Fatigue Damage Related to Corrosion

Corrosion significantly exacerbates fatigue issues in military aircraft, leading to premature material failure and compromised structural integrity. The interplay between corrosion and mechanical stresses, especially during flight operations, accelerates fatigue crack initiation and propagation, posing severe risks to aircraft longevity and safety [9]. Stress corrosion cracking (SCC), a critical concern, arises from the combination of tensile stress and corrosive environments, resulting in rapid micro-crack development that propagates under cyclic loading, potentially causing catastrophic failure [9].

Hydrogen embrittlement further contributes to corrosion-related fatigue damage, particularly in high-strength steels and alloys. Hydrogen infiltration into the metal lattice reduces ductility, increasing susceptibility to cracking under stress. This is especially problematic for TWIP steels, where hydrogen embrittlement at grain boundaries can lead to intergranular cracking, severely affecting fatigue resistance [22].

Pitting corrosion, a localized form creating small surface pits, serves as a stress concentrator, facilitating crack initiation. These pits reduce the effective cross-sectional area of structural components, elevating stress intensity and accelerating fatigue crack growth under cyclic loading. Hidden corrosion in inaccessible areas poses additional challenges, often remaining undetected until significant damage has occurred [9].

Advancements in phase-field simulations offer promising avenues for understanding and predicting the complex interactions between corrosion and fatigue damage. Enhanced model efficiency and real-time monitoring technologies can improve corrosion predictions and enable proactive maintenance strategies to mitigate fatigue-related failures [12]. Addressing these challenges is essential for ensuring the structural integrity and operational reliability of military aircraft, ultimately extending their service life and enhancing safety.

5.2 Hydrogen Embrittlement and Corrosion

Hydrogen embrittlement critically affects material degradation in military aircraft, particularly concerning corrosion and fatigue. This phenomenon occurs when hydrogen atoms penetrate the metal lattice, reducing ductility and tensile strength, leading to premature component failure. Joseph et al. highlight that high-temperature stress corrosion cracking (HSSCC) in Ti-6246 alloy is significantly influenced by oxidation and hydrogen charging, with crack initiation at elevated temperatures [19]. Understanding hydrogen embrittlement mechanisms in high-temperature environments common in military aviation is crucial.

Insights from Khanchandani et al. reveal that hydrogen and oxygen segregation at grain boundaries can lead to intergranular cracking through a hydrogen-enhanced decohesion mechanism [22]. This is particularly detrimental in high-strength steels and alloys, where hydrogen presence severely compromises resistance to fatigue and stress corrosion cracking.

In microbial corrosion contexts, Sigdel et al. discuss the role of biofilm matrices in enhancing corrosion resistance, potentially mitigating hydrogen embrittlement [15]. The biofilm matrix acts as a barrier, reducing hydrogen ingress into the metal substrate and alleviating hydrogen embrittlement effects.

Research by Dalhatu et al. demonstrates that L-arginine grafted onto chitosan significantly improves corrosion inhibition efficiency, presenting a promising approach to addressing hydrogen embrittlement [21]. Such advancements in corrosion inhibitors not only protect metallic components but also enhance the overall durability and reliability of military aircraft by mitigating hydrogen embrittlement's adverse effects.

A comprehensive understanding of hydrogen embrittlement and various corrosion processes interactions is essential for formulating effective prevention strategies. This knowledge is vital for maintaining structural integrity and operational reliability in demanding environments where exposure to diverse corrosive factors significantly impacts material performance and longevity. Addressing these issues is critical for enhancing safety and extending aircraft components' service life, often enduring aging and variable operational conditions [9, 11, 22].

6 Corrosion Prevention Measures

Category	Feature	Method
Innovative Coating Solutions	Predictive Modeling	HTCS[6]
Corrosion Inhibitors and Prevention Strategies	Eco-Friendly Solutions	Cs-g-L-Arg[21]
Eco-Friendly Corrosion Inhibitors	Surface Treatment Strategies	PP[3]
Microbiologically Influenced Corrosion Prevention	Biofilm Protection	BPCP[15]

Table 1: This table provides a comprehensive summary of various methods and strategies employed in corrosion prevention for military aircraft. It categorizes the methods into innovative coating solutions, corrosion inhibitors and prevention strategies, eco-friendly corrosion inhibitors, and microbiologically influenced corrosion prevention, highlighting specific features and methodologies referenced in recent studies.

Corrosion prevention is crucial for the longevity and operational readiness of military aircraft, as environmental and material interactions threaten structural integrity. A multifaceted approach is necessary, starting with advanced coating solutions that enhance protective barriers against corrosive elements. Table 1 presents an organized overview of the key methods and strategies discussed in the text, emphasizing the diverse approaches to enhancing corrosion resistance in military applications. Additionally, Table 2 offers a structured comparison of key corrosion prevention strategies, underscoring the diverse approaches to enhancing corrosion resistance in military applications.

6.1 Innovative Coating Solutions

Advanced coatings are essential for mitigating corrosion in military aircraft, offering superior protection and durability. Incorporating hexagonal boron nitride (h-BN) into anticorrosion coatings significantly improves performance, leveraging h-BN's unique properties to extend component lifespan [10]. Zeolite-based coatings utilize photocatalytic properties to create effective protective layers [1]. The application of BN nanosheets further enhances barrier performance against oxidation and corrosion [2].

Recent advancements in non-chromate coatings address environmental and health concerns, providing reliable protection in harsh environments [11]. Pre-passivation methods improve resistance by preventing chloride ion penetration [3]. Machine learning techniques in material development offer efficient predictions of corrosion-resistant Mg alloys [6]. Grafting L-arginine onto chitosan and developing biodegradable inhibitors align with sustainability goals [21, 14].

These innovations highlight advancements in corrosion protection, emphasizing novel materials and methodologies to enhance aircraft durability in corrosive environments. Future research should focus on advanced detection techniques and tailored prevention strategies [9].

6.2 Corrosion Inhibitors and Prevention Strategies

Effective corrosion inhibitors are vital for military aircraft longevity and reliability. Traditional inhibitors raise environmental concerns, prompting the development of biodegradable alternatives [4]. Dalhatu et al. present an eco-friendly inhibitor from natural materials, showcasing sustainable corrosion protection [21]. Biomass inhibitors, including plant-based, amino acid-based, and biosurfactant types, offer promising natural solutions [14]. L-arginine grafted onto chitosan exemplifies amino acid-based inhibitors in military contexts [21].

Understanding magnesium corrosion mechanisms can lead to improved strategies tailored to material vulnerabilities [23]. Atomic-scale studies suggest carbon segregation mitigates hydrogen embrittlement, enhancing material resilience [22]. Identifying efficient, environmentally friendly inhibitors remains challenging, especially in aggressive settings [16]. Addressing these challenges requires integrating advanced research, innovative materials, and sustainable practices to protect military assets.

6.3 Eco-Friendly Corrosion Inhibitors

Eco-friendly inhibitors are gaining traction as sustainable alternatives to traditional toxic inhibitors. Organic Green Corrosion Inhibitors (OGCIs) provide effective protection while minimizing ecological impact [4]. Biomass inhibitors offer cost-effective, renewable solutions [14, 16]. Microbial approaches, such as biofilm matrices, inhibit bacterial growth, offering non-toxic alternatives [15].

Future research should optimize pre-passivation conditions to enhance eco-friendly inhibitor efficacy, paving the way for robust strategies against chloride-induced alterations [3]. Integrating natural and biomass-based inhibitors represents a promising strategy, combining high efficiency with sustainability. Continued exploration of these alternatives is essential for advancing corrosion protection in military applications [14, 4, 16, 17].

6.4 Microbiologically Influenced Corrosion Prevention

Microbiologically influenced corrosion (MIC) presents significant challenges in aircraft maintenance. Biofilm matrices offer promising prevention, as demonstrated by Sigdel et al. with a Citrobacter sp. strain MIC21 biofilm on copper surfaces, effectively inhibiting microbial corrosion [15]. This is particularly relevant for copper components in military aircraft. Establishing stable biofilms reduces corrosion rates, aligning with sustainable methods like OGCIs from plant extracts [14, 4, 16].

Developing biofilm-based strategies requires understanding microbial interactions with metals. Optimizing biofilm properties is crucial for maximizing resistance and passivation [15, 5]. Identifying strains forming effective barriers without compromising structural integrity is essential. Continued research is vital for optimizing biofilm formation in diverse environments.

Integrating microbial approaches into prevention strategies marks significant progress in combating MIC. Leveraging biofilms' protective properties offers a sustainable solution for maintaining aircraft material integrity in corrosive environments, contributing to safer operations [11, 14, 9, 13, 15].

6.5 Advancements in Corrosion Resistance

Recent advancements have significantly enhanced corrosion resistance in military applications. Integrating h-BN into anticorrosion technologies represents a breakthrough, capitalizing on its unique properties [10]. BN nanosheets prevent galvanic corrosion, highlighting nanoscale materials' potential [2]. Zeolite-based coatings leverage photocatalytic properties for effective corrosion mitigation [1]. New inhibitors exhibit superior performance, enhancing aircraft resistance [8]. The KNN + VSG model improves prediction of inhibition efficiencies [17].

Phase-field models provide insights into corrosion processes, facilitating effective strategies [12]. Understanding magnesium dissolution pathways opens new prevention avenues [23]. Future research should focus on composite OGCIs and synergistic effects [4]. Exploring natural products indicates a shift towards sustainable solutions [14]. Advanced characterization techniques can highlight recent advancements relevant to military aircraft [5]. Efforts should target green inhibitors, leveraging nanotechnology, and exploring synergistic effects among inhibitors [16]. These initiatives are essential for advancing resistance technologies and ensuring aircraft durability in challenging settings.

Feature	Innovative Coating Solutions	Corrosion Inhibitors and Prevention Strategies	Eco-Friendly Corrosion Inhibitors
Material Type	H-BN, Zeolite, BN	Biomass, L-arginine	Ogcis, Biomass
Environmental Impact	Non-chromate, Sustainable	Eco-friendly, Biodegradable	Non-toxic, Renewable
Innovation Focus	Advanced Materials	Sustainable Practices	Sustainability

Table 2: This table provides a comparative analysis of various corrosion prevention methods, highlighting the distinctive features of innovative coating solutions, corrosion inhibitors and prevention strategies, and eco-friendly inhibitors. It emphasizes the material types, environmental impacts, and innovation focuses of each category, offering insights into sustainable practices and advanced materials for military applications.

7 Conclusion

The survey underscores the imperative to address corrosion challenges in military aircraft, with a particular focus on galvanic corrosion's adverse impact on structural integrity and operational efficacy. The exploration of advanced materials, such as hexagonal boron nitride and zeolite-based coatings, reveals their potential in significantly bolstering corrosion resistance and safeguarding against material deterioration. Additionally, the shift towards eco-friendly corrosion inhibitors supports sustainable practices, offering viable alternatives to traditional approaches.

The complex interplay between mechanical stress and corrosion phenomena, notably stress corrosion cracking and hydrogen embrittlement, poses considerable threats to aircraft integrity. The application of phase-field models, complemented by machine learning techniques, enhances the understanding of corrosion mechanisms, thereby refining predictive accuracy and steering future research directions.

Future research should focus on the effects of diverse environmental conditions and alloy compositions on high-temperature stress corrosion cracking susceptibility, and continue the development of corrosion-resistant materials. Addressing these areas is vital for advancing military aviation technology, ensuring aircraft resilience and performance in corrosive settings.

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