iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** IV **Month of publication:** April 2025

DOI: https://doi.org/10.22214/ijraset.2025.68490

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue IV Apr 2025- Available at www.ijraset.com

Corrosion Resistance in Aircraft: Evaluating Zirconium and Niobium Coatings for Fasteners and Leading-Edge Protection

Prajeesh Raj V[1], Shehna S[2], Anilu Anil[3], Gayathri Suresh[4], Revathy N B[5]
UG Scholar, Department Of Aeronautics, Jawaharlal College Of Engineering and Technology

I. INTRODUCTION

Aircraft operate in extreme environments, making them highly susceptible to corrosion caused by moisture, temperature fluctuations, and contaminants like salt and fuel residue. This corrosion weakens structural components, increases maintenance costs, and poses safety risks, especially in critical areas like the leading edge of the wing, which plays a key role in aerodynamics, stability, and efficiency. Various types of corrosion, including uniform, pitting, galvanic, and stress corrosion cracking, affect aircraft materials differently, necessitating protective measures such as coatings, corrosion-resistant alloys, and routine maintenance. Fasteners and rivets are particularly vulnerable due to their exposure to crevice and galvanic corrosion, making proper material selection, sealing, and inspections essential for ensuring aircraft longevity and safety.

A.Al-Waidh et al [1] Zirconium oxide (ZrO2) coatings were fabricated on stainless steel using a combined laser and sol-gel technique. A zirconium-based sol-gel solution was applied to the stainless steel surface, followed by laser irradiation to improve the coating's adhesion and surface morphology. Heat treatment was then applied to enhance the properties of the coating. The microstructure, phase composition, and corrosion resistance of the coatings were evaluated. The results showed that the laser/sol-gel process improved the adhesion strength and significantly enhanced the corrosion resistance of the zirconium oxide coatings on stainless steel, making them suitable for use in harsh environments.

Abirami Selvaraj et al [2] The impact of zirconium oxide (ZrO_2) nanoparticle coatings on stainless steel and nickel-titanium wires, commonly used in orthodontics.The coating’s ability to improve corrosion resistance, reduce friction, and enhance the biocompatibility of orthodontic wires. By applying zirconium oxide nanoparticles, the coating acts as a protective barrier, minimizing the wear and tear that occurs from constant mechanical movement in the oral environment and reducing the release of metal ions, which can cause adverse reactions. ZrO_2 coatings significantly enhance the durability and corrosion resistance of these wires, thus supporting safer and more efficient orthodontic treatment with reduced risk of adverse tissue response.

A.J.Cornet et al [3]As chromate-based coatings age, they become more susceptible to corrosion undercutting and pitting, particularly in high-stress areas where mechanical wear accelerates coating degradation. This deterioration can lead to localized corrosion, compromising the structural integrity of critical aircraft components, such as the fuselage and wing structures, which face constant exposure to varying temperatures, humidity, and airborne contaminants. Consequently, frequent inspection and maintenance cycles are essential to monitor coating condition and ensure early intervention, reinforcing the need for modern, eco-friendly alternatives that can provide sustained protection without the environmental and health hazards associated with chromates.

Alexy Vereschaka et al [4] ZrN coatings are already known for their hardness and durability, the addition of Nb and Hf results in a denser, more refined microstructure that improves wear resistance and reduces corrosion susceptibility. This doping also enhances the coating’s adhesion to metal substrates, preventing delamination and increasing component lifespan. Furthermore, the Nb and Hf doping optimizes the balance between hardness and elasticity, providing greater impact resistance and improving high-temperature oxidation resistance, making the coatings more suitable for demanding applications in industries like aerospace and marine engineering.

Arash Fattah-Alhosseini et al [5] The ZrN/CrN nano-multilayer coating significantly enhances the corrosion resistance and mechanical properties of AISI 304 stainless steel by providing a robust protective layer that acts as an effective barrier against aggressive environmental conditions. The alternating layers of zirconium nitride (ZrN) and chromium nitride (CrN) create a highly durable coating that improves not only the corrosion resistance but also the hardness and adhesion strength of the stainless steel substrate. This nano-multilayer structure is particularly effective at preventing the onset of corrosion by reducing the penetration of corrosive agents, making it more resistant to pitting and general corrosion compared to uncoated stainless steel.

This coating not only enhances the material's performance but also reduces maintenance costs and extends the operational lifespan of critical components, making it a highly effective strategy for improving the durability and reliability of stainless steel in corrosive environments.

Artem Okulov et al [6] The corrosion resistance properties of the in-situ C(B,Si) / Ni-Zr reinforced composite coatings on zirconium alloy are thoroughly analyzed in aggressive environments, such as acidic or high-salinity conditions, which are commonly encountered in industries like nuclear and aerospace. The incorporation of carbon-boron-silicon C(B,Si) and nickel-zirconium (Ni-Zr) reinforcement phases significantly improves the overall performance of the coatings. These phases contribute to enhanced hardness, making the coating more resistant to wear and mechanical degradation, while also improving the coating's ability to protect the zirconium alloy from corrosive agents. The addition of C(B,Si) and Ni-Zr not only reinforces the mechanical properties of the coating but also stabilizes the microstructure, making it more resilient under harsh operating conditions. This improved stability results in a coating that can withstand higher temperatures and more aggressive corrosive environments without losing its protective capabilities. This makes the composite coatings highly effective for extending the durability and performance of zirconium-based materials in extreme operational environments.

Babatunde Olamide Omiyale et al [7] Surface conditioning improved the corrosion resistance of 301 and 304 stainless steels. The treated samples showed better resistance to corrosion when subjected to the salt spray test, highlighting the effectiveness of surface conditioning in enhancing the durability of stainless steels in corrosive environments.

Bavanilatha Muthaiah et al [8] Zirconia is applied using Electron Beam Physical Vapor Deposition (EBPVD), a technique that allows for the creation of thin, dense, and uniform coatings. This enhances the coating's durability, making it suitable for prolonged exposure in bodily environments, essential for biomedical implants and prosthetics. The corrosion resistance of zirconia-coated metal substrates (e.g., titanium, stainless steel) in simulated body fluids, illustrating how the coating's non-toxic nature supports tissue integration, an important factor for applications like dental and orthopedic implants.

Behnam Abdollahi et al [9] The SiO2-ZrO2 nanocomposite coating is designed to provide enhanced protection against corrosion by forming a dense, stable, and durable layer that acts as a barrier to aggressive corrosive agents. The coating significantly improves the corrosion resistance of carbon steel 178, particularly in environments with high humidity and exposure to corrosive substances like acids or salts. The combination of SiO2 and ZrO2 in the nanocomposite enhances the mechanical and chemical properties of the coating, including its adhesion strength, hardness, and ability to resist degradation. This results in an effective and long-lasting protective layer that increases the lifespan of carbon steel components exposed to corrosive environments, making it suitable for various industrial applications, such as in the chemical, marine, and automotive sectors.

Bin Kang et al [10] Niobium carbide (NbC)-modified austenitic stainless steel (SS) bipolar plates were evaluated for their electrochemical behavior and surface conductivity in proton exchange membrane fuel cells (PEMFCs). The NbC modification enhanced the corrosion resistance and electrical conductivity of the bipolar plates. Results demonstrated that NbC-modified austenitic stainless steel exhibited improved electrochemical stability and surface conductivity compared to unmodified steel, indicating its potential to enhance the performance and durability of bipolar plates in fuel cell applications.

Brian Utri et al [11] Niobium Carbide (NbC) coatings on AISI 5200 bearing steel enhance corrosion resistance by creating a durable protective layer through deposition techniques like chemical vapor deposition (CVD) or physical vapor deposition (PVD). These techniques produce a uniform and adherent coating that acts as a barrier against corrosive agents. Microstructural analysis using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) reveals insights into the coating's thickness, crystalline structure, and potential defects, contributing to a better understanding of its protective properties. Corrosion resistance tests, such as salt spray exposure and electrochemical corrosion testing, simulate real-world conditions like seawater or acidic environments, quantifying the NbC-coated steel's resistance and comparing it to uncoated samples.

C.A Picon et al [12] Niobium Carbide coating on AISI 5200 steel improves both wear and corrosion resistance, which is beneficial for applications facing simultaneous physical and chemical stress. The coating's tribological properties, including hardness and wear rate, are measured under various loading conditions to determine its mechanical robustness. Wear and corrosion synergy is examined through tests like pin-on-disc in corrosive media, showing how NbC can minimize material degradation in harsh environments. Surface analysis techniques such as profilometry and microscopy reveal details about wear track morphology, surface roughness, and any signs of coating delamination, highlighting NbC's suitability for applications in environments with both wear and corrosive challenges.

C. Durga Prasad et al [13] Thermal spray coatings, including ceramic, metal, and composite materials, significantly improve the oxidation and corrosion resistance of components exposed to high-temperature environments. Various techniques such as plasma spraying, flame spraying, and high-velocity oxy-fuel spraying are utilized to apply these coatings.

These coatings play a vital role in enhancing the durability and protection of components in industrial applications subjected to extreme temperatures and corrosive conditions. The study demonstrates the effectiveness of different coating materials and methods in extending the lifespan of components exposed to harsh environments.

D. Lutsak et al [14] The development of niobium carbide (NbC)-based coatings and composites focuses on enhancing the mechanical properties and corrosion resistance of materials, particularly for applications in industries such as aerospace, automotive, and manufacturing, where components are exposed to extreme operating conditions. NbC is renowned for its high hardness, wear resistance, and thermal stability, making it an ideal candidate for reinforcing composite materials. Through the use of advanced processing techniques, such as high-energy laser cladding or chemical vapor deposition, the microstructure, hardness, and adhesion of these coatings are significantly improved, ensuring better performance in demanding environments. These techniques enable the formation of dense and durable coatings that offer exceptional protection against wear, corrosion, and oxidation, even under high temperatures. The incorporation of NbC as a reinforcing phase not only increases the overall hardness and wear resistance of the composite but also enhances its resistance to thermal degradation and chemical corrosion, ensuring longer service life and greater reliability.

D.M.Marulanda et al [15] Niobium-Chromium Carbide coatings, produced through Thermo-Reactive Deposition (TRD), significantly enhance the wear and corrosion resistance of AISI D2 tool steel. The coatings improve the material's performance in abrasive and corrosive environments, making it ideal for high-demand industrial applications. The study evaluates the microstructure and hardness of the coatings, demonstrating their ability to withstand harsh conditions.

E.K.Tendardini et al [16] Magnesium-sputtered Niobium Nitride (NbN) and Niobium-Aluminum-Nitride (Nb_xAl_xN) coatings on AISI 316L stainless steel show excellent corrosion resistance, particularly in chloride-rich environments. The coatings effectively prevent pitting and general corrosion, offering enhanced durability for applications in marine, medical, and industrial environments where corrosion resistance is critical.

Erika Judith Herriera Jimenez et al [17] The performance of protective coatings on aircraft engine components is influenced by growth conditions and surface treatments. Various parameters such as temperature, deposition rate, and surface roughness are studied to understand their impact on the adhesion, hardness, and overall protective properties of the coatings. By optimizing these conditions, the coatings can better withstand the extreme thermal and mechanical stresses encountered in aircraft engines. The research emphasizes how controlled deposition techniques and surface preparation contribute to improving the durability and operational efficiency of engine components, ensuring their safety and performance over time.

Esa Heinonen et al [18] Powder-precursor high-velocity oxygen fuel (HVOF)-sprayed Al2O3-YSZ/ZrO2 coatings were characterized for their microstructure, phase composition, wear resistance, and thermal stability. The coatings exhibited improved wear resistance and thermal stability, with a refined microstructure and favourable phase composition. These properties make them suitable for applications requiring enhanced wear resistance and thermal protection.

Fang Shao et al [19] The corrosion behavior of thermal sprayed ZrO2·38Y2O3 and ZrO2·18TiO2·10Y2O3 ceramic coatings with different metallic bonding layers was studied in acid solutions. The corrosion resistance of these coatings was significantly affected by the type of metallic bonding layer used. Both ceramic coatings showed varying levels of corrosion resistance, with specific bonding layers enhancing their overall performance. These findings indicate that selecting the appropriate metallic bonding layer can improve the corrosion resistance of ceramic coatings in aggressive environments.

Frantisek- Martinec et al [20] Corrosion of aircraft skin is a critical issue that can jeopardize the structural integrity of an aircraft. The study explores how environmental factors such as humidity, temperature, and exposure to de-icing chemicals contribute to the corrosion process. The research discusses the importance of protective coatings and materials designed to prevent corrosion and enhance the lifespan of aircraft. It also highlights the challenges associated with maintaining aircraft skin integrity, considering the impact of corrosion on the overall safety and operational performance of aircraft in harsh environmental conditions.

Fuhui Wang et al [21] The galvanic corrosion behavior of a three-metal system comprising ZM5 magnesium alloy, 6XXX series aluminium alloy, and 304 stainless steel was influenced by electrochemical interactions between the materials, with the magnesium alloy showing the highest corrosion rate. Numerical simulations, electrochemical methods, and salt spray tests provided insights into the corrosion mechanisms, emphasizing the role of material selection and coatings in mitigating galvanic corrosion in multi-material systems.

Greg M Swan et al [22] By adjusting aging parameters, the research shows how corrosion resistance can be optimized to protect the alloy from environmental degradation. The advantages of using trivalent chromium coatings, which provide a more environmentally friendly alternative to hexavalent chromium while offering comparable or improved protection against corrosion in challenging aerospace environments.

Haimin Zhai et al [23] The 304 stainless steel coating, applied through high-velocity oxy-fuel (HVOF) spraying, significantly improved the corrosion resistance of the 6061 aluminum alloy substrate in a 3.5 wt% NaCl solution. The coating effectively protected the substrate from corrosion, demonstrating the potential of HVOF spraying as a method to enhance the durability of aluminum alloys in corrosive environments.

Herbert Kappl et al [24] Hard coatings such as nitrides, carbides, and borides have been extensively studied for their ability to enhance the wear resistance and corrosion protection of steel. The evolution of these coatings, exploring newer technologies that improve their adhesion, hardness, and durability in aggressive environments. It also highlights ongoing research aimed at developing advanced coatings that provide superior performance in extreme conditions, offering enhanced longevity and reliability for steel components.

Hikaru Fujiwara et al [25] Zirconium Oxide coatings are fabricated on tubular steel using a metal-organic decomposition process, which results in a thin, corrosion-resistant layer. The study characterizes the coatings to assess their microstructure, thickness, and protective qualities. The research demonstrates that Zirconium Oxide provides a highly effective barrier against environmental degradation, particularly in applications such as oil and gas pipelines, where steel is exposed to aggressive conditions. The coatings' performance in terms of wear resistance and long-term durability under harsh conditions is thoroughly analyzed, making them a promising solution for corrosion protection in industrial environments.

Hirobumi Makiura et al [26] Carbon, zirconium, niobium, and titanium were found to improve the oxidation resistance of chromium stainless steel. Each element contributed in different ways, with zirconium and niobium providing the most significant enhancement in oxidation resistance. These findings suggest that alloying elements can effectively enhance the high-temperature performance of stainless steel.

Hung-Hua Sheu et al [27] Cr-C, Ni-P, and Ni-B coatings are electroplated onto 4140 alloy steel and compared for their corrosion and wear resistance behavior. The study evaluates each coating’s ability to protect the steel from both corrosion and mechanical wear, which are common challenges in industrial applications. The results show that while all coatings offer enhanced protection, specific compositions such as Cr-C provide superior wear resistance, while Ni-P coatings exhibit better corrosion protection. This comparison helps determine the most suitable coatings for different industrial applications, where both factors wear and corrosion resistance are critical.

Jimmy Mehta et al [28] Thermal spray coatings, including ceramic, metal, and composite materials, significantly improve wear, erosion, and corrosion resistance in materials exposed to harsh environments. Different coating materials and techniques have been shown to enhance the durability of components, providing better protection against extreme conditions. These coatings play a crucial role in extending the lifespan of materials used in various industrial applications.

Junwen Zheng et al [29] Niobium doping in stainless steel coatings significantly improves their corrosion resistance. The study explores how small additions of niobium alter the microstructure and enhance the stability of the oxide layer formed on the steel’s surface. These changes increase the material's ability to resist corrosion, particularly in aggressive environments such as acidic or saline conditions. The research demonstrates that niobium-doped coatings extend the service life of stainless steel in industries such as petrochemical, marine, and aerospace.

Suduman Sen et al [30] Niobium Boride coatings created by the Boro-Niobizing treatment form a dense, hard surface layer on AISI M2 tool steel, significantly enhancing its wear resistance by reducing the material's susceptibility to abrasion and erosion. Additionally, the coating improves the steel’s resistance to corrosion, especially in environments that involve high temperatures and chemical exposure, making it an excellent choice for tooling applications in the aerospace, automotive, and manufacturing industries. This treatment not only increases the longevity of tools but also reduces the frequency of maintenance, ensuring consistent performance even in challenging operational conditions.

II. CORROSION IN AIRCRAFT

Corrosion in aircraft is an important concern that affects the structural integrity, safety, and longevity of aerospace components. It occurs due to the exposure of aircraft materials to harsh environmental conditions, including moisture, salt-laden air, temperature variations, and chemical pollutants. Common types of corrosion in aircraft include uniform corrosion, pitting, crevice corrosion, galvanic corrosion, and stress corrosion cracking. Aircraft structures, particularly fasteners, rivets, wing edges, and landing gear, are highly susceptible to these forms of degradation. To mitigate corrosion, protective coatings, anodizing, cathodic protection, and the use of corrosion-resistant materials like titanium, aluminum alloys, and advanced nanocoatings are widely employed. Regular maintenance, inspections, and the application of innovative coating technologies are essential to ensuring aircraft durability and operational safety.

A. Types Of Corrosion In Aircraft

Aircraft are prone to different types of corrosion due to the harsh operating environments they face. The most common types include[1]:

1) Pitting Corrosion: This localized form of corrosion creates small pits or holes on the surface of the aircraft's metal parts, weakening the material. Pitting is often caused by salt water, acids, or moisture .
2) Galvanic Corrosion: Occurs when two different metals come into contact in the presence of an electrolyte (such as water), causing one metal to corrode faster than the other. This is a concern in areas where different materials are joined in aircraft construction .
3) Stress Corrosion Cracking: This type of corrosion happens under tensile stress and is particularly dangerous as it can lead to sudden failure. It is a primary concern in areas under constant mechanical load, such as the fuselage or wing structures .
4) Filiform Corrosion: This affects painted surfaces and occurs when moisture gets trapped between the paint and the substrate, causing a filament-like corrosion pattern. This is often seen in the areas exposed to rain or high humidity .

B. Environmental Factors Contributing To Corrosion

Aircraft components are exposed to extreme weather conditions, including fluctuating temperatures, humidity, de-icing chemicals, and saltwater in coastal areas. These environmental stressors can accelerate the onset of corrosion[2]:

1) Humidity And Moisture Exposure: Constant exposure to high humidity or moisture, especially in marine or tropical climates, increases the rate of corrosion, especially in metal parts like the fuselage and wing joints .
2) Temperature Extremes: Rapid temperature changes, particularly when flying at high altitudes where temperatures can plummet, contribute to the formation of condensation, leading to rusting and material degradation .
3) De-Icing Chemicals: The use of chemicals to prevent ice buildup on the aircraft during winter can cause corrosion when these chemicals remain on the surface after de-icing, leading to localized attacks on the material [7].

C. Coatings And Surface Treatments For Corrosion Protection

To combat corrosion, aircraft are often coated with protective layers. These include[10]:

1) Chromate-Based Coatings: Traditional coatings like zinc chromate provide excellent corrosion resistance but are being phased out due to environmental concerns, particularly regarding the toxicity of hexavalent chromium [8].
2) Eco-Friendly Coatings: As an alternative to chromates, newer, environmentally friendly coatings based on zirconium or cerium are being developed. These offer good corrosion protection without the harmful effects associated with traditional chromates [9].
3) Ceramic And Metallic Coatings: Thermal spray coatings, including ceramic-based coatings like $ZrO2$ (zirconia), are increasingly used for their excellent resistance to corrosion and wear, especially in critical engine parts or high-temperature zones [10].

D. Long-Term Durability And Maintenance

Aircraft require constant inspection and maintenance to ensure the integrity of their coatings. Over time, coatings degrade due to exposure to UV radiation, weather, and mechanical wear, necessitating frequent reapplication or repair. Modern advancements in self-healing coatings and sensor-embedded coatings that can detect corrosion early are helping to improve maintenance efficiency [11].

E. Case Studies Of Aircraft Corrosion

Case studies from real-world incidents, such as the corrosion found in critical components of older aircraft, provide valuable lessons. These studies highlight the importance of timely maintenance, proper material selection, and coating application. Notable examples include the corrosion issues found in Boeing 737 fuselage skin and Airbus A320 wing root areas [12].

III. ZIRCONIUM AND NIOBIUM-BASED COATINGS FOR CORROSION PROTECTION

A. Properties of Zirconium and Niobium in Coatings

1) Zirconium (ZR): Zirconium is highly resistant to corrosion due to its ability to form a stable oxide layer ($ZrO2$) on its surface. This oxide layer acts as an excellent barrier against corrosive agents, making zirconium and its alloys ideal for use in extreme environments such as nuclear reactors, aerospace, and chemical processing [13].

2) Niobium (NB): Niobium also forms a protective oxide layer (Nb2O5) when exposed to oxygen. This metal is highly resistant to corrosion, especially in acidic environments. Niobium-based coatings are known for their hardness and ability to withstand high temperatures, making them valuable for high-stress applications [14].

B. Comparative Analysis Of Zro2 and NBC Coatings: Zirconium Oxide (Zro2) And Niobium Carbide (NBC) Coatings Each Offer Distinct Advantages

1) Zro2 Coatings: Zirconium oxide coatings are renowned for their excellent corrosion resistance, especially in acidic and saline environments. They also provide high wear resistance, making them suitable for marine and industrial applications [15].
2) NBC Coatings: Niobium carbide coatings are more effective in applications where high hardness and wear resistance are needed, such as in tooling and high-temperature industrial environments. NbC coatings have a higher thermal stability compared to ZrO2, making them ideal for extreme heat conditions [16].

C. Coating Techniques For Zro2 And NBC

The application methods of zirconium oxide and niobium carbide coatings are crucial to their performance. Common techniques include:
1) SOL-GEL Process: For ZrO2 coatings, the sol-gel process is commonly used due to its ability to form dense, uniform films. It's often followed by heat treatment to enhance the coating's properties [17].
2) Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD): Both techniques are used for niobium carbide coatings. PVD allows for the deposition of thin, uniform films, while CVD provides coatings with excellent adhesion to the substrate, making them suitable for high-performance applications [18].

D. Performance of Zro2 vs. NBC coatings in Aggressive Environments

1) Zro2 : While ZrO2 is highly effective against corrosion, especially in acidic environments, its performance can degrade under high mechanical wear. However, it excels in preventing localized corrosion, such as pitting or crevice corrosion, commonly seen in marine and chemical industries [19].
2) NBC: Niobium carbide coatings are more resistant to wear and high-temperature oxidation. They are highly effective in preventing abrasion and are often used in high-wear environments such as turbines, cutting tools, or engine components [20].
3) Innovations in Zro2 and NBC Coatings: New advancements include the addition of elements like hafnium and titanium to improve the properties of ZrO2 coatings. These dopants refine the microstructure, enhance wear resistance, and improve the thermal stability of the coating. Similarly, NbC coatings are being explored for use in multi-layer coatings to improve toughness and resistance to thermal shock [21].

IV. WEAR AND CORROSION RESISTANCE OF COATINGS IN INDUSTRIAL APPLICATIONS

A. Thermal Spray Coatings For Corrosion Protection

Thermal spray coatings are widely used to protect industrial components from corrosion. Techniques like HVOF (High-Velocity Oxy-Fuel) and plasma spraying allow the deposition of wear-resistant and corrosion-resistant coatings such as ZrO2, Al2O3, and NiCr. These coatings form a robust layer that protects against both mechanical wear and corrosive attack, especially in marine or chemical environments [22].

B. Coatings In Harsh Environments

Industrial components, especially in the aerospace, automotive, and energy sectors, are subjected to extreme environments that require coatings with both corrosion and wear resistance. For example, turbine blades are coated with ceramic-based coatings (e.g., ZrO2) to withstand high temperatures and prevent oxidation, while components in marine environments benefit from niobium carbide (NbC) coatings that resist both wear and corrosion [23].

C. Impact Of Surface Treatments On Durability

Surface treatments like shot peening or nitriding are often combined with coatings to enhance overall durability. Shot peening induces compressive stress on the surface, improving fatigue resistance, while nitriding adds a hard nitride layer to improve wear resistance, making the underlying coating more effective in harsh conditions [24].

D. Corrosion In Industrial Equipment

Corrosion in industrial equipment can lead to costly downtime and repairs. Protective coatings applied to critical parts, such as pumps, valves, and reactors, can significantly extend their operational lifespan by providing resistance against corrosive agents like acids, salts, and high-temperature fluids [25].

E. Challenges In Coating Application And Longevity

The application of coatings in industrial environments often faces challenges like poor adhesion, uneven coverage, and the risk of delamination under extreme mechanical stress. Moreover, coatings degrade over time due to UV exposure, thermal cycling, and chemical attack. Advanced coating technologies, such as multi-layer coatings or self-healing coatings, are being developed to address these issues and enhance longevity [26].

V. ADVANCED COATINGS AND FUTURE TRENDS IN CORROSION PROTECTION

A. Eco-Friendly Alternatives To Chromate-Based Coatings

Environmental regulations are pushing industries away from toxic coatings like chromates, which have been used for their superior corrosion resistance but are harmful to both human health and the environment. New eco-friendly alternatives, such as zirconium-based or cerium-based coatings, are being developed and show promising results in terms of both performance and environmental safety [29].

B. Nanocomposite Coatings For Enhanced Corrosion Resistance

Nanocomposite coatings, which combine nanoparticles like SiO2 or ZrO2 with other materials, are gaining attention for their enhanced corrosion resistance. These coatings offer an increase in hardness, chemical resistance, and overall durability, providing better protection in aggressive environments, such as marine, chemical, and industrial [30].

REFERENCES

[1] A.Al-Waidh , F.Nabhania, M.C. Sharp , S.N.Hodgsona, Y. Adraidera & Y.X.Panga (2013). Fabrication of zirconium oxide coatings on stainless steelby a combined laser/sol–gel technique.School of Science and Engineering,Teesside University,Middlesbrough TS13BA,UK (2013). http://dx.doi.org/10.1016/j.ceramint.2013.05.089

[2] Abirami Selvaraj, Ashwin Mathew George & S Rajeshkumar (2021). Efficacy of Zirconium oxide nanoparticles coated on stainless steel and Nickel Titanium wires in orthodontic treatment. Department of Orthodontics and Dentofacial Orthopaedics, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai-77, India (2021). doi: 10.6026/97320630017760

[3] A.J. Cornet ,A.M. Homborg, J.M.C. Mol, L. 't Hoen-Velterop & P.R. Anusuyadevi (2024). Unravelling corrosion degradation of aged aircraft components protected by chromate-based coatings. Department of Materials Science and Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, Netherlands. https://doi.org/10.1016/j.engfailanal.2024.108070

[4] Alexey Vereschaka ,Anthon Keshin, Anton Seleznev, Catherine Sotova, Filipp Milovich, Tao He,Yuanming Huo & Zhylinski Valery (2023). Influence of Niobium and Hafnium doping on the wear and corrosion resistance of coatings based on ZrN. School of Mechanical and Automotive Engineering, Shanghai University of Engineering Science, No. 333 Longteng Road, Shanghai, China. https://doi.org/10.1016/j.jmrt.2023.11.086

[5] Arash Fattah-Alhosseini, Hassan Elmkhah, Omid Imantalab & Parviz Mohamadian Samim(2020). Structure and corrosion behavior of ZrN/CrN nano-multilayer coating deposited on AISI 304 stainless steel by CAE-PVD technique. Journal of Asian Ceramic Societies.https://doi.org/10.1080/21870764.2020.1750102

[6] Artem Okulov , Cong Xu , Guoxiang Xu, Haiyang Zhu, Hao Wang, Jie Li, Juan Wang, Kun Liu & Lixiang Wang (2023).Microstructural evolution and corrosion resistance property of in-situ C (B,Si) / Ni-Zr reinforced composite coatings on Zirconium alloy by lazer cladding. School of Materials Science and Engineering, Jiangsu University of Science and Technology, Zhenjiang, 212100, China. https://doi.org/10.1016/j.jmrt.2023.07.214

[7] Babatunde Olamide Omiyale & Temitope Olumide Olugbade (2021).Corrosion resistance of surface-conditioned 301 and 304 stainless steels by salt spray test. Federal University of Technology, Akure, Nigeria. https://doi.org/10.14232/analecta.2021.2.9-19

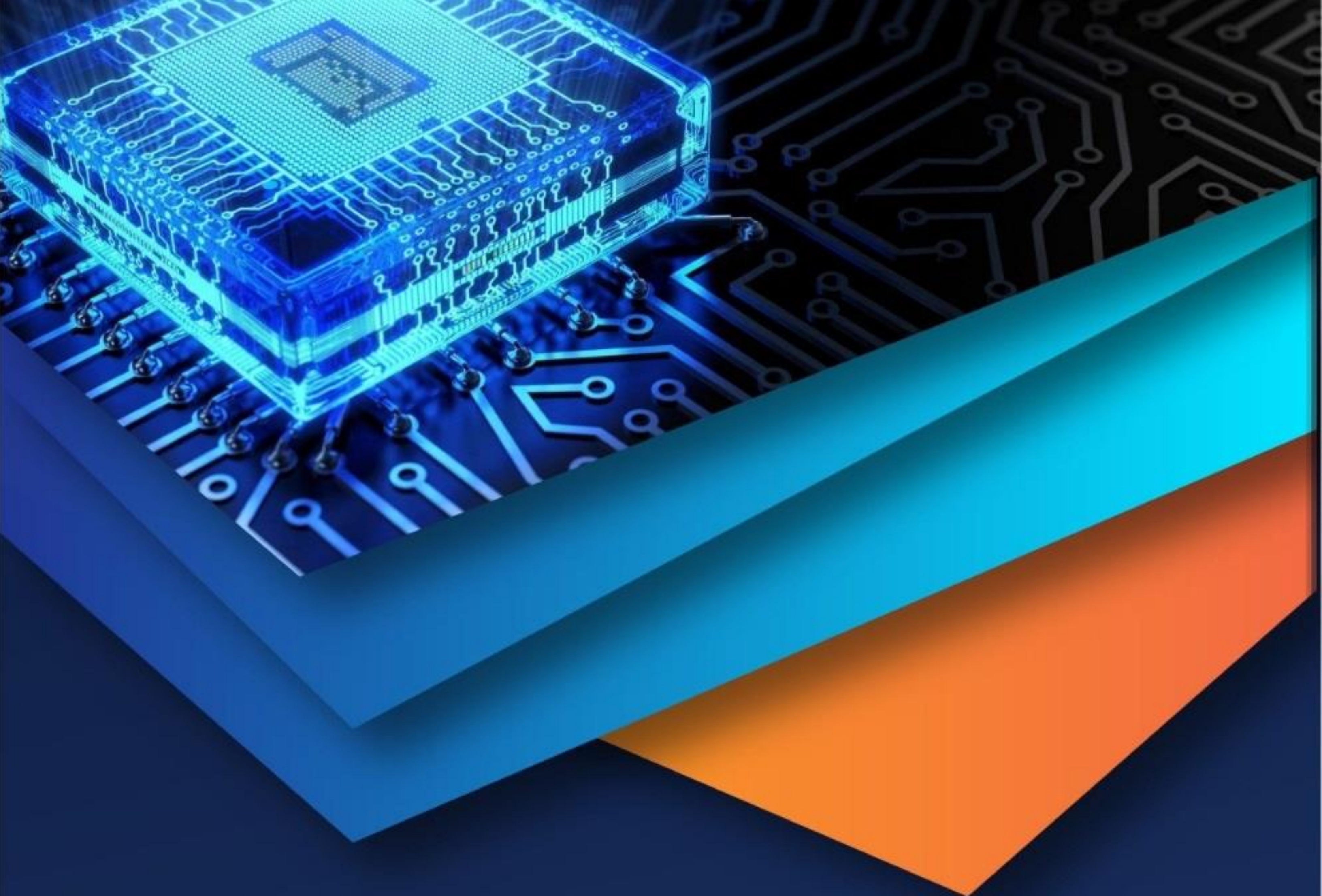
[8] Bavanilatha Muthaiah, D. Ramachandran,Gobi,Kamalan Kirubaharan, Saravanan Kaliaraj, T. Dharini & Vinita Vishwakarma. Corrosion and biocompatibility behaviour of zirconia coating by EBPVD for biomedical applications(2018). Centre for Nanoscience and Nanotechnology, Sathyabama University, Chennai 600 119, Tamilnadu, India. https://doi.org/10.1016/j.surfcoat.2017.11.047

[9] Behnam Abdollahi, Daryoush Afzali & Zahra Hassani (2017). Corrosion inhibition properties of SiO2-ZrO2 nanocomposite coating on carbon steel 178. Department of Material Engineering, Graduate University of Advanced Technology, Kerman, Iran.https://doi.org/10.1108/ACMM-12-2015-1618

[10] Bin Kang, Juncai Sun, Lixia Wang, Shijun Ji, Song Li, Xiaochun Wang & Zhongsheng Wen(2014).Electrochemical behaviour and surface conductivity of niobiumcarbide-modified austenitic stainless steel bipolar plate. Institute of Materials and Technology, Dalian Maritime University, Dalian 116026, China. https://doi.org/10.1016/j.jpowsour.2013.08.025

[11] Brian Utri, Everson do Prado Banczek, Paloma Detlinger (2018). Corrosion Resistance of Niobium-Coated Carbon Steel. Departamento de Química, Universidade Estadual do Centro-Oeste, UNICENTRO, Rua Simeão Varela de Sá,03, Guarapuava, PR CEP 85040-080, Brazil. https://doi.org/10.1007/s40735-018-0201-9

[12] C.A. Picon , F.A.P. Fernandes , G. Tremiliosi Filho, J. Gallego & L.C. Casteletti (2015).Wear and corrosion of Niobium Carbide coated AISI 5200 bearing steel. Departamento de Engenharia Mecânica, Faculdade de Engenharia de Ilha Solteira, Universidade Estadual Paulista, Av. Brasil Centro, n. 56, 15385-000 Ilha Solteira, SP, Brazil. https://doi.org/10.1016/j.surfcoat.2015.08.036
[13] C. Durga Prasad, K.B. Yogesha, Rakesh Kumar Phanden, S Chandrashekar Prasad, Srinivasa G & Virupakshappa Lakkannavar (2024).Thermal spray coatings on high-temperature oxidation and corrosion applications – A comprehensive review. Department of Mechanical Engineering, JSS Academy of Technical Education, Bengaluru and Visvesvaraya Technological University, Belagavi, Karnataka, India. https://doi.org/10.1016/j.rsurfi.2024.100250
[14] D. Lutsak , L. Lutsak, L. Shlapak, P. Prysyazhnyuk, T. Shihab & V.Aulin (2018) . Development of the composite material and coatings based on Niobium Carbide. Eastern-European Journal of Enterprise Technologies. https://dspace.kntu.kr.ua/handle/123456789/8456
[15] D.M. Marulanda, F.E. Castillejo, J.E. Alfonso & J.J. Olaya(2014). Wear and corrosion resistance of Niobium-Chromium Carbide coatings on AISI D2 produced through TRD. Grupo Ciencia e Ingeniería de Materiales (CIM), Universidad Santo Tomás, Street 9th, 51-11 Bogotá, Colombia. https://doi.org/10.1016/j.surfcoat.2014.05.069
[16] E.Tentardini, Rafaela Marinho Fonseca & Renata Braga Soares (2019).Corrosion behaviour of Magnesium sputtered NbN and Nbix AlxN coatings in AISI 316L stainless steel. Federal University of Minas Gerais. DOI:10.1016/j.surfcoat.2019.124987
[17] Erika Judith Herrera Jimenez(2021). Effect of growth conditions and surface treatment on the performance of protective coatings on aircraft engine components. Polytechnique Montréal. https://publications.polymtl.ca/5609/
[18] Esa Heinonen, Heli Koivuluoto, Jarkko Kiilakoski, Jouni Puranen, & Petri Vuoristo (2018). Characterization of Powder-Precursor HVOF-Sprayed Al2O3-YSZ/ZrO2 Coatings. Laboratory of Materials Science, Tampere University of Technology, Tampere, Finland. https://doi.org/10.1007/s11666-018-0816-x
[19] Fang Shao, Huayu Zhao, Jiasheng Yang, Jing Sheng, Jinxing Ni, Shunyan Tao, Tianze Xia & Yin Zhuang(2025). Corrosion Behavior of Thermal Sprayed ZrO2·38Y2O3 and ZrO2·18TiO2·10Y2O3 Ceramic Coatings with Different Metallic Bonding Layers in Acid Solution. J Therm Spray Tech. https://doi.org/10.1007/s11666-025-01972-y
[20] Frantisek Martinec , Jan Pila & Jarosław Kozuba(2021). Aircraft skin corrosion and structural safety considerations. Silesian University of Technology, Katowice, Poland. https://doi.org/10.34739/dsd.2021.02.10
[21] Fuhui Wang, Kun Hu, Qiangfei H, Shaohua Chen, Tao Zhang & Tianjun Diao(2021). Modeling of Galvanic Corrosion in three-metal Systems Consisting of ZM5 Magnesium Alloy, 6XXX Series Aluminium Alloy and 304 Stainless Steel under Thin Electrolyte Layer by Numerical Simulation, Electrochemical and Salt Spray Test. Anhui Province Engineering Laboratory of Advanced Building Materials, Anhui Jianzhu University,Hefei 230601, P. R. China. doi: 10.20964/2022.12.106
[22] Greg M. Swain & Liangliang Li (2015).Effects of aging temperature and time on the corrosion protection provided by trivalent Chromium process coatings on AA2024-T3. Department of Chemical Engineering & Materials Science Michigan State UniversityEast Lansing, MI 48824. https://doi.org/10.1021/am4020023
[23] Haimin Zhai, Jiabin Liang, Ting Zhang, Wensheng Li & Yaming Li (2024).Corrosion behavior of HVOF sprayed 304 stainless steel coating on 6061 substrate in 3.5 wt% NaCl solution. State Key Laboratory of Advanced Processing and Recycling of Non-ferrous Metal, College of Material Science and Engineering, Lanzhou University of Technology, Lanzhou, Gansu 730050, China. https://doi.org/10.1016/j.mtcomm.2024.108974
[24] Herbert Kappl, Martin Balzer & Martin Fenker(2014).Corrosion protection with hard coatings on steel: past approaches and current research efforts. fem Forschungsinstitut Edelmetalle & Metallchemie, Abteilung Plasma-Oberflächentechnik Materialphysik, Katharinenstr. 17, 73525 Schwäbisch Gmünd, Germany https://doi.org/10.1016/j.surfcoat.2014.08.069
[25] Hikaru Fujiwara, Juro Yagi, Kento Shirota, Khiem Do Duy, Marcin Rasinski, Ryosuke Norizuki, Takumi Chikada & Teruya Tanaka(2024). Fabrication and characterization of Zirconium Oxide coating in tubular steel by metal organic decomposition. Shizuoka University, Shizuoka, Japan. https://doi.org/10.1016/j.jnucmat.2024.155009
[26] Hirobumi Makiura, Hisao Fujikawa & Taishi Moroishi (2017).The Effect of Carbon, Zirconium, Niobium, and Titanium on the Oxidation Resistance of Chromium Stainless Steel. Journal of The Electrochemical Society, Volume 126, Number 12. DOI 10.1149/1.2128918
[27] Hung-Hua Sheu, Jian-Huang Syu, Kung-Hsu Hou, Ming-Der Ge & Yih-Ming Liu (2018).A comparison of the corrosion resistance and wear resistance behaviour of Cr-C,Ni-P and Ni-B coatings electroplated on 4140 alloy steel. Department of Chemical and Materials Engineering, Chung Cheng Institute of Technology, National Defense University, Taoyuan City, Taiwan. https://doi.org/10.20964/2018.04.49
[28] Jimmy Mehta , Pallav Gupta & Varinder Kumar Mittal (2017). Role of Thermal Spray Coatings on Wear, Erosion and Corrosion Behavior: A Review. Department of Mechanical Engineering, A.S.E.T., Amity University, Uttar Pradesh, Noida-201313, India. https://doi.org/10.6180/jase.2017.20.4.05
[29] Junwen Zheng, Xin Zhang & Zhongjie Wang (2022). The effect of Niobium Dopium on the corrosion resistance of stainless steel coatings. School of Materials Science and Engineering, Yancheng Institute of Technology, Yancheng, 224051,China. doi: 10.20964/2022.10.42
[30] Saduman Sen, Suleyman Serdar Pazarlıoglu & Ugur Sen (2018).Niobium Boride coating on AISI M2 steel by Boro-Niobizing treatment. Sakarya University, Engineering Faculty, Department of Metallurgy and Materials Engineering, Esentepe Campus, 54187, Sakarya, Turkey. https://doi.org/10.1016/j.matlet.2007.12.042International Journal of Bio-Inspired Engineering, Volume 32, Issue 03, March 2023.



10.22214/IJRASET

INDEX COPERNICUS

45.98

IMPACT FACTOR: 7.129

TOGETHER WE REACH THE GOAL

IMPACT FACTOR: 7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Call : 08813907089 (24*7 Support on Whatsapp)