INFORMATICS JOURNALS
The Journal of Electrochemical Society of India, Volume 74, Issue (1&2), January – March 2025; pp. 15-21
ISSN (Print) : 0013-466X
ISSN (Online) : xxxx-xxxx
DOI: 10.18311/JESCI/2025/51175

A Feasibility Study on the Corrosion Resistance of Wire Arc Sprayed Aluminium and Zinc Coatings on Steel

Rania Afia Nuamah[1], Saleema Noormohammed[1], Dilip Kumar Sarkar[1*] and Alexander Blackburn[2]

[1]Department of Applied Science, Aluminium Research Centre-REGAL, University of Quebec at Chicoutimi, Chicoutimi, Quebec - G7H 2B1, Canada

[2]Structures CPI INC., Construction PROCO Inc., La Baie, Quebec - G7B 3N8, Canada

Abstract

This study investigates the feasibility of Aluminium (Al) and Zinc (Zn) coatings applied on steel substrates using thermal spraying, specifically the wire arc spray technique, to compare their corrosion resistance. The coatings were characterised at laboratory scale to evaluate their physical properties, electrochemical behaviour, and industrial applicability. X-Ray Diffraction (XRD) analysis confirmed the presence of metallic aluminium and zinc phases on the coated steel substrates, indicating successful deposition by wire arc spraying. Electrochemical testing revealed that aluminium coatings exhibited superior corrosion resistance compared to zinc coatings. They demonstrated over 12 times lower corrosion current density, indicating significantly slower electrochemical degradation. During prolonged salt-spray exposure, uncoated steel exhibited extensive red rust formation, while zinc-coated samples developed white rust. In contrast, aluminium-coated specimens remained largely unchanged, highlighting aluminium's superior barrier properties and strong industrial potential for corrosion protection.

Keywords: Aluminium Coating, Corrosion Resistance, Steel Substrate, Sustainable Materials, Thermal Spray Coatings, Wire Arc Spray, Zinc Coating

1. Introduction

Corrosion of steel structures continues to pose significant challenges across marine, industrial, and infrastructure sectors, contributing to increased maintenance costs, reduced service life, and structural deterioration[1-3].

Thermal spray metallisation with metallic coatings has become a widely used method to mitigate these issues[4,5]. Zinc (Zn) has traditionally been the most common coating material due to its cathodic (sacrificial) protection mechanism, which ensures continued protection even when the coating is mechanically damaged[1,6,7].

Zinc coatings are extensively used in both hot-dip galvanising and thermal spray processes, and they have proven effective in atmospheric, inland, and industrial environments[8-10]. However, their long-term performance in marine or chloride-rich environments can be limited by porosity and the relatively soluble nature of zinc corrosion products, which accelerates coating degradation under aggressive conditions[1,6,11].

Aluminium (Al) coatings have emerged as promising alternatives, offering corrosion protection primarily through barrier mechanisms, resulting from the formation of a compact and adherent aluminium oxide (Al_2O_3) layer[12,13]. This passive film effectively slows down corrosion processes, particularly in saline and UV-exposed environments, where aluminium has demonstrated excellent chemical stability and durability[14,15]. While

*Email: dsarkar@uqac.ca

Al coatings do not provide the same level of sacrificial protection as Zn, their resistance to atmospheric and marine corrosion, along with low maintenance requirements, makes them well-suited for long-term applications in coastal and offshore infrastructures.

Several studies have confirmed the corrosion resistance of thermally sprayed aluminium coatings. For example, Senderowski *et al.*,[16,17] reported that electric arc-sprayed aluminium coatings exhibited uniform surface coverage and good adhesion on steel substrates, with corrosion current densities as low as 27 μA/cm²—significantly lower than values typically reported for Zn coatings. Similarly, Hinds *et al.*,[17] and de Oliveira and Spinelli[18] demonstrated that Al coatings showed superior performance under salt spray and electrochemical testing, particularly in chloride-rich environments.

Moreover, the economic and environmental sustainability of protective coatings has gained increasing attention. While zinc remains widely used, concerns about its global resource depletion, price volatility, and environmental impact are rising[1]. In contrast, aluminium is more abundantly available, especially in regions like Quebec, Canada, which contributes over 90% of Canada's aluminium production, leveraging hydroelectric power and a well-established bauxite processing infrastructure[19]. This regional abundance offers a strategic opportunity to substitute or complement zinc coatings with aluminium-based alternatives, especially for large-scale public infrastructure projects.

Although aluminium coatings offer well-documented advantages, their widespread adoption for structural steel protection remains limited. This is largely due to the entrenched use of zinc-based systems and the shortage of comparative studies conducted under standardised conditions, particularly using modern application techniques such as electric arc wire spraying.

To address this gap, the present study systematically evaluates the feasibility of aluminium metallisation on steel structures, directly comparing it to conventional zinc coatings. The investigation involves phase characterisation by XRD, assessment of corrosion behaviour through Tafel polarisation and salt spray testing in a 3.5 wt.% NaCl solution, and detailed analysis of electrochemical parameters such as corrosion potential, current density, and polarisation resistance to better understand the degradation mechanisms.

Beyond technical performance, the study also considers the economic and sustainability aspects of using aluminium, especially within the context of Quebec, Canada, where aluminium is locally abundant, unlike zinc, which is primarily imported. By offering a comprehensive comparison of these coating systems, this research supports informed material selection for corrosion protection in harsh environments and encourages the adoption of sustainable, regionally available alternatives.

2. Materials and Methods

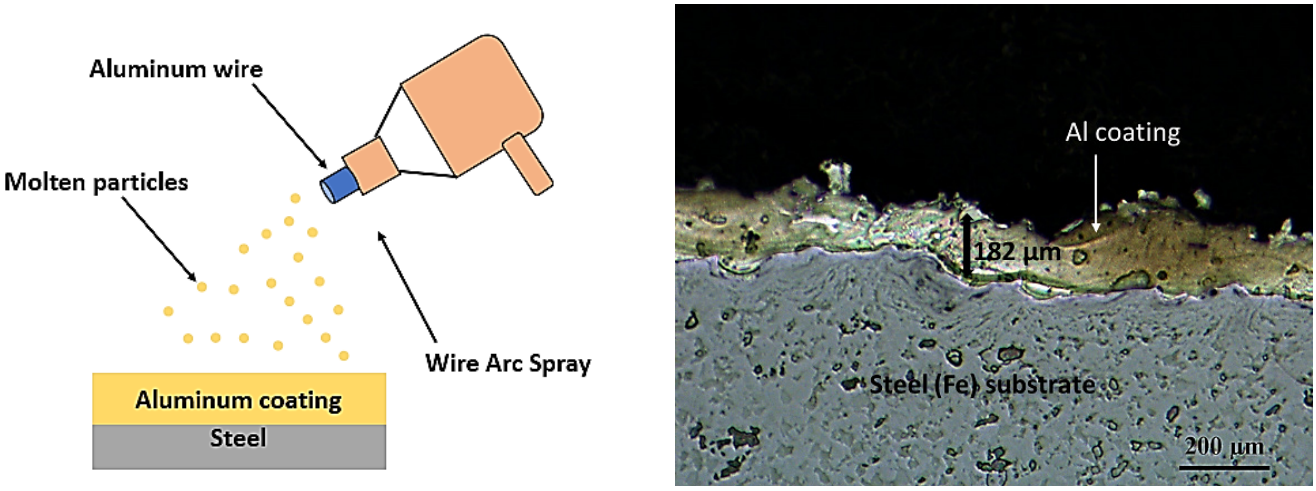
Low-carbon steel samples, measuring 50mm × 50mm × 5mm, in both coated and uncoated forms, were provided by Structures CPI Inc. The coated samples underwent a surface preparation process involving degreasing and alumina grit blasting to promote mechanical anchorage of the coating. Thermal spray coatings of aluminium and zinc were then applied using a Wire Arc Spraying (WAS) system. Commercially pure aluminum and zinc wires, each with 99.99% purity and supplied by Grillo, were used as feedstock materials for the coating process.

2.1 Coating Characterisation

The thickness of the deposited films was measured non-destructively using an Elcometer 456 (Tokyo, Japan) at seven different locations on each sample (dimensions: 5.9in × 3.9in). The average thickness was calculated, and film thickness was further confirmed through cross-sectional optical microscopy. XRD analyses were performed using a Bruker D8 Discover system to assess the crystallographic structure of the coatings.

2.2 Electrochemical Testing

A Voltalab potentiostat equipped with a 300 cm³ flat-cell was used to perform Open-Circuit Potential (OCP) measurements and potentiodynamic polarisation (Tafel) tests. A three-electrode configuration was employed, consisting of a platinum mesh counter electrode, a silver/silver-chloride (Ag/AgCl) reference electrode, and the coated or uncoated steel specimens as working electrodes, with a 1cm² exposed area in a 3.5 wt.% NaCl solution. Corrosion current density, corrosion potential, and polarisation resistance were obtained from the Tafel plots. Each test was conducted in triplicate, and average values were reported to ensure reproducibility.



(A) (B)

Figure 1. **(A)** Schematic representation of the wire arc spray (WAS) process used for depositing metallic coatings on steel substrates. **(B)** Cross-sectional optical micrograph of as-deposited aluminium coating on steel, showing a lamellar structure with overlapping splats and a thickness of approximately 180 ± 13µm.

A custom-built environmental chamber (approximately 1ft × 1ft × 1ft) made of plastic was used to simulate real-world marine exposure conditions. The samples were placed inside and partially exposed to 3.5 wt.% NaCl solution, with a thermometer and hygrometer installed to monitor temperature and relative humidity throughout the test period.

3. Results and Discussion

Figure 1 presents a schematic of the wire arc spray process alongside a representative optical cross-sectional image of an aluminium-coated steel substrate. The schematic representation illustrates the general deposition mechanism applicable to the two coatings investigated, Zn and Al-where molten particles are atomised and deposited onto the steel surface to form a lamellar coating.

The optical micrograph, shown here for the aluminium coating, reveals a thickness of 180 ± 13µm, with overlapping splats and moderate interfacial roughness, consistent with prior reports on arc-sprayed coatings[1,6,13,20]. Although only the aluminium coating is depicted, similar cross-sectional analyses were performed for the Zn coating to compare microstructural characteristics and evaluate relative performance. The aluminium coating exhibits good adhesion, clear splat morphology, and minimal porosity. This comparison validates the coating process and highlights microstructural features critical to corrosion protection.

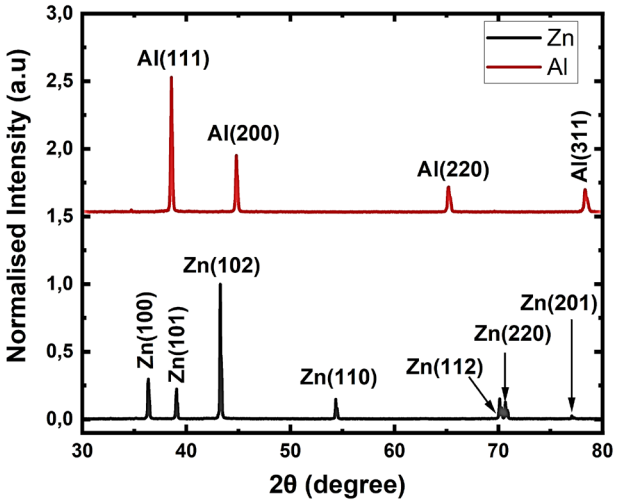


Figure 2. X-ray diffraction (XRD) patterns of zinc (Zn) and aluminium (Al) coatings deposited on steel substrates confirming the presence of their respective metallic phases.

The phase constitutions of the wire arc-sprayed Zn- and Al-coated steel were analysed using XRD (Figure 2). Due to the coating thickness exceeding 100µm, diffraction peaks from the steel substrate were not detected. For the Zn coating, the primary diffraction peaks correspond to Zn (100), (110), (112), and (201), in agreement with PDF No. 87-0713[6]. The Al coating showed characteristic

peaks for Al (111), (200), (220), and (311), consistent with JCPDS PDF No. 99-0005[6,21]. These findings align with previous literature[12,14,22].

Figure 3 displays the Tafel polarisation curves, highlighting electrochemical differences among the uncoated steel, Zn-coated, and Al-coated samples. Generally, a more positive (noble) corrosion potential suggests better corrosion resistance[22,23]. The uncoated steel had a corrosion potential of −0.60 ± 0.04 V, while the Al and Zn coatings exhibited lower values of −0.94 ± 0.04 V and −1.18 ± 0.04 V, respectively, in 3.5 wt.% NaCl solution. Despite these more negative values, both coatings still offer sacrificial protection to the substrate[16,22].

The corrosion current density, a direct indicator of corrosion rate[21,24,25], supports this trend. Bare steel exhibited a current density of 39 ± 5 μA/cm². In comparison, Al-coated steel demonstrated the lowest value (15 ± 7 μA/cm²), while Zn-coated steel showed a significantly higher value (200 ± 10 μA/cm²). The polarisation resistance (Rp) of the Al coating was 4.59 ± 0.43 kΩcm², substantially higher than that of the Zn coating. These findings are consistent with literature values[1,6,21,26]. For example, Senderowski *et al.*,[16] reported 27 μA/cm² for Al arc-sprayed coatings on steel, whereas Ding *et al.*,[22] observed 249 μA/cm² for arc-sprayed Zn coatings on hull steel. The significantly lower corrosion rate of Al-coated steel is attributed to its passive oxide layer, which serves as an effective barrier against aggressive ions[10,27,28].

Table 1 summarises the key electrochemical parameters, reinforcing the superior corrosion performance of the Al coating compared to both uncoated and Zn-coated steel. The markedly higher corrosion current density for the Zn coating can be attributed to the inherent characteristics of zinc in chloride-rich environments. Although zinc has a corrosion potential between steel and aluminium, its surface films are less stable in 3.5wt.% NaCl. Chloride ions readily penetrate and disrupt these films, leading to sustained anodic dissolution. In contrast, aluminium forms a dense and self-healing surface passive layer, which effectively suppresses further corrosion even in saline conditions. This difference in surface film integrity explains the elevated corrosion current observed for Zn coatings.

Figure 4 presents the salt spray test results. After prolonged exposure, the uncoated steel exhibited heavy red rust formation (ferrous oxides), indicating severe corrosion[6]. In contrast, both coated samples remained rust-free in terms of red corrosion. The Zn-coated specimens showed white, powdery corrosion products (white rust), characteristic of zinc oxidation[21,29]. The Al-coated samples displayed only minimal surface colour change, likely from the formation of a stable aluminium oxide film[2,21,30]. These observations further confirm that Al coatings provide superior barrier protection under aggressive salt spray conditions.

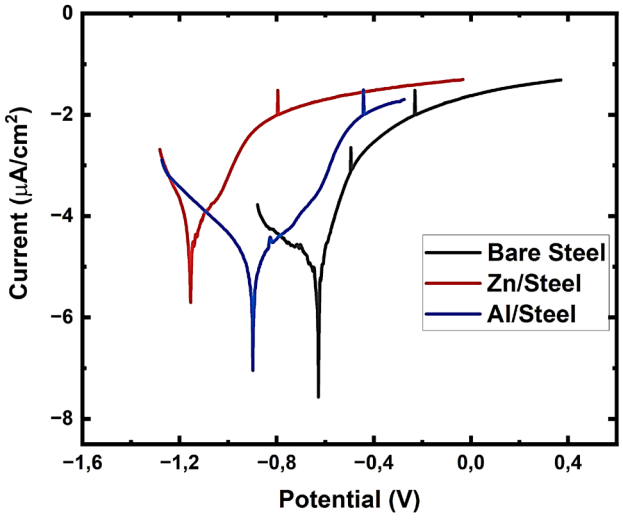


Figure 3. Potentiodynamic polarisation (Tafel) curves of uncoated steel and wire arc-sprayed aluminium (Al) and zinc (Zn) coatings on steel substrates, measured in 3.5 wt.% NaCl solution to evaluate their comparative corrosion behaviour.

Table 1. Summary of electrochemical corrosion performance of uncoated steel, zinc (Zn), and aluminium (Al) coatings in 3.5 wt.% NaCl solution, based on potentiodynamic polarisation measurements, including corrosion potential (E_{corr}), current density (I_{corr}), and calculated corrosion rates

Coating	Corrosion Potential (E_{corr}) (V vs. Ag/AgCl)	Corrosion Current (I_{corr}) Density (μA/cm²)	Corrosion Rate (μm/year)
Steel	-0.60 ± 0.04	39.36 ± 5.68	428.60 ± 15.28
Zn	−1.18 ± 0.04	200.89 ± 10.96	1268.25 ± 10.53
Al	−0.94 ± 0.04	15.68 ± 7.39	170.33 ± 25.46

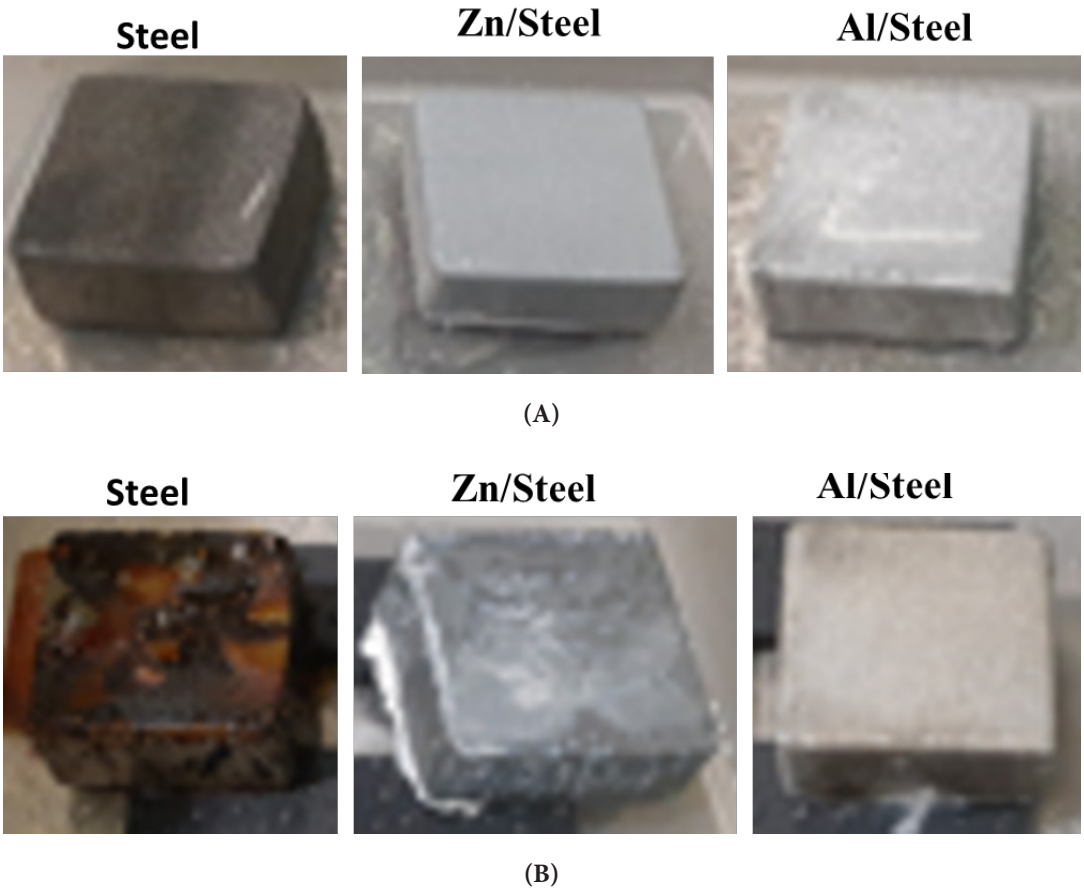


Figure 4. Salt spray test of **(A)** As-received **(B)** After 360 hours exposure of steel and the Zn- and Al-coated steel.

4. Conclusion

This study evaluated the corrosion resistance of aluminium (Al) and zinc (Zn) coatings deposited on steel substrates using the wire arc spraying technique. Through a combination of electrochemical testing, salt spray exposure, and microstructural analysis, aluminium coatings were shown to outperform zinc coatings in terms of protective behaviour in chloride-rich environments.

Although aluminium coatings exhibited a more active corrosion potential than zinc, they demonstrated significantly lower corrosion current densities and corrosion rates, indicating slower degradation under the tested conditions. Salt spray testing further confirmed the improved durability of aluminium coatings, which showed minimal surface changes, while zinc-coated samples developed white rust, and uncoated steel exhibited extensive red rust formation.

Given these findings, aluminium coatings present a highly effective barrier against corrosion for steel structures, particularly in marine or industrial conditions. Furthermore, considering the regional abundance of aluminium in Quebec and Canada, and the reliance on imported zinc, the use of aluminium coatings represents a sustainable, cost-effective, and locally supported solution for long-term steel protection. Future work should focus on long-term field exposure and the mechanical durability of aluminium coatings under cyclic loading to validate these findings under real service conditions.

5. References

1. Fuentes VA, Martos AM, Sánchez J, Cano IG, Evolution of TSA/TSZ coatings: A review on recent advances on cold gas spraying for steel corrosion protection. Corrosion Reviews. 2021; 39(3), 151-177. https://doi.org/10.1515/corrrev-2020-0102
2. Alparone GP, Penney D, Sullivan J, Edy J, Mills C, Al2O3 coatings for protection of stainless steel 316L against corrosion in Zn-Al and Zn-Al-Mg, Coatings. 2024; 14(5), 606. https://doi.org/10.3390/coatings14050606

3. Kania H, Sipa J. Microstructure characterization and corrosion resistance of zinc coating obtained on high-strength grade 10.9 bolts using a new thermal diffusion process, Materials. 2019; 12(9), 1400. https://doi.org/10.3390/ma12091400 PMid:31032815 PMCid:PMC6539789.
4. Qiao D, *et al*., Corrosion resistance of zinc-magnesium-aluminium alloy coated steel in marine atmospheric environments, International Journal of Electrochemical Science. 2024; 19(8), 100705. https://doi.org/10.1016/j.ijoes.2024.100705
5. Price SJ, Figueira RB. Corrosion protection systems and fatigue corrosion in offshore wind structures: Current status and future perspectives, Coatings. 2017; 7(2), 25. https://doi.org/10.3390/coatings7020025
6. Bonabi SF, Ashrafizadeh F, Sanati A, Nahvi SM, Structure and corrosion behaviour of arc-sprayed Zn-Al coatings on ductile iron substrate. Journal of Thermal Spray Technology. 2018; 27(3), 524-537. https://doi.org/10.1007/s11666-018-0694-2
7. Qi C, Dam-Johansen K, Weinell CE, Wu H, Synthesis of micro-structured zinc particles by thermal evaporation and their application in zinc-containing coatings for steel corrosion protection, Progress in Organic Coatings. 2024; 187. https://doi.org/10.1016/j.porgcoat.2023.108143
8. Büteführ M. Zinc-aluminium coatings as corrosion protection for steel. Materials and Corrosion. 2007; 589, 721-726. https://doi.org/10.1002/maco.200704058
9. Farh HMH, Ben Seghier MEA, Zayed T. A comprehensive review of corrosion protection and control techniques for metallic pipelines. Engineering Failure Analysis. 2023; 143, 106885. https://doi.org/10.1016/j.engfailanal.2022.106885
10. Galedari SA, Mahdavi A, Azarmi F, Huang Y, McDonald A, A comprehensive review of corrosion resistance of thermally-sprayed and thermally-diffused protective coatings on steel structures. Journal of Thermal Spray Technology. 2019; 28(4), 645–677. Springer. https://doi.org/10.1007/s11666-019-00855-3
11. Meng Y *et al*., Initial formation of corrosion products on pure zinc in saline solution, Bioact Mater. 2019; 4(1), 87-96. https://doi.org/10.1016/j.bioactmat.2018.08.003 PMid:30723841 PMCid:PMC6351358.
12. Peng J, Liu J, Xiao W, Zhang X, Wu K, Zhang T, Comparative study on the corrosion behavior of two arc spraying coatings in simulated marine environments. Surface Coatings Technology. 2024; 486. https://doi.org/10.1016/j.surfcoat.2024.130945
13. Pham TT, *et al*., Role of Al and Mg alloying elements on corrosion behavior of zinc alloy-coated steel substrates in 0.1 M NaCl solution. Materials and Corrosion. 2023; 74, 6, 903-919. https://doi.org/10.1002/maco.202213549
14. Esfahani EA, Salimijazi H, Golozar MA, Mostaghimi J, Pershin L, Study of corrosion behavior of Arc sprayed aluminium coating on mild steel. Journal of Thermal Spray Technology. 2012; 21(6), 1195-1202. https://doi.org/10.1007/s11666-012-9810-x
15. Gao Y, Kainuma S, Yang M, Ishihara S, InoueD. Galvanic corrosion behavior of hot-dip Al and 55Al-Zn coatings applied to steel bolted joints in atmospheric environments. Construction and Building Materials. 2023; 401. https://doi.org/10.1016/j.conbuildmat.2023.132694
16. Senderowski C, Rejmer W, Bilko P. Effect of low chloride and sulfate concentrations on corrosion behavior of aluminium and zinc arc thermal sprayed coatings. Coatings. 2022; 12(5), 653. https://doi.org/10.3390/coatings12050653
17. Hou BR., Duan J, Li Y, Zhang JL. Corrosion of thermally sprayed zinc and aluminium coatings in simulated splash and tidal zone conditions. Corrosion Engineering, Science and Technology. 2003; 38(2), 157-160. https://doi.org/10.1179/147842203767789258
18. de Oliveira MG, Spinelli D. Electrochemical behavior of thermally sprayed Zn, Al, and Zn-Al coatings in artificial seawater. Surface and Coatings Technology. 2005; 190(2), 244-252.
19. Natural resources Canada, minerals and metals facts - Aluminium, minerals and mining facts. 2025. https://www.nrcan.gc.ca/minerals-mining/mining-data/statistics-analysis/minerals-metals-facts/aluminum.
20. American Welding Society (AWS), NACE International and SSPC: The Society for Protective Coatings, Specification for the Application of Thermal Spray Coatings (Metallising) of Aluminium, Zinc, and Their Alloys and Composites for the Corrosion Protection of Steel, AWS C2.23M/M/C2.23:2018 (2nd Edition), NACE No. 12, SSPC CS 23, 2017. ISBN 978 0 87171 916 4
21. Zheng J *et al*., Surface characteristic and corrosion resistance of different plasma-sprayed coatings (Zn, Al6061, and Zn/23Al) on S960 high-strength steel with subsequent micro-shot peening. Surface Coatings Technology. 2022; 451, 129046. https://doi.org/10.1016/j.surfcoat.2022.129046
22. Ding Y. *et al*., Effect of Al content on the long-term corrosion behavior of arc-sprayed ZnAl alloy coatings. Coatings. 2023; 13(10), 1720. https://doi.org/10.3390/coatings13101720
23. Zhixiang Z *et al*., Study on the corrosion electrochemistry behavior and wear resistance of the arc thermal sprayed Zn-Al alloy coating. Journal of Materials Research and Technology. 2023; 24, 8414-8428. https://doi.org/10.1016/j.jmrt.2023.05.109
24. Yadav A, RVS Yadav, Performance evaluation of thermally sprayed Al, Zn, and Zn-Al alloy coatings on steel substrates.

Journal of Thermal Spray Technology. 2020; 29(5), 1003-1015.

25. Liu Y *et al*., Corrosion mechanism of a high corrosion-resistance Zn-Al-Mg coating in typical extremely harsh marine and cold environments, Journal of Materials Research and Technology. 2024; 33, 4290-4302. https://doi.org/10.1016/j.jmrt.2024.10.080
26. Lee HS, Singh JK, M. Ismail MA, Bhattacharya C, Corrosion resistance properties of aluminum coating applied by arc thermal metal spray in SAE J2334 solution with exposure periods. Metals (Basel). 2016; 6(3), 55. https://doi.org/10.3390/met6030055
27. Steven F. Daily, galvanic cathodic protection of reinforced and prestressed concrete using a thermally sprayed aluminum coating. Concrete Repair Bulletin. 2003; 9(4), 12-15.
28. de Rincón O *et al*. Evaluating Zn, Al and Al-Zn coatings on carbon steel in a special atmosphere. Construction Building Materials. 2009; 23(3), 1465-1471. https://doi.org/10.1016/j.conbuildmat.2008.07.002
29. Ni W, Li P, Zhu Y, Di Z, Guo L, Liu Y. Comparative study of anti-corrosion properties and lifespan prediction model for inorganic zinc-rich coating and thermal-spray zinc coating. Coatings. 2022; 12(4), 505. https://doi.org/10.3390/coatings12040505
30. Syrek-Gerstenkorn B, Paul S, Davenport AJ. Sacrificial thermally sprayed aluminium coatings for marine environments: A review. Coatings. 2020; 10(3), 267. https://doi.org/10.3390/coatings10030267