Süleyman Demirel Üniversitesi
Fen Bilimleri Enstitüsü Dergisi
Cilt 29, Sayı 2, 440-451, 2025

Süleyman Demirel University
Journal of Natural and Applied Sciences
Volume 29, Issue 2, 440-451, 2025

DOI: 10.19113/sdufenbed.1693318

Corrosion Performance and Protection of Centrifuged Hot-Dip Galvanized Coatings (CHDG) on St37 Steel Hooks in GFRC Façade Systems: A Case Study

Hüsnü GERENGİ[1], Muhammed MARAŞLI[2], Doğu RAMAZANOĞLU[3], Kader COŞKUN[*4], Mesut YILDIZ[5], Gözen BEREKET[6]

[1,5]Duzce University, Engineering Faculty, Department of Mechanical Engineering, Corrosion Research Laboratory, 81620 Düzce, Türkiye

[2,4]Fibrobeton Company R&D Center, 81100 Düzce, Türkiye

[3]Istanbul Gedik University, Engineering Faculty, Department of Nanotechnology Engineering, 34876, Istanbul, Türkiye

[6]Eskisehir Osmangazi University, Faculty of Arts and Science, Department of Chemistry, 26480 Eskisehir, Türkiye

(Alınış / Received: 06.05.2025, Kabul / Accepted: 08.08.2025, Online Yayınlanma / Published Online: 25.08.2025)

Keywords
Corrosion resistance,
Centrifuged hot-dip galvanization,
St37 steel,
Hook,
GFRC

Abstract: St37 steel hooks are used to attach glass fiber-reinforced concrete (GFRC) panels to the surface of buildings. The corrosion products formed on the surface of the hooks cause tensile stresses in the surrounding concrete, resulting in cracking and potentially decreasing the load-carrying capacity of the hooks. It is, therefore, essential to protect these hooks from corrosion. Centrifugal hot-dip galvanizing (CHDG) is the preferred process, particularly for protecting small metal parts used in outdoor applications. This study is the first one aiming to investigate the protection effect of the CHDG coating on hooks used in the assembly of GFRC panels. GFRC panel hooks are often used in three different configurations during the assembly process. To evaluate this, the three most common hook assemblies were tested: unmounted (A), hooks embedded in GFRC (PD), and mounted with the hot-dip galvanized profile (KT). These were investigated for 96 hours at 35 ± 2 °C in a continuous salt fog environment with 5 wt.% NaCl solution, according to ASTM B117 standards. The cross-sectional morphologies of the St37 steel hook coated with CHDG before and after the salt spray test were examined using a scanning electron microscope (SEM) and energy-dispersive X-ray spectrometry (EDS). The test results show the absence of red rust in all the test specimens, indicating that the CHDG coating protects the tested hooks from corrosion. The formed ZnO layer allows the repair of coating defects and provides physical protection of the coatings against the penetration of aggressive ions.

GFRC Cephe Sistemlerinde St37 Çelik Kancalar Üzerinde Santrifüjlü Sıcak Daldırma Galvaniz Kaplamaların (CHDG) Korozyon Performansı ve Korunumu: Bir Vaka Çalışması

Anahtar Kelimeler
Korozyon direnci,
Santrifüjlü sıcak daldırma galvaniz,
St37 çelik,
Kanca,
GFRC

Öz: St37 çelik kancalar, cam elyaf takviyeli beton (GFRC) panelleri binaların yüzeyine tutturmak için kullanılmaktadır. Kancaların yüzeyinde oluşan korozyon ürünleri çevredeki betonda çekme gerilmelerine neden olarak çatlamalara yol açmakta ve kancaların yük taşıma kapasitesini potansiyel olarak azaltmaktadır. Bu nedenle, bu kancaları korozyondan korumak çok önemlidir. Santrifüj sıcak daldırma galvanizleme (CHDG), özellikle dış mekan uygulamalarında kullanılan küçük metal parçaların korunması için tercih edilen bir işlemdir. Bu çalışma, GFRC panellerin montajında kullanılan kancalar üzerinde CHDG kaplamanın koruma etkisini

*Corresponding author: kader.dikmen@fibrobeton.com.tr

araştırmayı amaçlayan ilk çalışmadır. GFRC panel kancaları, montaj işlemi sırasında genellikle üç farklı konfigürasyonda kullanılmaktadır. Bunu değerlendirmek için en yaygın üç kanca düzeneği test edilmiştir: monte edilmemiş (A), GFRC'ye gömülü kancalar (PD) ve sıcak daldırma galvanizli profil ile monte edilmiş (KT). Kancalar, ASTM B117 standartlarına göre %5 NaCl çözeltisi ile sürekli tuz sisi ortamında 35 ± 2 °C'de 96 saat süreyle incelenmiştir. Tuz püskürtme testinden önce ve sonra CHDG ile kaplanmış St37 çelik kancanın kesit morfolojileri taramalı elektron mikroskobu (SEM) ve enerji dağılımlı X-ışını spektrometresi (EDS) kullanılarak incelenmiştir. Test sonuçları, tüm test numunelerinde kırmızı pas bulunmadığını göstererek CHDG kaplamanın kancaları korozyondan koruduğunu ortaya koymuştur. Oluşan ZnO tabakası kaplama kusurlarının onarılmasına olanak tanır ve kaplamaların agresif iyonların nüfuzuna karşı fiziksel olarak korunmasını sağlamaktadır.

1. Introduction

Corrosion is a significant challenge in maintaining the integrity and longevity of materials, particularly metals like steel, which are widely used in critical infrastructure. The deterioration of these materials occurs due to chemical or electrochemical reactions with their environment, leading to loss of structural integrity and functionality [1-3]. To combat corrosion, various protective strategies are employed, including cathodic and anodic protection, protective coatings, and the use of inhibitors [4-6].

St37 carbon steel is commonly employed in the construction industry due to its advantageous mechanical characteristics, ease of fabrication, and economic feasibility [7,8]. A notable area of application involves the use of St37 steel hooks to connect or support GFRC components. These hooks play a crucial role in transferring loads and securing prefabricated concrete panels to the main structural framework. Since GFRC panels are frequently used in exterior façade and cladding systems, the durability of the embedded steel elements under environmental exposure becomes a key concern. In particular, corrosion in humid or saline atmospheres can significantly compromise the structural reliability of these connectors. Therefore, implementing effective corrosion protection strategies is essential. Among these, hot-deep galvanizing is a highly effective method, offering both barrier and sacrificial protection by forming a durable zinc coating that shields the steel from corrosive attack, thereby extending its service life in aggressive environments [9-11].

Hot-dip galvanizing is an established surface treatment technique in which steel components are coated by immersion in molten zinc, resulting in a continuous and adherent protective layer. The process ensures a strong metallurgical bond between the zinc coating and the steel substrate, enhancing the material's resistance to oxidation and corrosive environments. Hot-dip galvanizing is typically employed for coating larger metallic components, whereas the centrifugal hot-dip galvanizing (CHDG) technique is specifically developed for smaller-sized parts. This method involves spinning the steel item within a crucible to apply centrifugal force, which facilitates the removal of surplus zinc from the surface. This approach results in a thinner, more evenly distributed zinc coating that enhances both the quality and durability of the protective layer [2].

CHDG is a process that involves immersing steel in molten zinc at approximately 450°C. This method not only provides a robust metallurgically bonded coating but also enhances the corrosion resistance of steel through a dual protective mechanism. The zinc coating acts as a physical barrier against corrosive agents while also serving sacrificially; it corrodes preferentially to protect the underlying steel from corrosion even if the surface coating is compromised [12-16].

The application of CHDG is prevalent across various industries such as automotive, construction, and appliances due to its numerous advantages, including strength, formability, low weight, cost-effectiveness, and recyclability. Research has demonstrated the effectiveness of CHDG in improving the corrosion resistance of steel grades like St37 under various environmental conditions [17-20].

Previous studies have shown that spin hot-deep galvanizing coatings, commonly used on small components such as screws and bolts, not only enhance mechanical strength but also alter the failure mechanism, leading to detachment of the zinc layer under stress [21]. In a study, the application of four different oxide-based coatings to St37 low-carbon steel via plasma spraying was found to significantly improve its surface properties [22]. A recent study investigated the application of tungsten carbide and chromium carbide–nickel chromium coatings on St37 steel surfaces using the High Velocity Oxy-Fuel (HVOF) spraying technique, revealing notable improvements in the mechanical and tribological properties of the coated material [23]. Another study examined the application of a nanoceramic sealant over white zinc coatings to improve the durability of metallic fasteners exposed to corrosive environments. Although the sealant significantly reduced the corrosion rate, its poor adhesion resulted in limited wear resistance [24]. A ZnAl coating was applied to SKL14 tension clamps to improve corrosion resistance. While uncoated samples rusted completely within 1 hour, the coated samples showed only ~3% rust after 720 hours in 5% NaCl, demonstrating a significant improvement in durability [25].

CHDG and other advanced coatings offer a versatile approach to corrosion control [26]. By understanding the mechanisms behind these protective strategies - whether through physical barriers or electrochemical modifications- engineers can make informed decisions regarding material selection and treatment processes. This knowledge is vital for ensuring the longevity and reliability of structures exposed to corrosive environments [27].

Through rigorous testing methods such as the Neutral Salt Spray Test (NSS) under controlled conditions, this research aims to elucidate the performance characteristics of CHDG-coated steel in real-world scenarios [28]. The findings will not only advance theoretical knowledge but also provide practical insights for industry applications where corrosion poses a persistent threat.

While CHDG is a well-known method for enhancing the corrosion resistance of small steel components, limited research exists on its performance when applied to St37, particularly in structurally critical applications like GFRC panel anchorage. In our previous study, CHDG-coated nut samples were subjected to a 13-day corrosion test following ASTM B117, and SEM-EDS analyses confirmed the protective effectiveness of the zinc layer. The formation of a stable zinc patina through sequential reactions with oxygen, moisture, and carbon dioxide contributes significantly to long-term corrosion resistance [2].

This study specifically investigates how CHDG-coated St37 steel hooks used in GFRC panel assemblies can mitigate corrosion risks associated with their deployment in outdoor environments. Since corrosion products can induce tensile stresses leading to cracking in surrounding concrete structures, understanding and enhancing protective measures for these hooks is essential for maintaining their load-carrying capacity and overall structural integrity.

2. Material and Method

2.1. Test specimens

The specimens examined in this study consisted of St37 steel hook units categorized as follows: unmounted hooks (referred to as A), hooks embedded in GFRC panels (referred to as PD), and unmounted hook sets (referred to as KT).

These hook units were selected due to their prevalence in various engineering and construction applications. Each specimen was carefully prepared to ensure uniformity in surface conditions and dimensions (Figure 1).

2.2. Methods

2.2.1. Test standards

The corrosion resistance evaluation followed the ASTM B117 standard [29] (Table 1), utilizing the Neutral Salt Spray Test methodology. This standard is widely recognized for its applicability in assessing the corrosion performance of materials exposed to corrosive atmospheres.

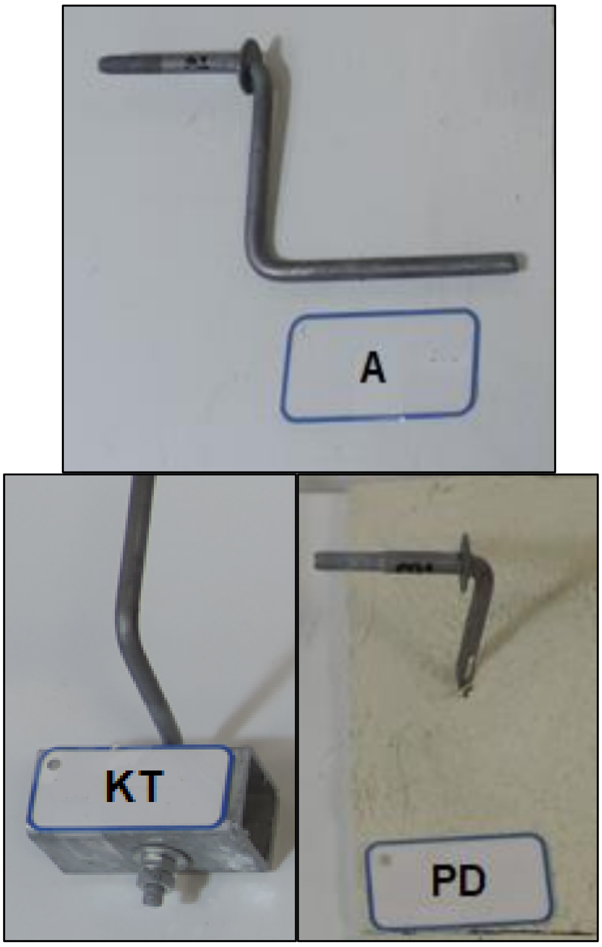

Figure 1. General view of the specimens before the test

Table 1. The ASTM B117 standard

Test Name	Test Standard	Intermediate Control Time	Test Duration
Neutral Salt spray experiments	ASTM B117	48 and 72 hours	96 hours

2.2.2. Test conditions

To replicate corrosive environmental conditions, the hook units were subjected to controlled conditions within a Salt Fog Test Chamber MT-SIS-087 (Q-LAB). The test chamber was maintained at a temperature of 35±2°C and a relative humidity of 50±5% in a 5% NaCl environment, by ASTM B117 requirements (Figure 2). The 5% NaCl solution was prepared using deionized water and analytical grade sodium chloride. The specimens were exposed to the salt spray for 96 hours. Visual inspections were conducted at 48 and 72 hours.

Figure 2. Salt spray test chamber

2.2.3. Visual assessment

The data collected from visual assessments were analyzed to determine the corrosion resistance exhibited by the CHDG St37 steel hook units. The specimens used in the test are named and sized as shown in Table 2.

Table 2. St37 steel hook units used in the test

Specimens Names	Size
A	8 cm vertical, 11 cm horizontal length with L-shaped sample
PD	25x25 cm
KT	8x4 cm
	15x4 cm

2.2.4. SEM-EDS analysis

The FEI Quanta FEG 250 model scanning electron microscope (SEM) with an energy dispersive X-ray spectroscopy (EDS) detector was used to observe the changes that occurred on the surfaces of the metals and to determine the elemental composition of the St37 steel hook before and after the salt spray experiments.

3. Results

3.1. Visual assessment findings

Upon completing the 96-hour neutral salt spray test, visual assessments of the St37 steel hook units with CHDG coatings revealed distinct corrosion behaviors across different specimen categories.

Observations included the presence of white rust, discoloration, and the absence of red rust. The extent of corrosion was evaluated on a percentage scale based on the surface area exhibiting corrosion-related phenomena. Visual inspection after the salt spray test revealed that specimens A and KT exhibited white rust and blackening on 40-50% of their test surfaces, while specimen PD exhibited these effects on 20-30% of its surface. Importantly, no red rust was observed on any specimen.

3.1.1. Hook units (A)

Figure 3 shows the appearance of the St37 steel hook unit-A before the neutral salt spray test. For hook unit A, visual inspections revealed corrosion primarily affecting 40% to 50% of the total surface area. White rust formation and localized discoloration were observed. Notably, there was no evidence of red rust on the samples, indicating a significant level of corrosion resistance (Figures 4, 5 and 6).

Figure 3. Appearance of unit-A before the salt spray test

Figure 4. Appearance of unit-A after the 48th hour interim control

Figure 5. Appearance of unit-A at the 72nd hour interim control

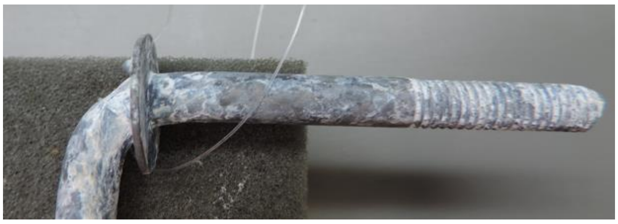

Figure 6. Appearance of unit-A after the 96th hour

3.1.2. Embedded hooks (PD)

The appearance of the St37 steel hook unit-PD before the neutral salt spray test is shown in Figure 7. In contrast to unit-A, the embedded hooks, PD, exhibited corrosion effects covering approximately 20% to 30% of their respective surfaces. The rust amount increased as the salt spray exposure time extended. Before and after the salt spray test results are shown in Figures 8, 9, and 10.

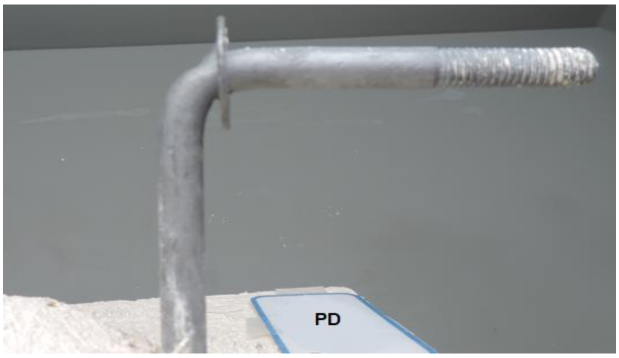

Figure 7. Appearance of unit-PD before salt spray test

Figure 8. The appearance of unit-PD, after the 48th hour

Figure 9. The appearance of unit-PD, after the 72nd hour

Figure 10. The appearance of unit-PD, after the 96th hour

White rust formation and localized discoloration were again noted, while the absence of red rust suggested moderate corrosion resistance. The metal parts embedded in the concrete panel were tested for corrosion due to water-salt penetration using 'bonding pad test' device. It was observed that the parts separated under a force of 350 kN. No discoloration due to corrosion was detected on the removed metal anchor element (Figure 11).

3.1.3. Hook sets (KT)

Figure 12 shows the appearance of the St37 steel hook sets before the neutral salt spray test. The hook sets exhibited similar corrosion patterns to the hook units, with approximately 40% to 50% of the surface area affected. White rust and localized discoloration were observed, but red rust was not evident (Figures 13, 14, and 15).

Figure 11. No rust was observed on embedded parts after severe corrosion

Figure 12. The appearance of the hook sets, before the salt spray test

Figure 13. The appearance of the hook sets, after the 48th hour interim control

Figure 14. The appearance of the hook sets after the 72nd hour interim control

Figure 15. The appearance of the hook sets after the 96th hour interim control

The results from visual assessments indicate that all specimens exhibited varying degrees of corrosion resistance. The absence of red rust across all specimen categories suggests that the CHDG coatings effectively protected against severe corrosion.

3.2. SEM-EDS analysis

The cross-sectional SEM images were obtained for the St37 steel hook coated by the CHDG method before (Figure 16) and after (Figure 17) the salt spray test, and the compositional analysis was performed by EDS.

Galvanic protection through the CHDG process enhances the overall corrosion resistance of zinc by keeping the steel passive while allowing Zn to form ZnO (Figure 18) [30]. The protective capabilities of the CHDG coating are attributed to three main effects: the barrier effect, the galvanic protection, and the self-healing ability. These properties enable their widespread use in industry by significantly extending the lifespan of metals in corrosive environments. The barrier effect occurs when zinc coatings prevent direct contact between the underlying metal and the corrosive environment, inhibiting the ingress of water and oxygen, thereby effectively reducing corrosion rates. This effect is primarily achieved by coatings that prevent corrosive agents from reaching the metal surface. Notably, even if the zinc coating is damaged, the barrier effect continues to provide protection against environmental factors [31].

Figure 16 shows that the coating thickness of the St37 steel hook coated by the CHDG method before the experiment was 82.79 μm. The results of the EDS and elemental mapping analyses showed that the metal surface was coated with Zn. The EDS analysis performed on Spot 1 showed a composition of 89.4% Zn, 7.6% Fe, and 3.1% O, while the results from Spot 2 showed a Fe ratio of 97.3% and an O ratio of 1.3%, with no Zn detected. Examination of the SEM images taken from the section after the corrosion test revealed that the coating thickness had increased to 135.83 μm (Figure 17). The increase in the thickness of the zinc (Zn) layer can be attributed to the formation of oxide layers on the surface. EDS analysis of the cross-section of the St37 steel hook after the salt spray test revealed the elemental composition at Spot 1 as follows: 39.2% Zn, 55.2% O, and 0.5% Fe. The EDS results obtained from Spot 2 showed a composition of 71.5% Zn, 19.2% O and 5.8% Fe. In contrast, the EDS results from Spot 3 showed a different composition consisting of 94.7% Fe and 1.6% O, with no detectable zinc present. Based on the EDS and elemental mapping results, it was observed that distinct oxide layers had formed on the upper surfaces of the coating. These results indicate a significant chemical transformation, probably due to oxidation processes during the test or environmental exposure. Elemental mapping clearly highlighted the distribution of oxygen across the surface, indicating that oxide formation was concentrated in the upper regions of the coating. According to the EDS results from Spot 1 and Spot 2 in Figure 16 and Figure 17, the increase in O ratio (52.1%) and decrease in Zn (50.2%) ratio on the St37 steel hook's surface could be attributed to the formation of various oxide and hydroxide layers.

Potential substances that might be responsible for the corrosion layer seen on the CHDG-coated surface include zinc oxide (ZnO), zinc hydroxide chloride hydrate ($Zn_5(OH)_8Cl_2{\cdot}H_2O$), and zinc carbonate hydroxide ($Zn_5(CO_3)_2(OH)_6$) [32]. Among these compounds, white rust—which is largely made up of zinc hydroxide ($Zn(OH)_2$) and basic zinc salts like $Zn_5(OH)_8Cl_2{\cdot}H_2O$—typically occurs in environments with high humidity and low oxygen levels. Although white rust can serve as a temporary shield initially, it is generally viewed as an unfavorable corrosion product in the long run due to its porous and weakly attached quality. In contrast to stable and tightly bonded ZnO layers, which provide long-lasting protection, white rust has poor adhesion and barrier characteristics, ultimately diminishing the overall effectiveness of corrosion resistance over time [33]. Still, the findings from this study indicate that the CHDG technique successfully safeguards the St37 steel hook from corrosion, as demonstrated by the lack of red rust on all the specimens tested [34].

4. Discussion and Conclusion

The results of this research confirm that CHDG coatings significantly enhance the corrosion protection of St37 hooks used in GFRC panel façades. The absence of red rust in all samples tested highlights the effectiveness of CHDG in corrosive environments. A noteworthy observation was the thin ZnO layer formed on the surface of the coated hooks, which not only covers any cracks but also provides self-healing properties to areas where the coating may have deteriorated. This uniform thickness of the ZnO layer ensures prolonged protection for the steel substrate, even when the coating experiences surface damage or interruptions. The SEM-EDS analysis reveals the morphology of the samples and elemental distribution, demonstrating that the CHDG method is an effective way to safeguard St37 steel hooks against corrosion.

These findings hold considerable practical implications for materials engineering and design, especially in applications where corrosion poses a critical challenge. The incorporation of CHDG coatings in infrastructure and construction can greatly extend the service life and structural integrity of vulnerable components exposed to harsh climatic conditions.

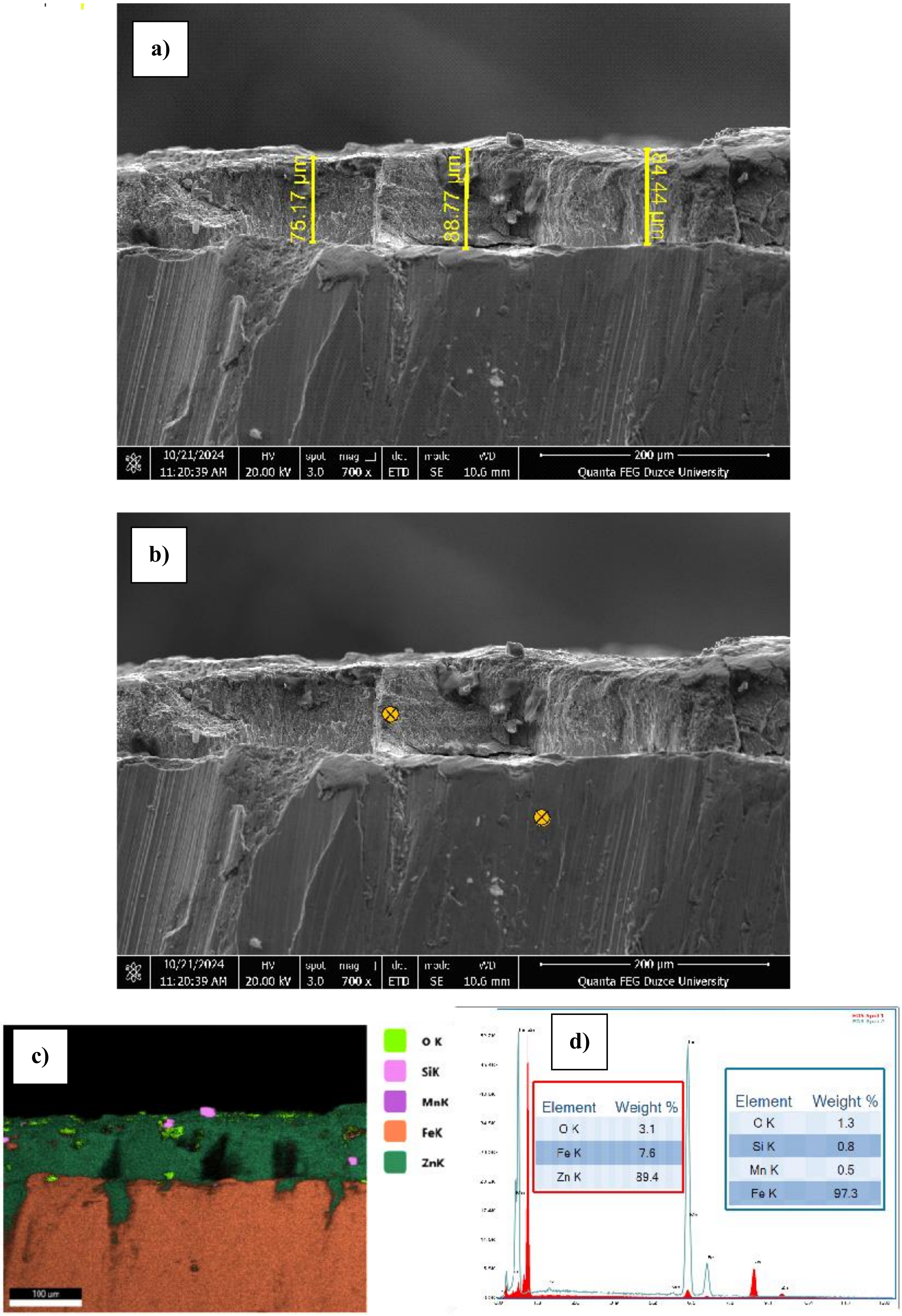

Figure 16. SEM-EDS analysis of the cross-section of CHDG coated St37 steel hook before salt spray test; a) thickness of the coating, b) SEM image (200 µm), c) elemental mapping, d) EDS spectrum

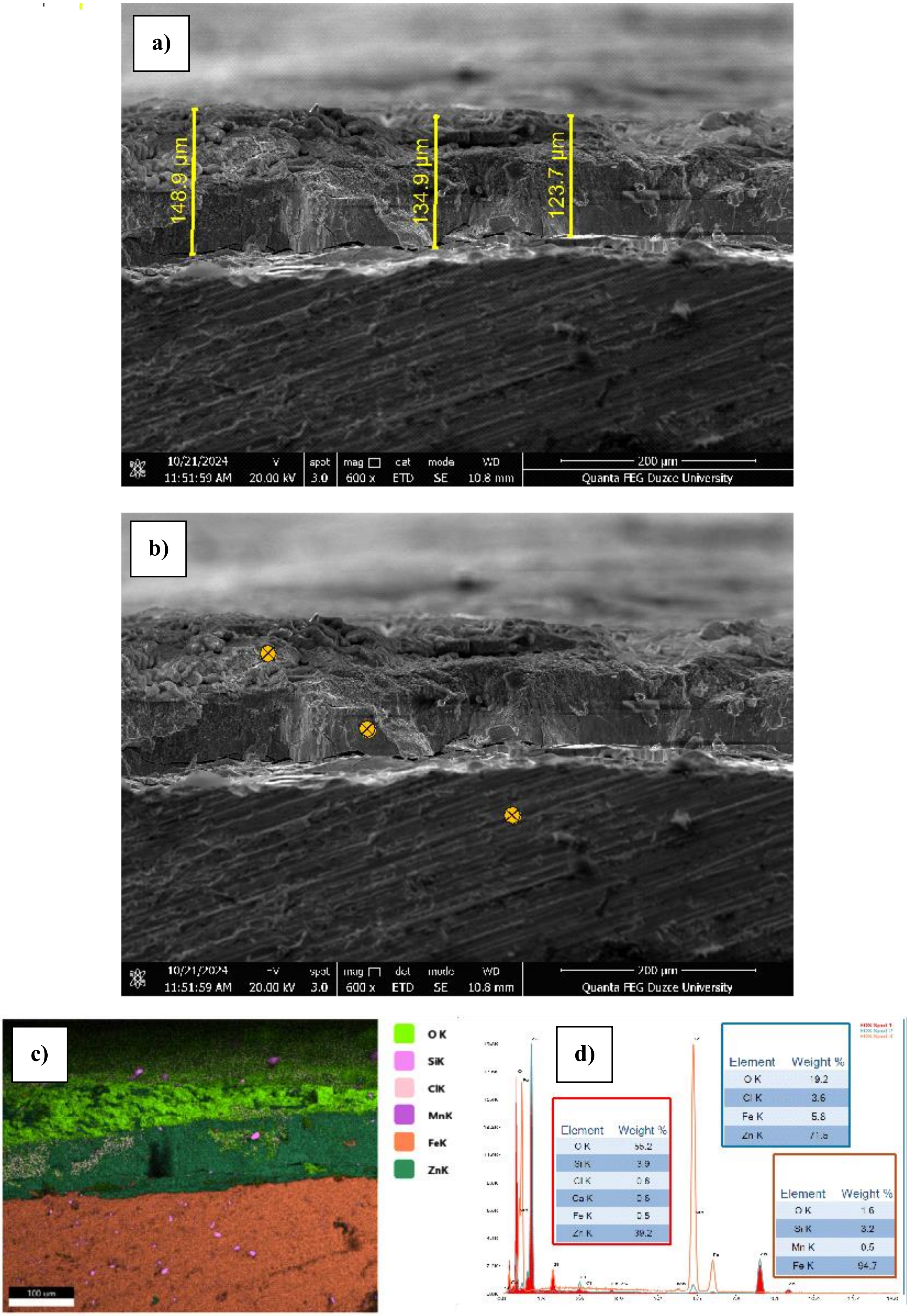

Figure 17. SEM-EDS analysis of the cross-section of CHDG coated St37 steel hook after salt spray test; a) thickness of the coating, b) SEM image (200 µm), c) elemental mapping, d) EDS spectrum

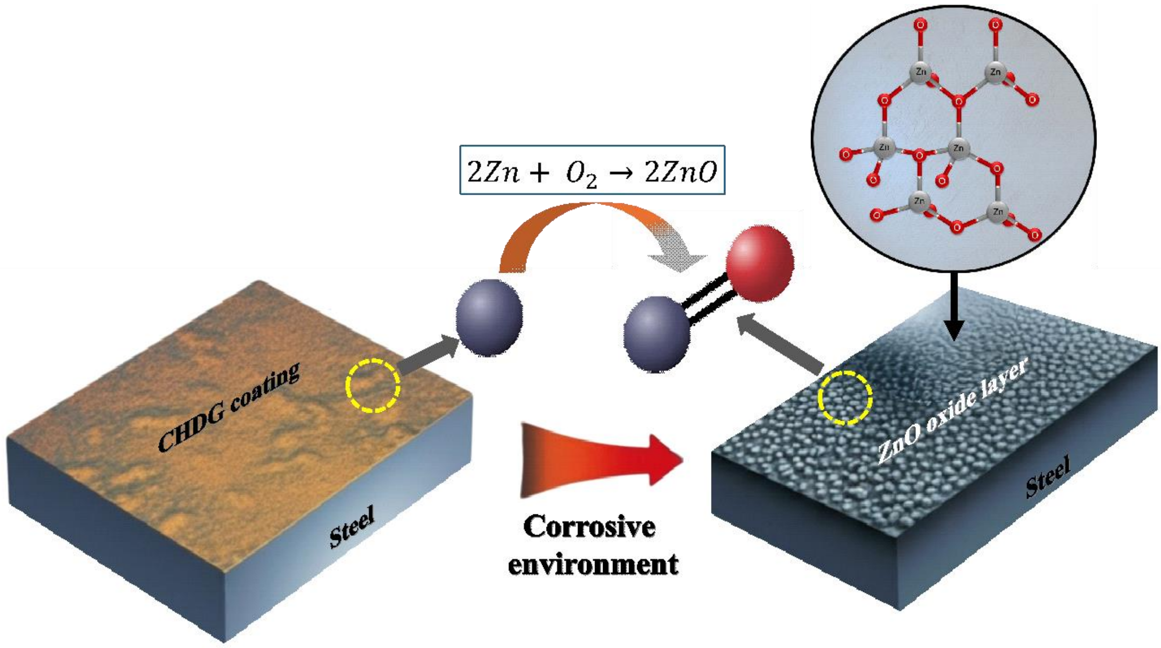

Figure 18. The formation of ZnO on the surface of steel coated with CHDG in a corrosive environment

Future research should focus on exploring the long-term performance of CHDG-coated components in a variety of environmental conditions to validate and expand upon existing findings. To achieve this, it would be beneficial to apply simulated real-world test protocols involving cyclic changes in temperature, humidity, etc. and electrochemical corrosion measurement methods. Such dynamic environmental testing will provide valuable data on the durability of the coatings, while also elucidating the effect of increased ZnO film thickness on corrosion resistance and structural integrity. To effectively demonstrate the advantages of CHDG coatings, future studies should also include comparative analyses with uncoated (bare) St37 steel façades. Results obtained under identical environmental and mechanical conditions will reveal the protective benefits provided by the coating.

This study clearly demonstrates that CHDG coatings significantly improve the corrosion resistance of St37 steel hooks used in GFRC façades, providing durable solutions for the construction industry and paving the way for future research in this field.

Acknowledgment

This scientific study was conducted through a university-industry collaboration between the Corrosion Research Laboratory of Düzce University and the R&D Centre of Fibrobeton Company. The authors would like to extend their sincere thanks to Faik Ali Birinci, Volkan Özdal, Volkan Akmaz, Sedat Enveş, Yasemin Hatipoğlu, and from the Fibrobeton R&D Centre, as well as Buse Tezcan from DİBA Research and Development Engineering Co., for their valuable contributions to the research.

This work was supported by the Düzce University Scientific Research Projects Coordination Unit (Project No: 2024.06.05.1549), titled 'Investigation of the Corrosion Mechanism of Metals Coated by Centrifugal Hot-Dip Galvanizing (CHDG) Method

References

[1] Gerengi, H., Maraşlı, M., Kohen, B., Ramazanoğlu, D., Coşkun, K. 2025. Effectiveness of zinc-rich coating in preventing weld zone corrosion in GFRC facade anchorage elements. 9th International Engineering and Technology Management Congress, April - May 29-30-01, Istanbul, Türkiye.

[2] Gerengi, H., Maraşlı, M., Yıldız, M., Coşkun, K., Güner, Y., Aşıkoğlu, B. 2025. The effect of Centrifuged Hot-Dip Galvanisation (CHDG) Process on the Corrosion on Nuts. Duzce University Journal of Science and Technology, 13, 13-25.

[3] Wang, J., An, L., Wang, J., Gu, J., Sun, J., Wang, X. 2023. Frontiers and advances in N-heterocycle compounds as corrosion inhibitors in acid medium: Recent advances. Advances in Colloid and Interface Science, 321, 103031.

[4] Kurtay, M., Gerengi, H., Chidiebere, A., Yıldız, M. 2022. Corrosion inhibition of reinforcement steel in mixture water by caffeine and L-arginine. Journal of Adhesion Science and Technology, 36, 134–167.

[5] Ananthkumar, M., Mini, K.M., Thilagavathy, P. 2025. Eco-friendly corrosion protection of steel in simulated concrete environments using cassia fistula leaf extract: Electrochemical and surface

characterization study. South African Journal of Chemical Engineering, 54, 44–49.

[6] Liu, Y., Shi, J. 2025. Exploring a feasible inhibitor-coating protective system for corrosion protection of steel in mortar. Cement and Concrete Composites, 161, 106109.

[7] Gerengi, H., Uygur, I., Solomon, M., Yildiz, M., Goksu, H. 2016. Evaluation of the inhibitive effect of Diospyros kaki (Persimmon) leaves extract on St37 steel corrosion in acid medium. Sustainable Chemistry and Pharmacy, 4, 57–66.

[8] Solomon, M.M., Gerengi, H., Kaya, T., Umoren, S.A. 2017. Enhanced corrosion inhibition effect of chitosan for St37 in 15% H2SO4 environment by silver nanoparticles. International Journal of Biological Macromolecules, 104–A, 638–649.

[9] Liu, Y., Gao, H., Wang, H., Tao, X., Zhou, W. 2024. Study on the corrosion behavior of hot-dip galvanized steel in simulated industrial atmospheric environments. International Journal of Electrochemical Science, 19, 100445.

[10] Guo, Y., Chen, R., Zhang, C., Xiao, H., Wu, G. 2025. Assessment of the corrosion state of carbon steel galvanized layers based on laser-induced breakdown spectroscopy. Measurement, 253–B, 117518.

[11] Ghazaee, A., Pour-Ali, S., Mahdavi, S., Tavangar, R., Khalili, M. 2024. Corrosion inhibition of steel rebar in chloride-contaminated concrete pore solution: Ecofriendly glutamic acid inhibitor and its synergy with galvanized coating. Inorganic Chemistry Communications, 167, 112832.

[12] Coşkun, K., Gerengi, H., Maraşlı, M., Birinci, F.A., Özdal, V. 2023. Use of corrosion inhibitors in stainless steel anchors used in glass fiber reinforced concrete (GRC) precast facade elements. The European Journal of Research and Development, 3, 1–15.

[13] Gerengi, H., Maraşlı, M., Rizvi, M., Kohen, B., Taşkıran, I. 2024. Protection of steel hooks embedded in glass-fiber-reinforced concrete against macrocell corrosion. Petroleum Research, 9, 317–326.

[14] Özdal, V., Marasli, M., Gerengi, H., Dikmen, K. 2023. Corrosion behavior of embedded pad hook in glass fiber reinforced concrete. Civil Engineering Design, 5, 18–24.

[15] Pop, A.B., Iepure, G., Titu, A.M., Ravai-Nagy, S. 2023. Characterization and corrosion behavior of zinc coatings for two anti-corrosive protections: A detailed study. Coatings, 13, 1460.

[16] Šmak, M., Kubíček, J., Kala, J., Podaný, K., Vaněrek, J. 2021. The Influence of Hot-dip galvanizing on the mechanical properties of high-strength steels. Materials, 14, 5219.

[17] Anaee, R.A., Salih, W.M., Abdullah, H.A. 2017. Anodic inhibitor doped polypyrrole coating to reduce corrosion in petroleum medium. Engineering and Technology Journal, 35, 878–886.

[18] Poppy, P., Chrisye, A., Aripriharta Jeefferie, A. R., Mirza Abdillah Pratama, M. 2020. Corrosion resistance analysis of st37 carbon steel material using phosphate conversion coating in various immersion durations. Key Engineering Materials, 851, 61–67.

[19] Qingdong, Z., Rohwerder, M., Zhao, Z., Hamidah, I., Wati, R., Hamdani, R. A. 2018. Analysis of AISI 304 tensile strength as an anchor chain of mooring system. IOP Conference Series: Materials Science and Engineering, 367, 012058.

[20] Yang, N., Wang, W., Cai, W., Lu, K. 2020. Corrosion and tribocorrosion mitigation of perhydropolysilazane-derived coatings on low carbon steel. Corrosion Science, 177, 108946.

[21] Abeln, B., Pinger, T., Richter, C., Feldman, M. 2023. Adhesion of batch hot-dip galvanized components. The International Journal of Advanced Manufacturing Technology, 125, 5197-5209.

[22] Benli, B., Celik, I., 2024. Surface Modification and Analysis of St37 Steel with Al2O3-TiO2, ZrO2, and Cr2O3 Ceramic Coatings: Structural, Mechanical, and Tribological Properties. Tribology International, 191, 109183.

[23] Celik, I., Benli, B. 2024. The effect of WC-12Co and CrC-NiCr hard coatings applied by HVOF method on the microstructure, mechanical, and surface properties of steel. Metallurgical Research & Technology, 121, 318.

[24] Krelling, A.P., Jeronimo, J.L., Bonetti, I., Rabethge, G. 2024. Micro-Scale Abrasive Wear Resistance of a Nanoceramic Sealant Applied on Galvanized Low Carbon Steel. Tribology in Industry, 46, 116–125.

[25] Dursunlar, M., Taş, Z., Çelebi, M., Akgül, B., Çuğ, H. 2025. Enhanced corrosion resistance of high-speed railway fastening systems: ZnAl coating on 38Si7 steel. Kovove Materialy, 63, 119–134.

[26] Saleh, B., Fathi, R., Shi, H., Wei, H. 2023. Advanced Corrosion Protection through Coatings and Surface Rebuilding. Coatings, 13, 180.

[27] Li, G., Du, M., Wang, J., Huang, G., Ma, L. 2023. Effect of hydrogen on pitting corrosion of 2205 duplex stainless steel under alternating dry/wet marine environment. International Journal of Hydrogen Energy, 48, 17983–17994.

[28] Ozakgul, K., Baydogan, M., Piroglu, F. 2023 Postfire damage assessment of a steel industrial building exposed to fire. Journal of Performance of Constructed Facilities, 37, 04023055.

[29] Wan, Y., Macha, E. N., Kelly, R. G. 2012. Modification of ASTM B117 salt spray corrosion test and its correlation to field measurements of silver corrosion. Corrosion, 68.

[30] Baird, L. M., Patchan, M. W., Morris, M., Maisano, A. J., Phillips, T. E., Benkoski, J. J., Srinivasan, R. 2015. Synergy between galvanic protection and self-healing paints. Langmuir, 31, 10610–10617.

[31] Zhang, X. G. 1996. Corrosion and Electrochemistry of Zinc, Springer: New York.

[32] Zhang, K., Song, R., Gao, Y. 2019. Corrosion behavior of hot-dip galvanized advanced high strength steel sheet in a simulated marine atmospheric environment. International Journal of Electrochemical Science, 14, 1488–1499.

[33] Meng, Y., Liu, L., Zhang, D., Dong, C., Yan, Y., Volinsky, A.A., Wang, Lu. 2019. Initial formation of corrosion products on pure zinc in saline solution. Bioactive Materials, 4, 87–96.

[34] Gerengi, H., Maraşlı, M., Solomon, M. M., Coskun, K., Guner, Y. 2024. Corrosion of Centrifuged Hot Dip Galvanized Pad Hooks used in GFRC Panels. Metals and Physical Chemistry of Surfaces, 60(5), 1-7.