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Investigation of the corrosion behavior of carbon steel coated with zinc electrochemically at different current densities in chloride solutions

Elektrokimyasal olarak farklı akım yoğunluklarında çinko kaplanan karbon çeliğin klorürlü çözeltilerdeki korozyon davranışının incelenmesi

Behçet Kağan BÖLÜK [1], Sibel Demirel ZOR*[1]

[1]*Kocaeli University, Science-art Faculty, Chemistry Department 41001, Kocaeli, Türkiye*

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Abstract

In this study, the surface of high carbon steel (0.83 % C) was electrolytically coated in Zn coating solution at constant current densities of 1 A/dm², 2 A/dm², 3 A/dm², 4 A/dm² and 5 A/dm² for 30 minutes. The corrosion resistance of zinc-coated carbon steel in 3.5 % NaCl solutions was determined by Tafel polarization measurements. According to the Tafel polarization results, the corrosion current density was 105 µA/cm² for uncoated carbon steel, while this value was 85.7 µA/cm² with Zn coating at 1 A/dm², and the decrease in corrosion current density was determined as 10.8 µA/cm² with 5 A/dm² coating. A 90 % decrease in corrosion current density was observed in the Zn coating to which 5 A/dm² current was applied. Accordingly, as the coating applied constant current density increased, the corrosion current density decreased. In addition, the changes that occur over time on the surfaces of Zn-coated and uncoated steel exposed to a constant current of 5 A/dm² in a 3.5 % NaCl solution for 0, 4, 24, 48, and 120 hours were investigated by SEM images and EDS analyses. The experimental results indicated that the Zn coating was denser and more homogeneous coating under the 5 A/dm² constant current application conditions. After 240 hours, 5 A/dm² constant current, the coating maintained its corrosion protection in corrosive environments such as chlorides, and the surface coating remained relatively intact. Additionally, coating thicknesses were determined using an optical microscope. The thickness of the Zn coating was determined as 2 µm at a constant current of 1 A/dm², while this ratio was determined as 14 µm at 5 A/dm². Accordingly, the coating thickness increased homogeneously with the increase in the constant current density applied in electroplating. As a result, it was observed that the Zn coating at a constant current of 5 A/dm² was effective in preventing the corrosion of high carbon steel in aggressive environments containing chlorides.

Keywords: Carbon steel, Corrosion resistance, Current density, Electrodeposition, Zinc coating

Öz

Bu çalışmada, yüksek karbonlu çeliğin (% 0,83 C) yüzeyi, 1 A/dm², 2 A/dm², 3 A/dm², 4 A/dm² ve 5 A/dm² sabit akım yoğunluklarında 30 dakika süreyle Zn kaplama çözeltisinde elektrolitik olarak kaplanmıştır. Çinko kaplı karbon çeliğinin %3,5 NaCl çözeltilerindeki korozyon direnci Tafel polarizasyon ölçümleri ile belirlenmiştir. Tafel polarizasyon sonuçlarına göre, saf çelik için korozyon akım yoğunluğu 105,0 µA/cm² iken, 1 A/dm²'lik Zn kaplama ile bu değer 85,7 µA/cm² olmuş ve 5 A/dm² kaplama ile korozyon akım yoğunluğundaki azalma 10,8 µA/cm² olarak belirlenmiştir. 5 A/dm² akım uygulanan Zn kaplamada korozyon akım yoğunluğunda % 90 azalma gözlenmiştir. Buna göre, uygulanan kaplamanın sabit akım yoğunluğu arttıkça korozyon akım yoğunluğu azalmıştır. Ayrıca, %3,5'luk NaCl çözeltisinde 5 A/dm² sabit akıma 0, 4, 24, 48 ve 120 saat maruz bırakılan Zn kaplı ve kaplamasız çelik yüzeylerinde zamanla oluşan değişimler SEM görüntüleri ve EDS analizleriyle incelenmiştir. Deneysel sonuçlar, 5 A/dm² sabit akım uygulama koşulları altında Zn kaplamanın daha yoğun ve daha homojen bir kaplama olduğunu göstermiştir. 240 saat, 5 A/dm² sabit akım sonunda kaplama, klorürler gibi korozif ortamlarda korozyon korumasını sürdürmüş ve yüzey kaplaması fazla bozulmamıştır. Ayrıca, optik mikroskop kullanılarak kaplama kalınlıkları belirlenmiştir. 1 A/dm² sabit akımda elde edilen kaplamanın kalınlığı 2 µm olarak belirlenirken, bu oran 5 A/dm² de 14 µm olarak belirlenmiştir. Buna göre elektrokaplamada uygulanan sabit akım yoğunluğunun artmasıyla kaplama kalınlığı homojen bir şekilde artmıştır. Sonuç olarak, klorür içeren agreseif ortamlarda yüksek karbonlu çeliğin korozyonunu önlemede 5 A/dm² sabit akımdaki Zn kaplamanın etkili olduğu görülmüştür.

Anahtar kelimeler*: Karbon çeliği, Korozyon direnci, Akım yoğunluğu, Elektrokimyasal çöktürme, Çinko kaplama*

*Sibel Demirel ZOR; szor2001@yahoo.com, merve@kocaeli.edu.tr

1. Introduction

Today, steel material is used in the automotive, construction, mining, marine, transportation, space industry, water-oil pipelines, and household appliances, in short, in every field where production and consumption are present. The most commonly used alloy today is steel. New studies on steel alloys and new forms developed are proof that steel alloys will not be given up easily. Carbon steels have the widest range of use among steels. Fe-C alloys containing up to 1.4% carbon (C) are defined as carbon steel. One of the important reasons for the widespread use of carbon steels is that they have lower costs compared to other materials. However, carbon steels have lower resistance to environmental corrosion, so their losses are higher. Corrosion is seen everywhere where metallic materials are used, such as tanks, warehouses, underground pipelines, reinforced concrete bars, scaffolding concrete and steel legs, ships, machine parts, and treatment plants. Metals used in all these structures are out of service much earlier than their designed service life due to corrosion, which causes great economic losses. In addition, with the understanding of the real dimensions of the economic losses caused by corrosion losses, studies on developing methods to protect carbon steels with high corrosion rates from corrosion have increased. One solution proposed to combat corrosion is the use of a metallic protective coating that can increase the corrosion resistance of ferrous steel materials such as mild steel/carbon steel, low-alloy steels, etc. These coatings should protect metal structures by acting as a physical barrier or sacrificial coating (Kranthi & Shiladitya, 2021). They should have high corrosion resistance and pose a minimum environmental threat. For this purpose, zinc coating is of great importance in the manufacturing industry (Oluwasegun et al., 2015). Zinc coating is carried out using hot-dip galvanizing or electroplating methods, particularly to protect metallic substrates from corrosion. Compared to hot-dip galvanizing, electroplating produces a thinner and more uniform zinc coating on the metal surface. Electroplating is an electrochemical process in which a metal is used as the anode, the substrate to be coated is used as the cathode, and this electrode surface is coated in a metal salt solution using direct current. In this method, the substrate to be coated must be electrically conductive (Abioye et al., 2019).

Zinc coatings tackle corrosion by corroding themselves to shield the steel underneath—a process rooted in zinc's anodic properties (Zhang, 1996; Jones, 1996). This sacrificial mechanism, well documented in early studies, makes zinc a cornerstone for protecting steel in harsh environments (Brenner, 1963) They don't just stop rust but also extend steel's life in all sorts of use cases, such as from galvanized roofing in construction to durable fasteners in car manufacturing (Lin & Huang, 2006). In harsh marine environments, zinc coatings protect steel from chloride ions, which is critical for ships and dock equipment (Jones, 1996). Without them, steel would quickly pit and corrode (Maniam & Paul, 2021). Electrodeposition is a practical and easy way to apply these coatings, especially for complex shapes like structural beams (El Fazazi et al., 2021). It creates even layers, and studies show the process can be optimized to enhance zinc's performance (Ramesh et al., 1998; Kanani, 2006). This project builds on that idea, focusing on pure zinc coatings to explore how current density alone influences corrosion protection without alloying elements (Bhat et al., 2021). Zinc coatings play a critical role in industries such as oil and gas and coastal construction, where corrosion can lead to expensive failures or safety risks (Zhang, 1996; Maniam & Paul, 2021). Unlike studies focusing on alloyed or composite coatings, the present research examines pure zinc coatings on hight carbon steel, applied at current densities ranging from 1 to 5 A/dm² and evaluated in 3.5% NaCl using Tafel polarization and SEM/EDS to explore how current density alone influences corrosion protection in chloride-rich environments—without the added complexity of alloying elements (Bhat et al., 2021; Jiang et al., 2022).

2. Materials and methods

2.1. Bath solution and substrate preparation

Zinc coatings were applied to high carbon steel produced by Arcelorr- Mittal, France substrates through electrodeposition, using an aqueous electrolyte based on sulfate compounds. The chemical composition of the high carbon steel used in the experiments is presented in Table 1. The solution was made by dissolving high-purity chemicals in 1 liter of deionized water. As shown in Table 2, the bath contained 150 g/L of $ZnSO_4 \cdot 7H_2O$, 20 g/L of Na_2SO_4, 20 g/L of H_3BO_3, and 0.5 g/L of SDS. This composition follows established methods for producing consistent zinc layers on steel surfaces (El Fazazi et al., 2021). For electrochemical experiments, high carbon steel was shaped into cylindrical rods (1 cm diameter, ~10 cm long), with a 1 cm² area exposed and the rest sealed with ~0.5 cm thick epoxy. For surface studies, square samples (1 cm × 1 cm × 3 mm) were

used. The steel pieces were first ground using SiC papers (180, 400, 800, 1200 grit) at 220 rpm on a Metkon Gripo 2V grinder, then polished with a 6 µm felt cloth. Afterward, they were washed with purified water, dried, etched in concentrated H_2SO_4 for 40 seconds, and rinsed thoroughly.

Table 1. Percentage composition of high carbon steel

	C	Mn	Si	P	S
Composition %	0.83	0.50	0.19	0.013	0.006

Table 2. Zinc plating bath solution composition

Component	Concentration (g/L)	Purpose
$ZnSO_4 \cdot 7H_2O$	150	Zinc ion source
Na_2SO_4	20	Conductivity enhancer
H_3BO_3	20	pH stabilizer
SDS	0.5	Surfactant/Dispersion aid

2.2. Electrodeposition process

Electrodeposition was conducted at room temperature (25 °C) in a 400 mL beaker with a 2 cm electrode spacing, using a GW PPE-3323 DC power supply in constant current mode. High carbon steel samples served as cathodes, connected via copper cables (rods) and strings through a ~2 mm hole (squares). Lead anodes (1 cm diameter, ~10 cm length, 1 cm² exposed) were connected similarly. Current densities of 1–5 A/dm² were applied for 30 minutes, with the electrolyte stirred at 600 rpm. Coated samples were rinsed and air-dried before testing in 3.5 % NaCl.

2.3. Corrosion measurements and characterization

The classical three-electrode method was used for electrochemical measurements. The high-carbon steel coated with Zn was used as the working electrode, a platinum wire as the counter electrode, and a calomel electrode as the reference electrode. The reference electrode was placed in a Lugin capillary to prevent ohmic potential drop. Measurements were performed in a 3.5% NaCl solution after electroplating. The electrode potential was stirred for 30 minutes before starting the polarization measurements to equilibrate and OCP values was measured after 30 minutes. Potentiodynamic Tafel polarization curves were obtained automatically with a Gamry Reference 600 galvanostat/potentiostat at a scan rate of 1 mV/s over a potential range of -250 mV/+250 mV. All potentials were measured against a saturated calomel electrode (SCE, Hg (l), Hg_2Cl_2 (s)). Surface morphology and composition were examined using a Zeiss Gemini Sigma 300 SEM with EDS, imaging bare and coated samples (1 A/dm^2 and 5 A/dm²) at 0, 4, 24, 48, and 240 hours in NaCl, at 20 kV and magnifications of 1x–5x.

3. Results and discussion

3.1. Electrochemical behavior

The open circuit potential (OCP) is the corrosion equilibrium potential, which is the equilibrium potential obtained after 30 minutes under conditions where no current flows in order for the system to reach equilibrium before taking the Tafel polarization measurement. To understand how the samples would behave electrochemically before corrosion testing, OCP values were recorded for both bare high carbon steel and zinc-coated samples. The coatings were applied using current densities between 1 A/dm^2 and 5 A/dm², and each sample for 30 minutes in 3.5% NaCl before readings were taken. The values are listed in Table 3. As expected, the bare steel showed an OCP of -0.59 V vs SCE, which is fairly typical for unprotected carbon steel exposed to chloride-rich environments—where corrosion tends to initiate rapidly (Jones, 1996). The zinc-coated samples showed significantly more negative OCP values, landing between -1.07 V and -1.08 V. These results were consistent regardless of the current density used during coating. This kind of shift in potential is

Table 3. OCP values of coated and uncoated carbon steel at different current densities

Sample	OCP (V vs. SCE)
Bare Steel	-0.59
1 A/dm²	-1.07
2 A/dm²	-1.07
3 A/dm²	-1.08
4 A/dm²	-1.08
5 A/dm²	-1.11

what is anticipated from sacrificial coatings like zinc—it corrodes first, shielding the steel underneath (Zhang, 1996; Jones, 1996). Interestingly, the fact that the OCP did not vary much between coatings at different current densities suggests the protective behavior is fairly stable across that range. These results with what other studies have shown, where OCP values for zinc-based coatings generally range between -1.0 and -1.1 V. (Ramanauskas et al., 1997; El Fazazi et al., 2021; Kwon et al., 2026).

3.2. Corrosion kinetics

Tafel polarization curves of zinc-coated and uncoated high carbon steel at different current densities in 3.5 % NaCl are given in Figure 1. The electrochemical parameters obtained by extrapolation of Tafel Curves are presented in Table 4. According to Table 4, Icorr of bare steel exhibited 105 µA/cm², an Ecorr of -0.57 V, a corrosion rate of 61.32 mpy, and a polarization resistance of 361.8 Ω. These values show the typical corrosion behavior of uncoated steel due to the corrosive effect of chloride ions (Jones, 1996). For Zn-coated samples, icorr decreased progressively with increasing current density: from 85.7 µA/cm² at 1 A/dm² (Ecorr: -1.06 V, corrosion rate: 50.00 mpy, polarization resistance: 141.8 Ω) to 10.8 µA/cm² at 5 A/dm² (Ecorr: -1.21 V, corrosion rate: 6.32 mpy, polarization resistance: 958.8 Ω). This trend shows that higher current density during electrodeposition enhances corrosion resistance, with the 5 A/dm² coating showing the lowest corrosion rate and highest polarization resistance. Intermediate coatings followed a similar pattern: 2 A/dm² (i_{corr}: 73.3 µA/cm², Ecorr: -1.07 V, corrosion rate: 42.81 mpy, polarization resistance: 161.7 Ω), 3 A/dm² (i_{corr}: 62.9 µA/cm², Ecorr: -1.07 V, corrosion rate: 3618.3 mpy, polarization resistance: 254.0 Ω), and 4 A/dm² (i_{corr}: 19.5 µA/cm², Ecorr: -1.09 V, corrosion rate: 11.35 mpy, polarization resistance: 431.4 Ω), highlighting a clear improvement in protective properties as current density rises.

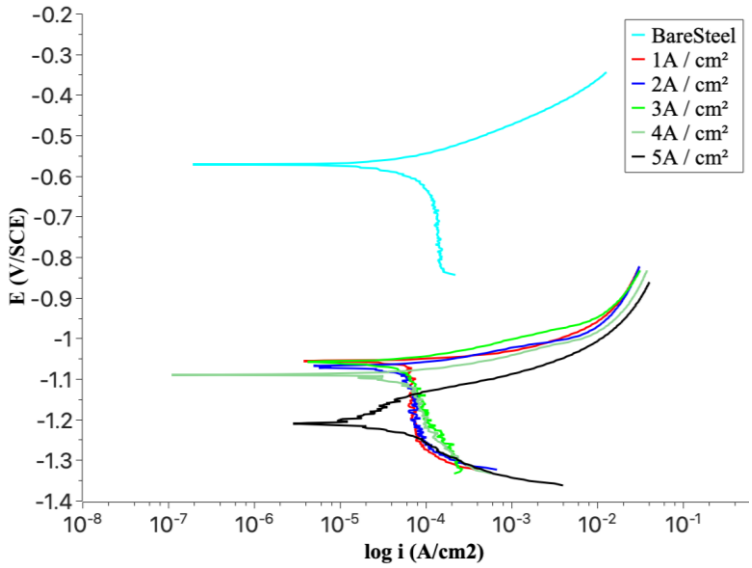


Figure 1. Tafel polarization curves of Zn - coated and uncoated high carbon steel at different current densities in 3.5 % NaCl

This trend suggests that increased current density forms a denser or thicker Zn coating, reducing corrosion rates by creating a more effective barrier. Similar studies report comparable improvements: pure Zn coatings

at optimized conditions yielded icorr as low as 10–15 µA/cm² in chloride solutions (Byk et al., 2008; Vatsala & Venkatesha, 2011). The 5 A/dm² coating's icorr (10.8 µA/cm²) and corrosion rate (6.32 mpy) underscore pure Zn's potential when deposited at higher current densities, further supported by its high polarization resistance (958.8 Ω). From the Tafel curves, anodic current density decreases with increasing deposition current density, indicating anodic protection by limiting metal dissolution. This aligns with findings on Zn coatings, where higher current density refined grain structures, reducing corrosion susceptibility (Mosavat et al., 2012; Kwon et al., 2016). The improved performance at 5 A/dm², with an Ecorr of -1.21 V and polarization resistance of 958.8 Ω, likely stems from a more uniform coating microstructure, as noted in studies of electrodeposited zinc under similar conditions (Vatsala & Venkatesha, 2011).

Table 4. Electrochemical parameters of coated and uncoated carbon steel at different current densities in 3.5 % NaCl

Sample	icorr (µA/cm²)	Ecorr (V/SCE)	Corrosion Rate (mpy)	Polarization Resistance (Ω)
Bare Steel	105.0	-0.57	61.32	361.80
1 A/dm²	85.70	-1.06	50.00	141.80
2 A/dm²	73.30	-1.07	42.81	161.70
3 A/dm²	62.90	-1.07	36.71	254.00
4 A/dm²	19.50	-1.09	11.35	431.40
5 A/dm²	10.80	-1.21	6.325	958.80

Corrosion mechanism of pure steel in NaCl:

$Fe \rightarrow Fe^{+2} + 2e$ Anodic reaction (1)

$O_2 + 2H_2O \rightarrow 4\ OH^- + 4e$ Cathodic reaction (2)

Corrosion of Zn coatings is generally explained by dissolution-precipitation mechanisms (Mosavat et al., 2012; Sajjadnejad et al., 2014). In time-dependent measurements on the Zn coated steel surface, it is observed that the Fe ratio on the surface increases while the Zn ratio decreases, as seen in the EDS results due to the aggressive effect of chloride ions. Accordingly, the corrosion mechanism is due to the increasing pH of the environment (Salgueiro-Azevedo et al., 2015).

$Zn^{+2} + 2OH^- \rightarrow Zn(OH)_2$ (or $ZnO + H_2O$) (3)

$5Zn^{+2} + 8OH^- + 2Cl^- \rightarrow Zn_5(OH)_8Cl_2$ (4)

In these mechanisms, Zn^{2+} ions are released from the anodic sites and hydroxide ions are formed at the cathodic sites due to oxygen reduction. These Zn^{2+} and OH^- ions (and their combinations with other ions already present in the electrolyte) can precipitate forming different corrosion products. Corrosion products can limit the corrosion rate by altering the mass and charge transport to/from the surface (Salgueiro-Azevedo et al., 2015).

3.3. Surface morphology and composition

SEM and EDS investigated the surface morphology and composition of bare and Zn-coated high-carbon steel (1 A/dm² and 5 A/dm²) in 3.5% NaCl at 0, 4, 24, 48, and 240 hours. Time-dependent SEM films and EDS measurement results of the bare steel are presented in Figures 2 and 3. The bare steel at 0 h showed a uniform microstructure. Pitting of pure steel in 3.5 % NaCl solution initially initiated with the formation of Fe^{+2} ions on the surface due to the aggressive action of chloride ions on the surface (Figure 2 b, c). Over time, pitting occurred on the metal surface due to the aggressive action of chloride ions on the surface as a result of the anodic reaction ($Fe \rightarrow Fe^{+2} + 2e$). After 240 hour, it is observed that corrosion increased, and pitting and oxide formation occurred simultaneously (Figure 2 d, e). In EDS analyses, changes in Fe and oxygen ratios due to corrosion are observed, depending on the location where EDS measurements were made, as seen in SEM photographs (Figure 3 a-e). At the point where the measurements were made after 240 hour, there was a partial decrease in the iron percentage due to corrosion, while the oxygen percentage

increased due to the formation of corrosion products such as iron hydroxide ($Fe(OH)_2$) and iron oxide on the metal surface (Figure 3 e).

Figures 4 (a-e) and 6 (a-e) show SEM films of high carbon steel coated with zinc at current densities of 1 A/dm^2 and 5 A/dm^2 in 3.5% NaCl solution for 0, 4, 24, 48 and 240 hours, respectively. The hexagonal crystal structure of the coated zinc on the steel surface of the Zn coating at constant currents of 1 A/dm^2 and 5 A/dm^2 is seen in Figures (4a, 6a). The crystal structure of the zinc is clearly visible in the first 4 hours, and it is observed that $Zn(OH)_2$ ions are formed on the surface due to corrosion at 24 and 48 hours. (Figures 4 b, c, d, Figures 6 b, c, d). After 240 hours, the coated Zn on the surface corroded due to chloride ions, resulting in increased corrosion products such as ZnO (zincite), $Zn(OH)_2$ (Wulfingite), and $Zn_5(OH)_8Cl_2$ (simonkolleite) (Kranthi & Shiladitya, 2021). This increase was more pronounced in the coating at a constant current of 5 A/dm² (Figure 6e).

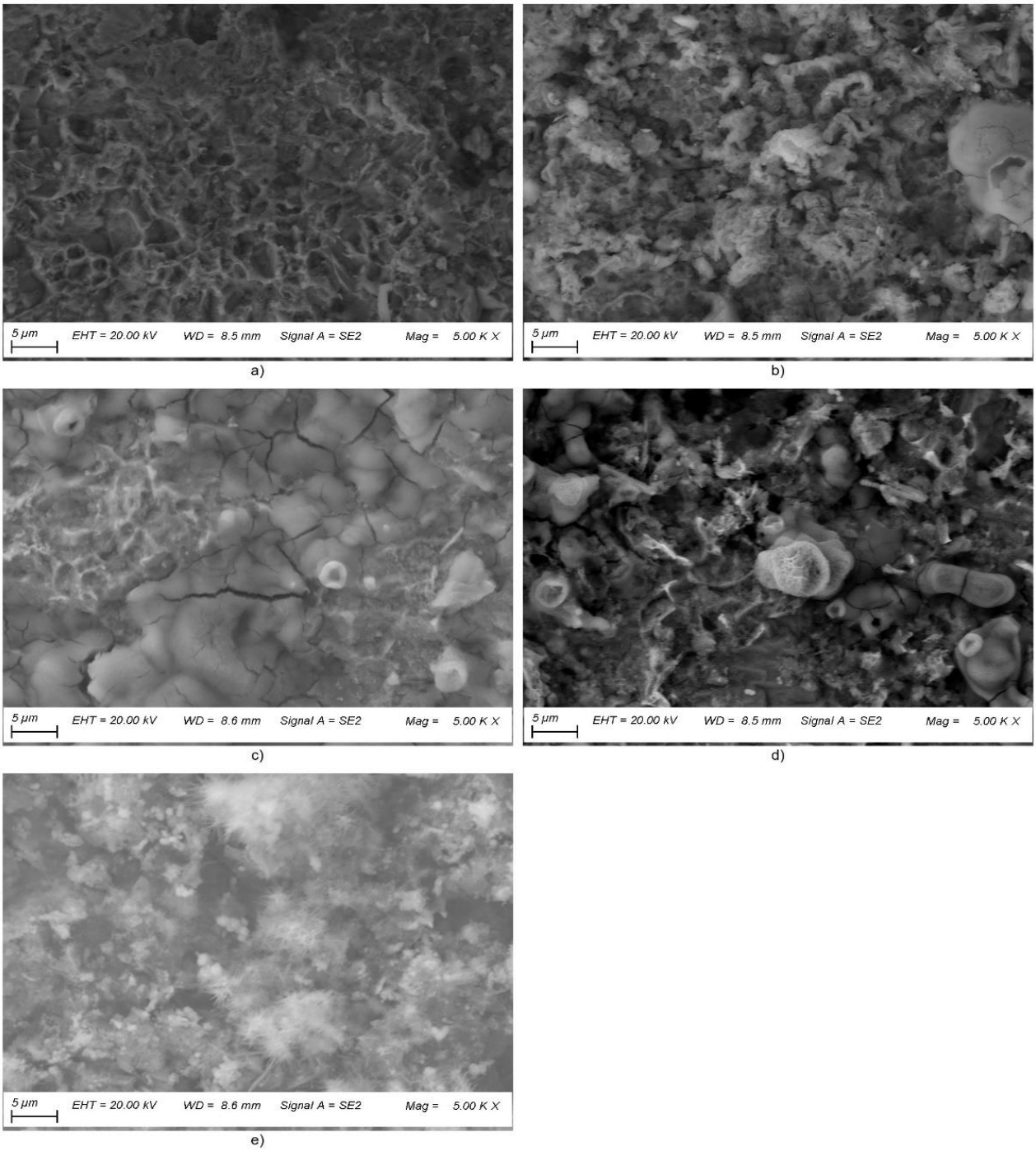


Figure 2. SEM results of bare high carbon steel a) 0, b) 4, c) 24, d) 48, and e) 240 hours of immersion in 3.5% NaCl

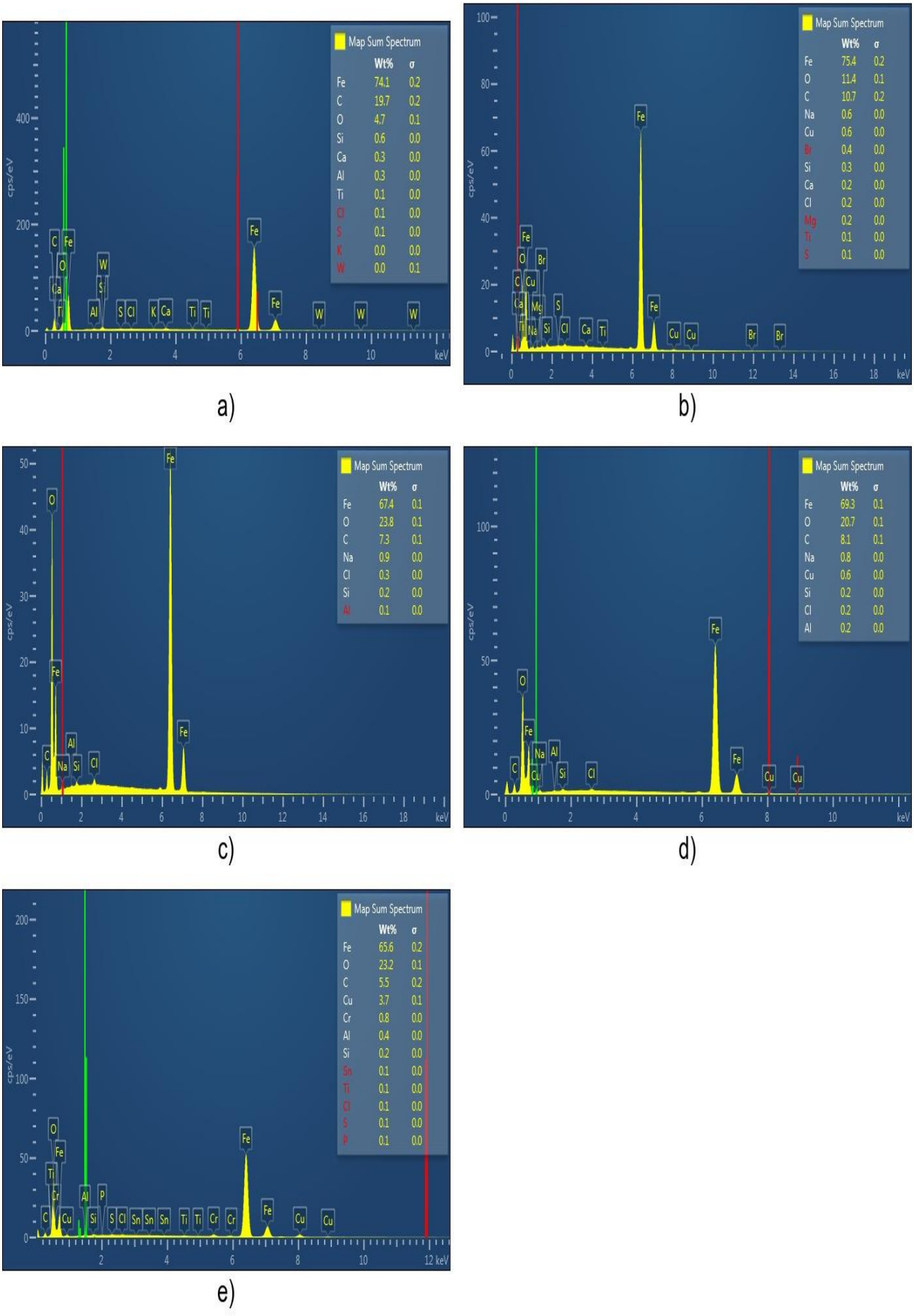


Figure 3. EDS results of bare high carbon steel a) 0, b) 4, c) 24, d) 48, and e) 240 hours of immersion in 3.5% NaCl

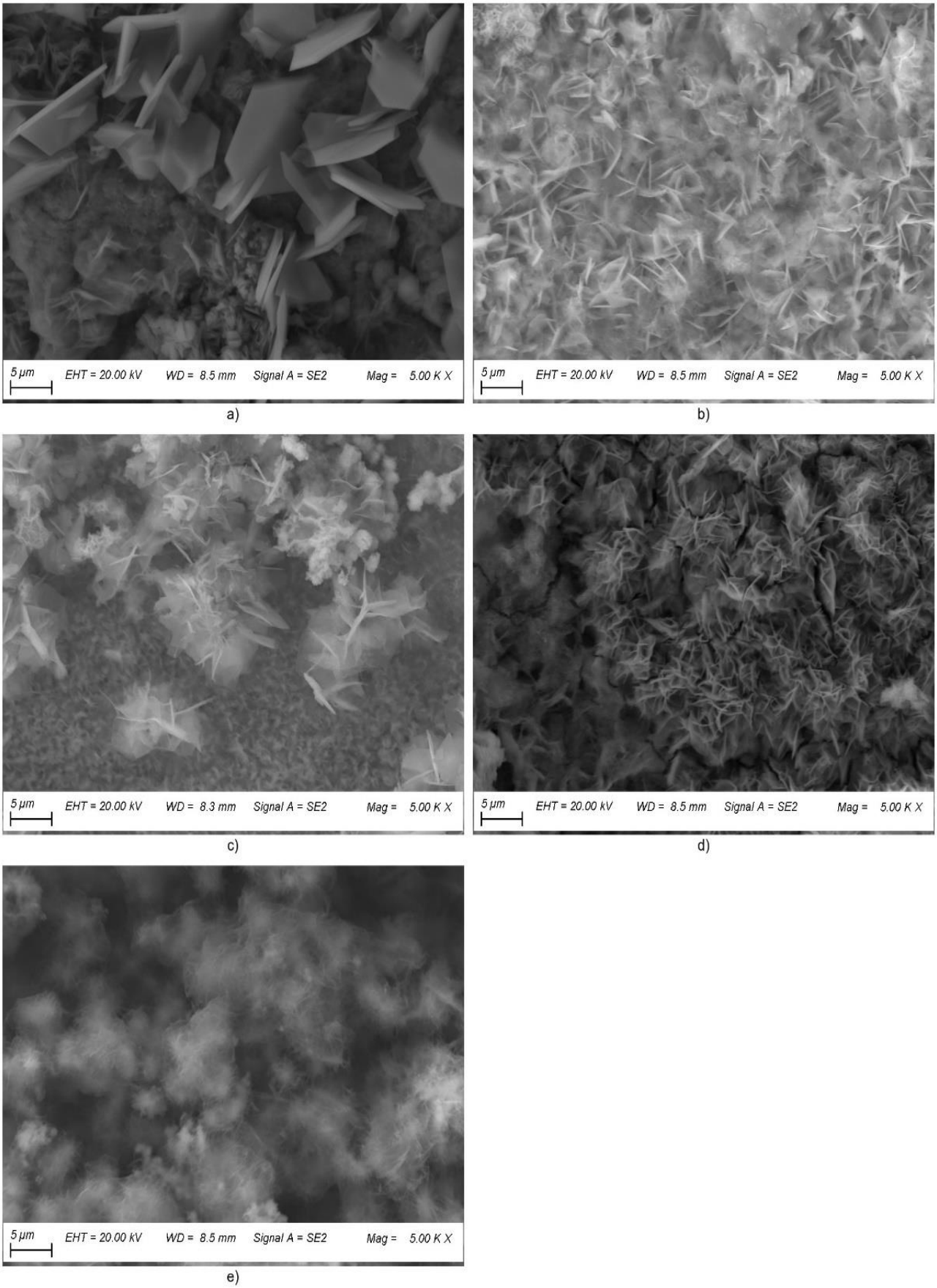


Figure 4. SEM results of Zn-coated high carbon steel at 1 A/dm² a) 0, b) 4, c) 24, d) 48, and e) 240 hours of immersion in 3.5% NaCl

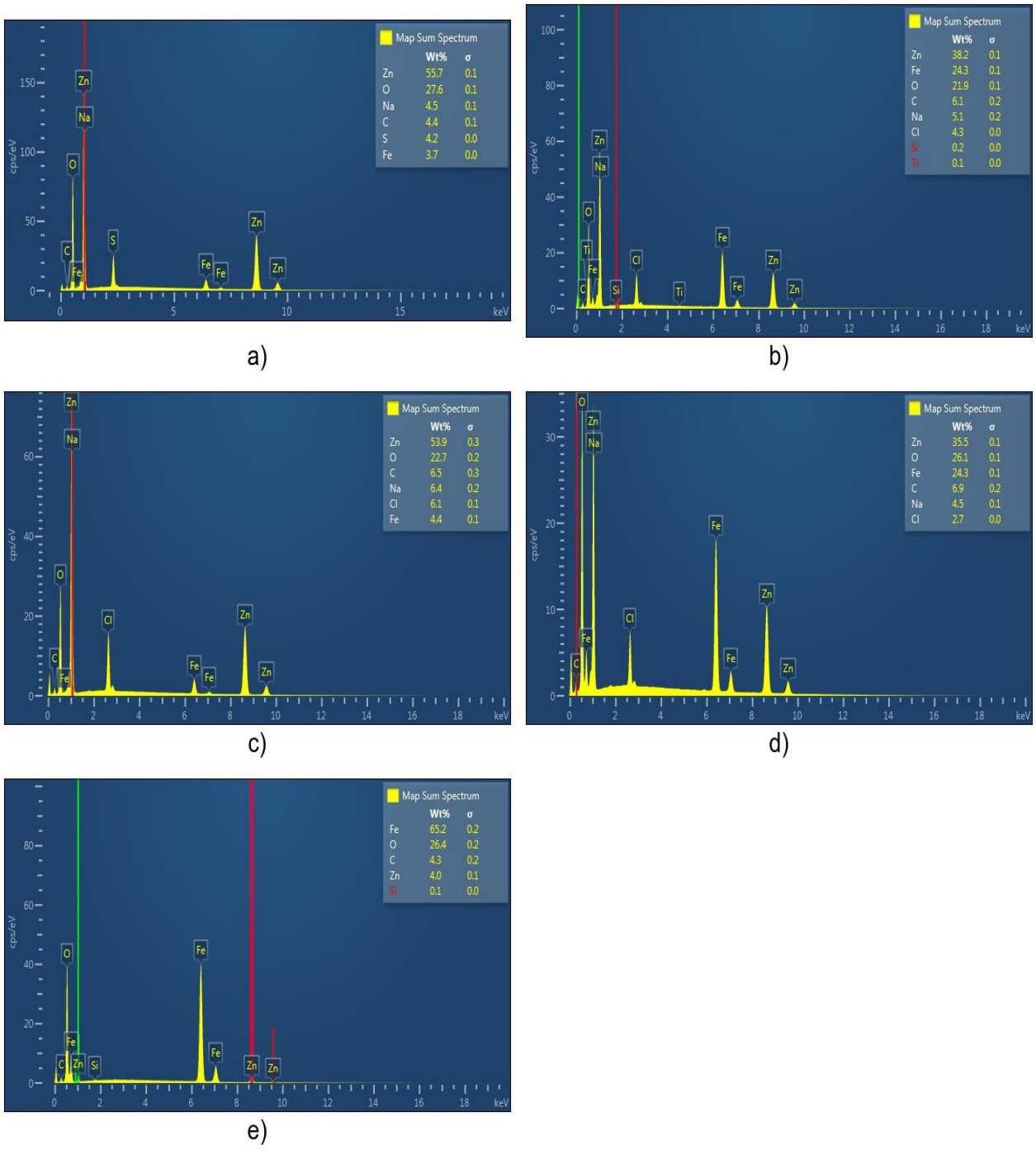


Figure 5. EDS results of Zn-coated high carbon steel at 1 A/dm² a) 0, b) 4, c) 24, d) 48, and e) 240 hours of immersion in 3.5% NaCl

The EDS results of high-carbon steel coated with zinc in a 3.5% NaCl solution at current densities of 1 A/cm² and 5 A/cm² at 0, 4, 24, 48, and 240 hours are presented in Figure 5 (a-e) and Figure 7 (a-e), respectively. Accordingly, the initial Zn content was 55.7-53.8%, while the Fe content was 3.7 % -3.6 %, in the coatings at constant currents of 1 A/dm² and 5 A/dm². After 240 hours, due to the aggressive effect of chloride ions, the Zn content in the 1 A/dm^2 constant current coating became 4.0 % due to the corrosion of the metal, while in the 5 A/dm^2 constant current coating the Zn content became 30.6 % (Figures 5e, 7e). After 240 hour, the Fe content also increased due to corrosion; this increase was 65.2 % in the Zn coating obtained with 1 A/dm^2 constant current, where corrosion was more intense, while the Fe content was determined to be 34.6 % in the Zn coating obtained with 5 A/dm^2 constant current (Figures 5e and 7e). This result shows that Zn coatings obtained at higher current densities are more effective in reducing the corrosion rate, and therefore the Fe content of the coating at 5 A/dm^2 constant current was determined to be lower.

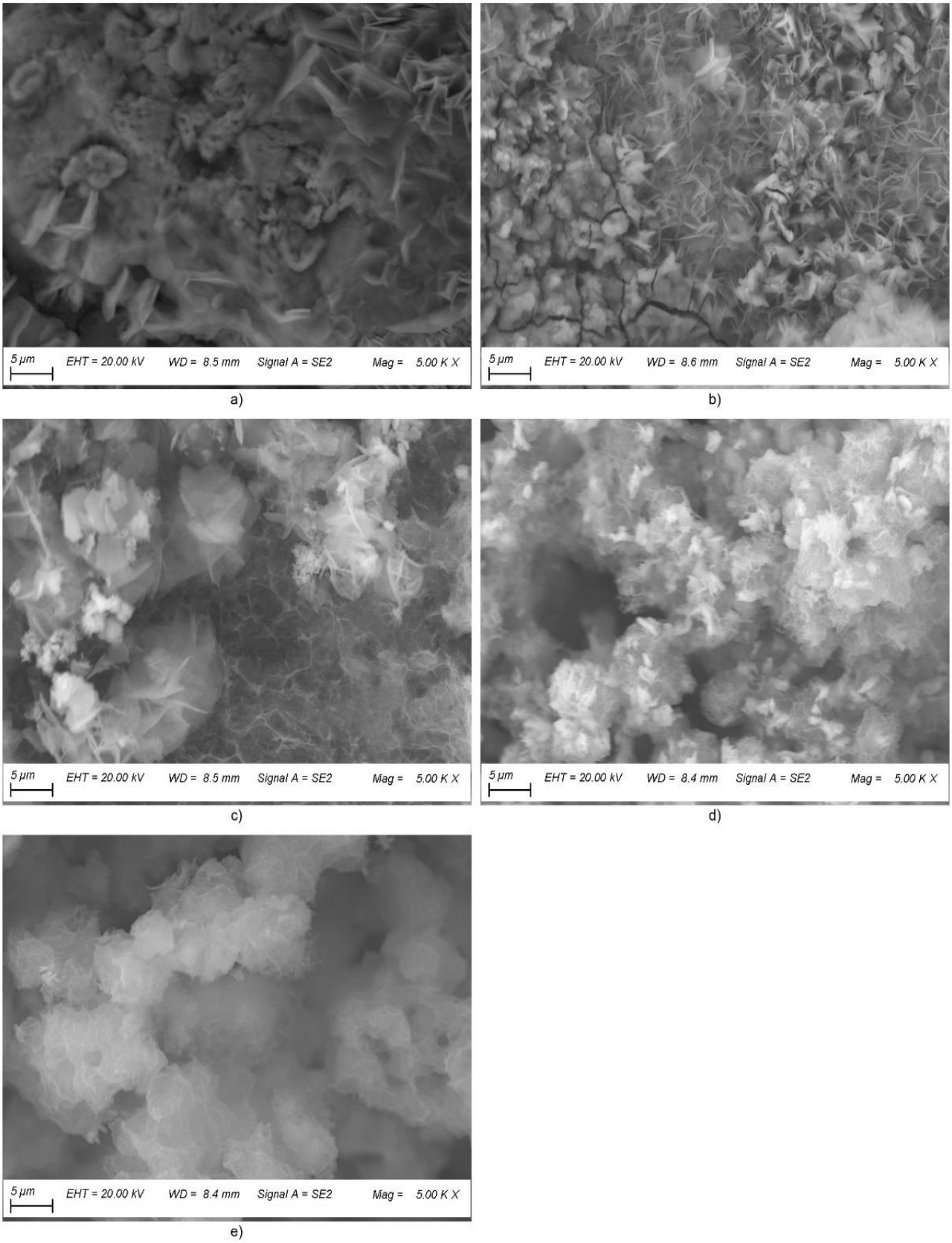


Figure 6. SEM results of Zn-coated high carbon steel at 5 A/dm² a) 0, b) 4, c) 24, d) 48, and e) 240 hours of immersion in 3.5% NaCl

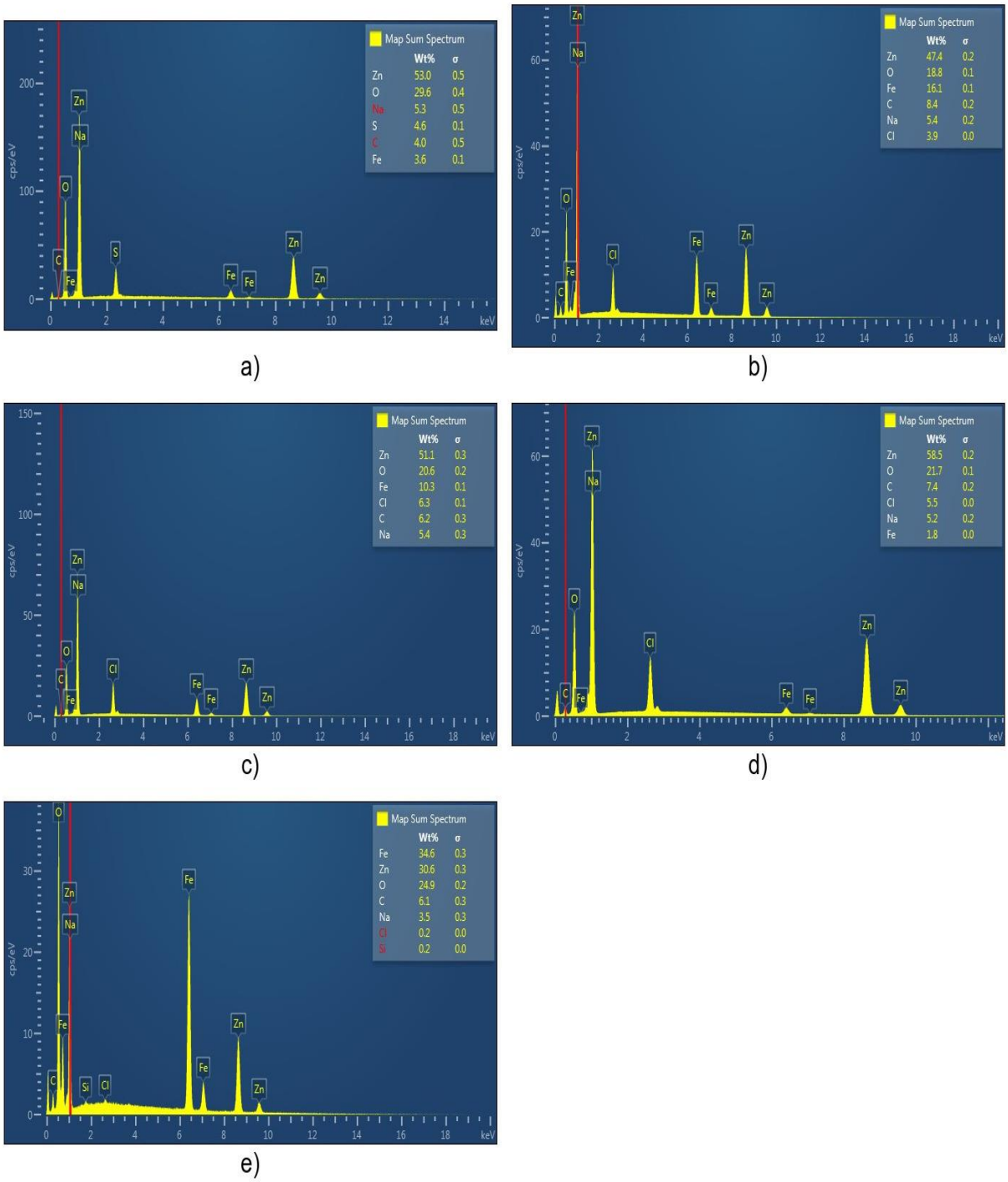


Figure 7. EDS results of Zn-coated high carbon steel at 5 A/dm² a) 0, b) 4, c) 24, d) 48, and e) 240 hours of immersion in 3.5% NaCl

Studies have determined that Zn coating thickness is effective in reducing the corrosion rate (Oluwasegun et al., 2015). The obtained coating thicknesses were determined from sample cross-sections using an optical microscope. The coating thickness obtained with a constant current of 1 A/dm^2 was 2 µm, while this ratio was determined as 14 µm for the Zn coating obtained with a constant current of 5 A/dm^2. From the SEM images, it was determined that as the Zn coating thickness increases, a more homogeneous and protective layer is formed, increasing the corrosion resistance. These results are consistent with the Tafel polarization results. This durability seen at the low icorr (10.8 µA/cm²) obtained at 5 A/dm^2 reflects the findings of optimized Zn coatings at higher current densities, where denser microstructures increase corrosion resistance (Fratesi et al., 1997; Fashu et al., 2014). Research on Zn coatings reports that long-term protection is achieved due to the smooth, compact layers formed at higher deposition currents (Popoola et al., 2016; Oluwasegun et al., 2015).

4. Conclusions

This study demonstrates that zinc electrodeposition at higher current densities significantly enhances the corrosion resistance of high carbon steel in 3.5% NaCl solution, with 5 A/dm² outperforming 1 A/dm² and bare steel exhibiting the poorest durability. The OCP values, shifting from -0.59 V for bare steel to ~ -1.07 to -1.08 V for Zn-coated samples, confirm zinc's sacrificial protection, while icorr decreases from 105 µA/cm² (bare) to 10.8 µA/cm² (5 A/dm²), reflecting improved coating efficacy with increased current density. SEM and EDS analyses corroborate these findings, showing severe corrosion in bare steel, rapid Zn depletion at 1 A/dm², and persistent Zn at 5 A/dm² after 240 hours. These results suggest that higher current densities yield thicker or denser coatings, offering robust protection against chloride-induced corrosion. The performance of pure Zn coatings at 5 A/dm² aligns with trends observed in optimized Zn coatings This underscores the potential of optimized pure zinc coatings for industrial applications, such as marine and coastal infrastructure, where durability in chloride-rich environments is critical.

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Author contribution

B. K. B. and S. Z. designed, interpreted, and assisted in writing this study. B.B. provided data collection and interpretation, S.Z. provided material support. All authors discussed the results and contributed to the final manuscript.

Declaration of ethical code

The authors of this article declare that the materials and methods used in this study do not require ethics committee approval and/or legal-special permission.

Conflict of interest

The author has declared no conflict of interest or common interest.

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