

Enhanced corrosion resistance of high-speed railway fastening systems: ZnAl coating on 38Si7 steel

Mustafa Dursunlar^{1*}, Zakir Taş², Müslim Çelebi³, Bekir Akgül⁴, Harun Çuğ⁵

¹Yozgat Bozok University, Department of Transportation Services, Yozgat, Türkiye

²Yozgat Bozok University, Department of Mechanical Engineering, Yozgat, Türkiye

³Karadeniz Technical University, Department of Metallurgical and Materials Engineering, Trabzon, Türkiye

⁴Sivas University of Science and Technology, Department of Aeronautical Engineering, Sivas, Türkiye

⁵Karabük University, Department of Mechanical Engineering, Karabük, Türkiye

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Abstract

In this study, a ZnAl coating was applied to the SKL14 tension clamp, which is made of 38Si7 chemical composition, one of the HM-type rails fastening components, and its corrosion performance was evaluated. The corrosion test was conducted according to the EN ISO 9227 standard in a 5% NaCl environment for 720 hours. The test results were analyzed by ASTM D610-01. As a result, the non-coated sample completely rusted within 1 hour. The ZnAl coating successfully passed the corrosion test, showing only approximately 3 % rust. Weight losses for the non-coated samples, which completely rusted within the first hour, were found to be 0.02 g, whereas the ZnAl-coated samples exhibited a weight loss of 1.23 g after 720 hours of continuous exposure. The ZnAl coating improved the corrosion resistance of the tension clamp over 720 times and enhanced its mechanical properties.

Key words: railway, rail fastening, tension clamp, ZnAl coating, corrosion

1. Introduction

Technological advancements in the iron and steel industry have brought significant changes to railway superstructures [1, 2]. Notably, improvements in the chemical composition of rails, their increased length, expanded profiles, hardened heads, and ability to be welded have enhanced their mechanical properties [3–6]. In response to the dynamic and static loads from these advanced rails, the development and modification of sleepers and rail fastenings have become inevitable [7]. In the past, traditional fishplate and bolted rail fastenings, which were popular for wooden and steel sleepers, were now mechanically insufficient under modern conditions [8]. Consequently, these connections have been replaced by HM-type fastening, a flexible rail fastening system designed for concrete sleepers [9, 10]. The primary reasons for this transition include the increased speed and axle loads on railways [11]. The increased rigidity in rail-sleeper connections has introduced serious challenges regarding comfort,

safety, operation, and maintenance of the superstructure [12, 13]. To address these issues, the HM-type fastening, which is currently the only connection type providing the necessary flexibility for high-speed, conventional, and urban rail lines, is widely used [14]. The tension clamp typically provides sufficient flexibility in HM-type fastenings, which is crucial in the rail-sleeper connection [8, 10]. A visual representation of the HM-type fastening is provided below in Fig. 1.

Tension clamps of alloyed spring steel are typically manufactured by different chemical compositions and standards, including 38Si7, 51CrV4, 54SiCr6, 60SiMn, and 62Si2CrA. In recent years, tension clamps made from 38Si7, which have the lowest carbon content, have been widely used. The low carbon content mitigates the weakness in plasticity, enhances toughness, and extends fatigue life. The prolonged fatigue life reduces repair, maintenance, and operational costs. This, in turn, supports the principles of sustainability and partial carbon neutrality, contributing to the fight against global warming and the climate crisis [15–17].

*Corresponding author: e-mail address: mustafa.dursunlar@yobu.edu.tr

Table 1. Chemical composition of 38Si7

Element	C	Si	Mn	P	S	Fe
Percentage (%)	0.35–0.42	1.50–1.80	0.5–0.8	max. 0.025	max. 0.025	Balance

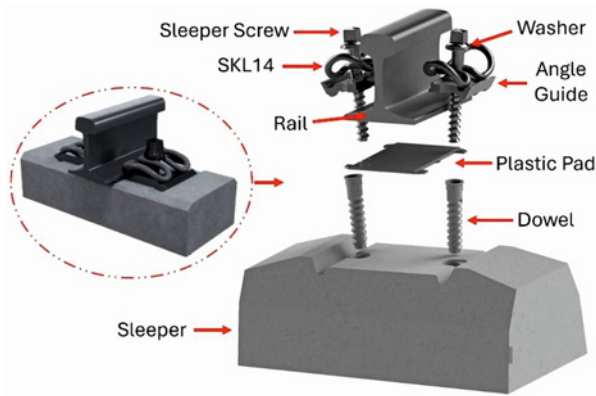


Fig. 1. HM type fastening systems in high-speed railway.

In recent years, global climate change has had increasing impacts worldwide. Particularly, the effects of climate change negatively influence the corrosion resistance of railway components and their mechanical properties. As a result, railways that operate almost entirely in open environments, except for metro systems, face significant risks. This risk is particularly critical for tension clamps, the sole components directly connecting the rail and the sleeper [18–20]. Therefore, improving the mechanical properties of tension clamps is crucial for railway safety. To enhance their mechanical properties, heat treatment, decarburization, and coating processes are typically applied to tension clamps [21, 22]. Zinc (Zn) galvanizing is commonly used for coating. Additionally, to further improve the mechanical properties and corrosion resistance of the coating, zinc baths have recently been reinforced with aluminum (Al) [23, 24].

The lack of sufficient research in the literature on the mechanical properties of tension clamps further supports the originality of this study. Ferreño et al. [25] developed a finite element model of the SKL-1 system, experimentally validated its accuracy, successfully reproduced its mechanical response and fatigue behavior, implemented an innovative method to evaluate the effect of mean stress on fatigue, and demonstrated that spring clips in service conditions cannot fail solely due to fatigue. Yirmibes [26] investigated the effect of heat treatment on the fatigue behavior of 54SiCr6 and 38Si7 spring steels. They concluded that the fatigue strength of 38Si7 spring steel was higher than that of 54SiCr6 spring steel under different conditions and environments. Wang et al. [22] conducted

a study on the heat treatment optimization for 38Si7 spring steel, which has excellent mechanical properties and controlled decarburization. They reported that optimizing the heat treatment, quenching, and tempering processes improved the mechanical properties of the tension clamps. Holder et al. [27] performed a laboratory investigation of the lateral load performance of the SKL-type fastening system under heavy freight railway loads. They demonstrated that even under high-pressure loads, the lateral wheel force remained below the fatigue and compressive strength limits of the sleeper, ensuring the safety of the fastening system, even in worst-case scenarios. Cho et al. [28] conducted an experimental and finite element analysis study on improving the fatigue strength of the SKL15 tension clamp by adjusting its installation tightness. They reported that the fatigue strength of the tension clamps increased when mounted at the recommended torque values, as proposed in the study.

2. Methodology

2.1. Material

This study used SKL14-type tension clamps with a diameter of $\varnothing$ 13 mm, made from 38Si7 chemical composition, as the base material. The tension clamps were supplied by Gürmak Railway and share the same casting and manufacturing batch number. The chemical composition of the tension clamps is provided in Table 1.

2.2. ZnAl coating

The ZnAl coatings were applied at Gürmak Railway by railway standards. Before coating, all samples were sandblasted with a grain size of 230 μ m. The coating thickness was approximately 20 μ m, and the coating composition was adjusted to contain around 60 % Zn and 40 % Al. The coating was applied via a multi-step hot-dip technique, involving alkaline degreasing, acid pickling, fluxing, drying, immersion in a molten Zn + Al alloy bath, centrifuging, and passivation. Each stage is critical in promoting adhesion, reducing surface oxides, and enhancing coating uniformity. Specifically, fluxing and hot air drying minimize oxidation before immersion, while centrifuging ensures uniform coating thickness. The molten bath consisting of 60 % Zn and 40 % Al facilitates the formation of

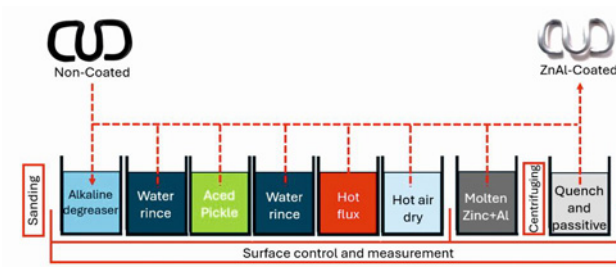


Fig. 2. ZnAl coating process.

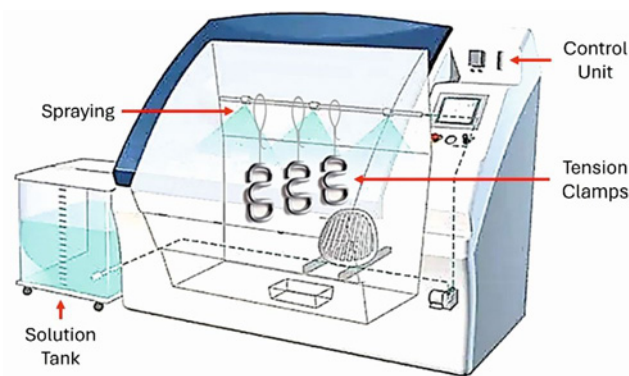


Fig. 3. Corrosion test process.

a dense, lamellar intermetallic layer. This layer serves as a physical barrier and provides sacrificial anodic protection. The resulting coating structure enhances corrosion resistance and preserves the mechanical integrity of the SKL14 tension clamps under aggressive salt spray conditions. A schematic illustration of the full coating process is provided below in Fig. 2.

2.3. Corrosion test

The corrosion tests were conducted as salt spray tests in an artificial atmosphere according to the EN ISO 9227 standard, in a 5% NaCl environment, at room temperature, with a test duration of 720 hours at Gürmak Railway. A detailed process of the corrosion test is provided below in Fig. 3.

2.4. Characterization

Microstructure studies were conducted at Sivas University of Science and Technology laboratories and Karadeniz Technical University. The microstructures were examined using a Zeiss Evo LS10 high-resolution SEM device, while coating thicknesses and cross-sectional images were obtained using a computer-aided SOIF MDS400 optical device. The crystal and phase structural properties of the prepared samples were analyzed with a Rigaku MiniFlex 600 X-ray

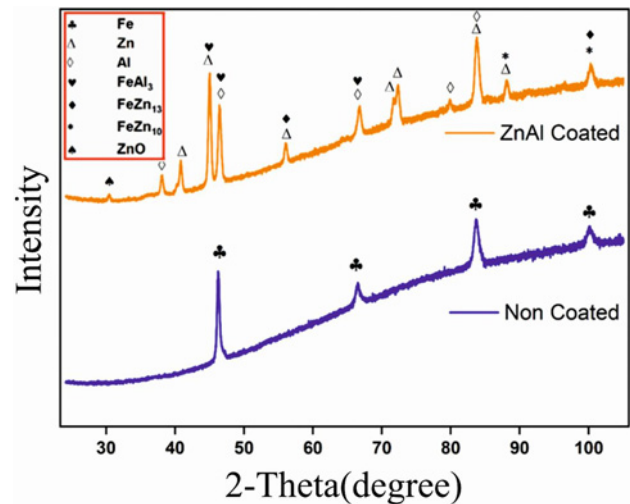


Fig. 4. XRD diffraction results of samples of base metal (non-coated) and ZnAl-coated.

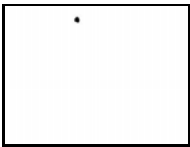
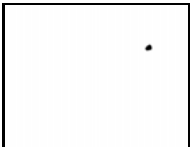
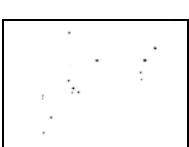
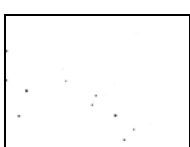
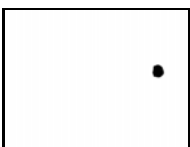
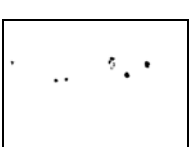
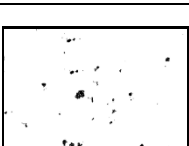
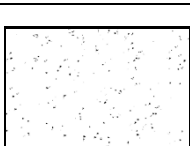
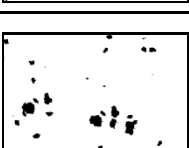
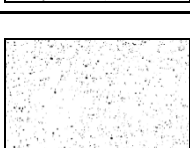
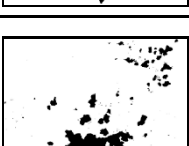
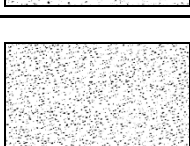
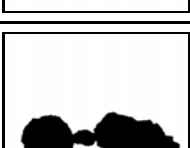
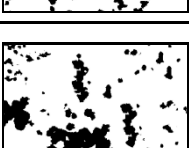
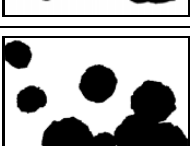
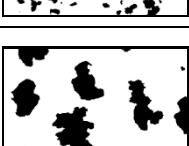
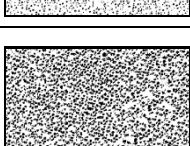
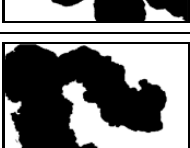
diffractometer (XRD) at 40 kV, using Cu K α radiation at a scanning speed of 2.5° min⁻¹. The type of corrosion, rust surface, and rating were evaluated according to the ASTM D610-01 standard. A table from the relevant standard is provided below in Table 2.

3. Results

3.1. XRD analysis

Figure 4 illustrates the XRD results of non-coated and ZnAl-coated 38Si7 spring steel samples. The strongest peaks of the non-coated sample, identified using ICDD card 06-0696, correspond to characteristic α -Fe peaks with maximum intensity at 45° 2 θ on the (110) plane, attributed to its minimal surface energy of 2.34 J m⁻² [29, 30]. For the ZnAl-coated substrate, the XRD analysis revealed dominant phases corresponding to Zn (ICDD card no: 004-0831), Al (ICDD card no: 004-0787), FeAl₃ (ICDD card no: 047-1420), FeZn₁₃ (ICDD card no: 034-1314), FeZn₁₀ (ICDD card no: 045-1184), and ZnO (ICDD card no: 036-1451). During the galvanizing process, Zn and Al from the Zn-Al bath react with Fe near the steel substrate, forming intermetallic phases such as FeAl₃, FeZn₁₃, and FeZn₁₀ [31, 32]. Additional intermetallic phases, including Fe₄Zn₉ and Fe₂Al₅, are theoretically expected but were not distinctly observed in the XRD patterns due to their trace amounts. Despite Al's higher oxygen affinity compared to Zn, a ZnO peak was detected in the XRD analysis, while Al₂O₃ was not discernible, likely due to its comparatively lower concentration. However, SEM/EDS mapping (Fig. 5) indicates the spatial distribution of O,

Table 2. Scale and description of rust rating

Scale rating	Percentage of the surface found rusted	Expression of rust found (S = spots; G = general; P = pinpoint)	Spot rusting surface	General rusting surface	Pinpoint rusting surface
10	≤ 0.01	–	–	–	–
9	> 0.01 to 0.03	9S, 9G, 9P			
8	> 0.03 to 0.1	8S, 8G, 8P			
7	> 0.1 to 0.3	7S, 7G, 7P			
6	> 0.3 to 1.0	6S, 6G, 6P			
5	> 1.0 to 3.0	5S, 5G, 5P			
4	> 3.0 to 10.0	4S, 4G, 4P			
3	> 10.0 to 16.0	3S, 3G, 3P			
2	> 16.0 to 33.0	2S, 2G, 2P			
1	> 33.0 to 50.0	1S, 1G, 1P			
0	> 50.0	–	–	–	–

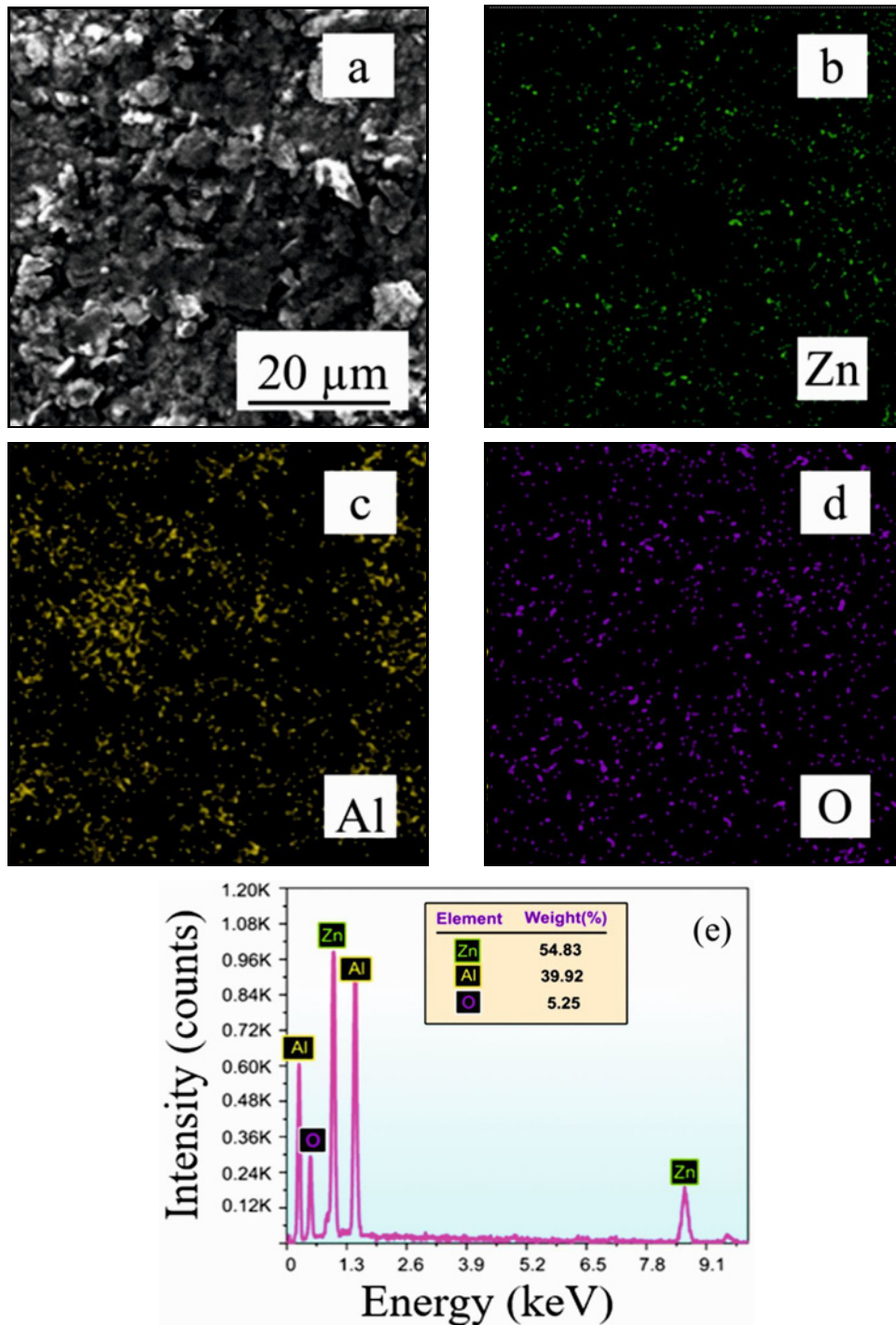


Fig. 5. EDS analysis of the ZnAl coating surface: (a) SEM microstructure, (b)–(d) distribution of Zn, Al, and O in the mapping analysis, and (e) EDS spectrum displaying the elemental composition.

Al, and Zn, confirming the presence of these elements. A FeZn_{13} intermetallic phase containing 5–6.2 % Fe was identified near the steel substrate, formed via a peritectic reaction between Zn and Fe below approximately 530 °C. Similarly, FeZn_{10} forms through the peritectic reaction of a Zn-rich gamma phase (17–19 % Fe) with liquid Zn below 660 °C [33]. The Al-rich FeAl_3 phase (76–77 % Al) was identified as form-

ing through a peritectic reaction and the diffusion of highly mobile Al atoms at the liquid-solid interface along Fe grain boundaries [34]. Literature reports suggest that Fe_2Al_5 forms initially during the galvanizing process, followed by the $\text{Fe}_2\text{Al}_5 + \text{L} \rightarrow 2\text{FeAl}_3$ reaction during the early cooling stages, resulting in a thin FeAl_3 layer. Subsequently, proeutectic FeAl_3 precipitates from the melt during cooling [35, 36].

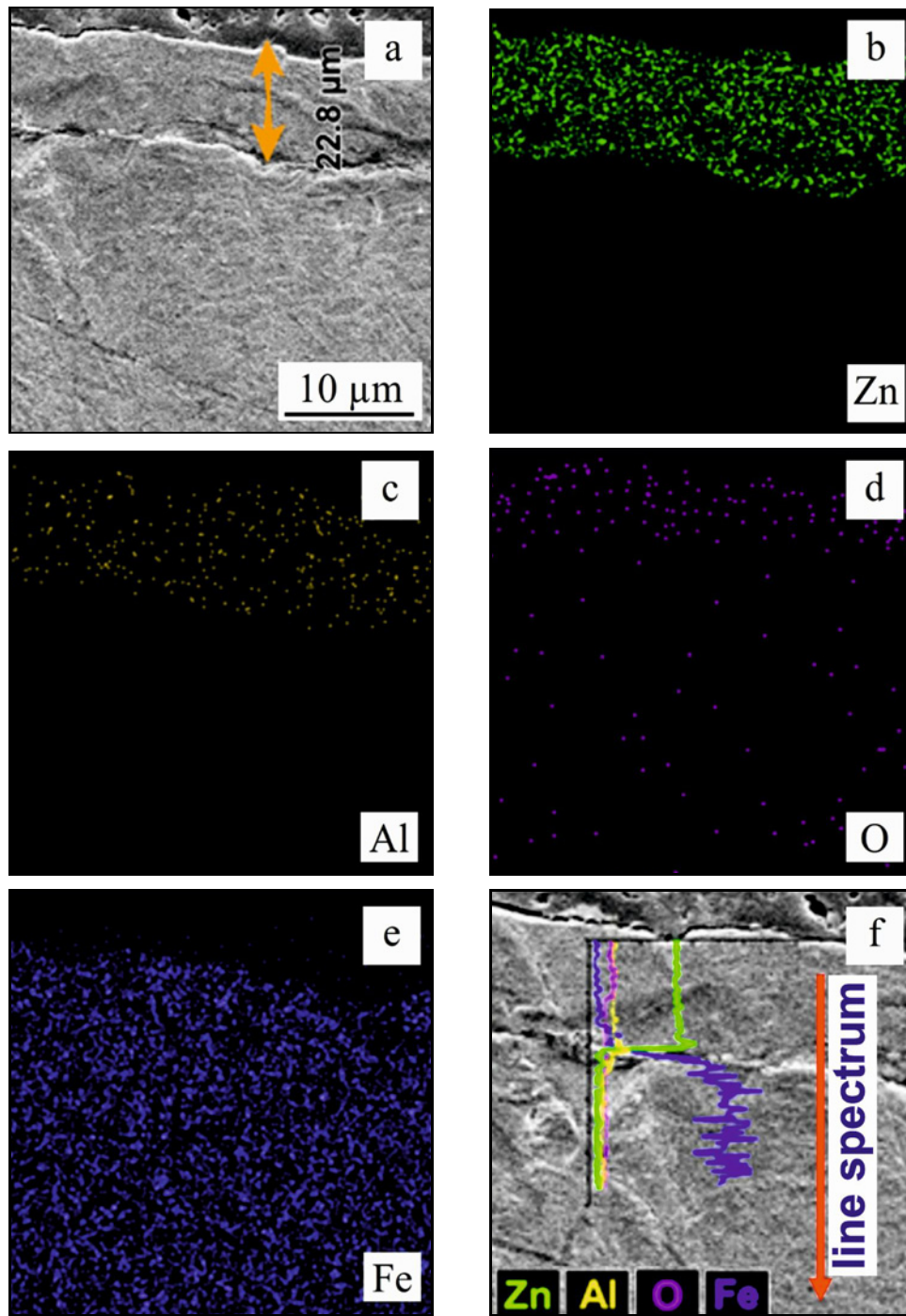


Fig. 6. Cross-sectional SEM and EDS analysis of the ZnAl coating on 38Si7 steel: (a) SEM image highlighting the ZnAl coating layer morphology, (b)–(e) elemental mapping showing the spatial distribution of elements, and (f) line scan analysis across the coating.

3.2. Microstructure analysis

Figure 5 illustrates the surface morphology and elemental distribution of a ZnAl coating applied to a 38Si7 alloy substrate, as analyzed through SEM imaging and EDS mapping. The deposition process of Zn and Al results in a surface with notable heterogeneity and roughness, as observed in Fig. 5a. These fea-

tures can be attributed to the inherent nature of co-deposition, where variations in local deposit rates, alloy solidification, and subsequent stress relaxation introduce morphological irregularities. Figure 5a reveals distinct voids and cracks on the coating surface. The formation of these defects likely arises from the thermal and mechanical stresses induced during cooling, as well as the differential contraction rates between the

Table 3. Weight loss and rust status of samples after corrosion testing

Sample	Test time (hours)	Rust status (%)	First weight W_0 (g)	Final weight W_1 (g)	Weight loss W_L (g)
Non-coated	1	100	495.90	495.88	0.02
ZnAl-coated	720	3	496.80	495.57	1.23

ZnAl coating and the steel substrate. These imperfections could also be exacerbated by localized diffusion of Al and Zn atoms, leading to inhomogeneous phase distributions that weaken the coating integrity. EDS mapping depicted using distinct colors for Zn (green), Al (yellow), and O (purple) provides a spatial representation of elemental distribution. Zn is relatively evenly dispersed across the surface, while Al is concentrated in specific areas, as highlighted in Figs. 5b and 5c. This non-uniform Al distribution indicates its higher diffusivity and mobility during the deposition process, which leads to localized accumulation in areas of reduced Zn activity. The homogeneous oxygen distribution across the surface suggests widespread oxidation of Zn and Al during or immediately after deposition, consistent with their strong affinity for oxygen.

Quantitative analysis of the coating composition using EDS spectra (Fig. 5e) shows an approximate elemental composition of 55 wt.% Zn, 40 wt.% Al, and 5 wt.% O. The close alignment of Al content with the Zn-Al bath composition indicates efficient deposition control, with minimal losses due to side reactions or volatilization. The higher Zn content on the surface suggests preferential oxidation of Zn, forming a ZnO-rich oxide layer. This is supported by the XRD results in Fig. 4, which confirm the presence of ZnO as a dominant phase. Despite the presence of oxygen and Al, the absence of Al_2O_3 peaks in the XRD analysis indicates that Al_2O_3 exists in trace amounts below the detection limit. This can be attributed to Zn's faster oxidation kinetics, which outcompete Al for available oxygen during the early stages of oxidation. Additionally, forming ZnO as a stable oxide may further inhibit Al_2O_3 formation by reducing local oxygen availability. These results underscore the dynamic interplay between Zn and Al during the coating process, where their differing reactivities and diffusion behaviors dictate the final microstructure and phase composition of the coating.

Figure 6 illustrates the cross-sectional SEM image of the ZnAl coating applied to the 38Si7 steel substrate, accompanied by EDS mapping and line analysis data. The cross-section examination reveals that the ZnAl coating has an average thickness of $22.8 \pm 3.4 \mu\text{m}$, with slight thickness variations observed across different regions. The uniform appearance of the coating, free from detectable porosity, cracks, or other discontinuities, suggests a consistent and high-quality deposition process that ensures

structural stability throughout the layer. The interface between the coating and the substrate is sharply defined, indicating a strong adhesion likely facilitated by the development of intermetallic phases during the coating procedure. This boundary reflects the diffusion and reaction of Zn and Al with Fe at elevated temperatures, forming characteristic intermetallic structures that enhance mechanical bonding. The EDS mapping analysis provides insights into the elemental composition and distribution within the coating. Using blue, green, yellow, and burgundy to represent Fe, Zn, Al, and O, respectively, the mapping reveals a uniform dispersion of Zn and Al across the coating layer (Figs. 6b and 6c). Near the substrate, a marked increase in Fe concentration is evident, confirming the penetration of Fe into the coating region and the subsequent formation of intermetallic compounds. These intermetallic phases are visually distinguishable in the SEM images, appearing as lighter gray regions, and are further verified through XRD analysis (Fig. 4). Additionally, the presence of oxygen is notably higher in the upper portions of the coating, which is indicative of surface oxidation. This observation aligns with the formation of oxide compounds, specifically ZnO and Al_2O_3 , due to the high affinity of Zn and Al for oxygen during or after deposition (Fig. 6d). The dominance of ZnO compared to Al_2O_3 is consistent with the faster oxidation kinetics of Zn and its preferential reaction with atmospheric oxygen. The line scan EDS analysis (Fig. 6f) describes the elemental gradient across the interface. Zn and Al concentrations within the coating are initially high but diminish as the scan approaches the substrate. Conversely, Fe concentration is minimal within the coating but rises sharply near the interface. This transition highlights the diffusion-driven interaction between the coating and the substrate, where Zn and Al atoms migrate towards Fe, forming intermetallic phases at the boundary. The abrupt reduction in Zn and Al peaks, alongside the rapid increase in Fe intensity, emphasizes the structured arrangement of intermetallic compounds at the interface.

3.3. Weight loss and corrosion rate analysis

Table 3 illustrates the test duration, rust condition, and weight losses of the samples. The tension clamps used in the study are identical, and the initial weight differences within the tolerance range stem

from manufacturing processes such as casting, rolling, heat treatment, decarburization, and coating. An examination of Table 3 reveals that the initial weight of the non-coated samples was 495.90 g, and the post-test weight was 495.88 g. This indicates a weight loss of 0.02 g after one hour of testing. For the ZnAl-coated samples, the initial weight was 496.80 g, with a post-test weight of 495.57 g, and a weight loss of 1.23 g after 720 hours of testing. Despite being exposed to corrosion for a longer period, the ZnAl-coated samples experienced significantly less weight loss per unit of time than the non-coated material. This indicates that the ZnAl coating effectively insulated the base material from environmental factors. Moreover, the substantial weight loss observed in the non-coated sample after a short test duration suggests a very low corrosion resistance. In conclusion, the ZnAl coating acts as an effective corrosion-preventive barrier, providing long-term corrosion resistance to the base material.

The corrosion rate was calculated using the weight loss method, based on the equation commonly used in the literature and industry [37, 38]. The equation is provided below in Eq. (1). The parameters for Eq. (1) are defined as follows: CR is corrosion rate (mm year^{-1}), k is unit conversion factor (8.76×10^4 , a constant value), W_L is weight loss ($W_L = W_0 - W_1$, in grams; W_0 is first (initial) weight and W_1 is final weight), ρ is metal density (g cm^{-3}), A is metal surface area (cm^2), and t is corrosion test time (hours):

$$\text{CR} = (k \times W_L) / (\rho \times A \times t). \quad (1)$$

According to Eq. (1), the corrosion rate for the non-coated sample was $0.000749 \text{ mm year}^{-1}$, while the corrosion rate for the ZnAl-coated sample was $0.000093 \text{ mm year}^{-1}$. The findings from the corrosion test reveal considerable weight loss and an elevated corrosion rate in the material, as outlined below in Fig. 7. When examining the corrosion rates, it is evident that the ZnAl coating reduces the corrosion rate by approximately 8 times. As a result, the ZnAl coating significantly reduces the effects of corrosion, providing long-term protection. This phenomenon is explained in the literature by the fact that the ZnAl coating forms a galvanic barrier on the base material, and the tendency of aluminum to form an oxide layer positively contributes to its corrosion performance [23, 24, 39, 40].

As illustrated in Fig. 8, in the absence of a protective layer on the material's surface, particularly in a harsh environment such as 5% NaCl, the anodic and cathodic reactions, along with the ensuing reaction products, become evident. As stated in the extensive literature, corrosion in a 5% NaCl environment is found to be strongly influenced by the oxide layers that develop on the material's surface and their electrochemical properties. Chloride ions (Cl^-)

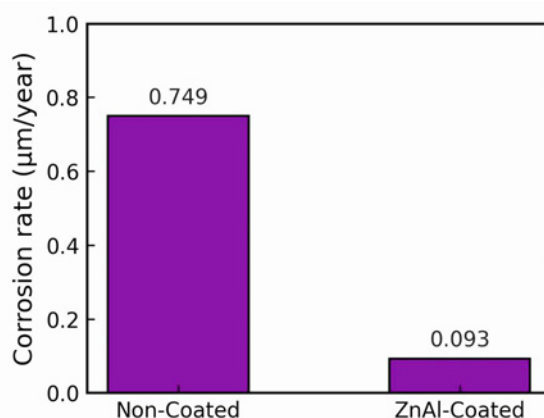


Fig. 7. Corrosion rates of samples.

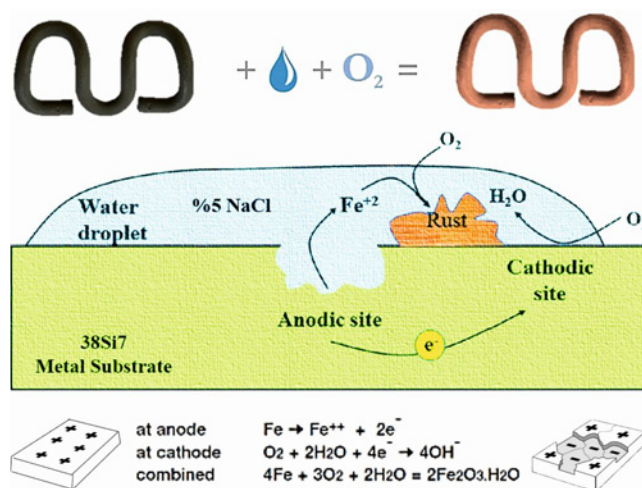


Fig. 8. Corrosion mechanism on 38Si7 metal substrate in 5% NaCl solution.

are known to penetrate and destabilize the iron's protective passive layer, thereby accelerating the corrosion process. Initially, a $\gamma\text{-FeOOH}$ (gamma-iron oxyhydroxide) layer forms on the surface, followed by the development of a Fe_3O_4 (iron oxide) layer. These oxide layers function as cathodic regions within the corrosion cell, enhancing the dissolution of iron at an accelerated rate [41, 42]. The observed weight loss and high corrosion rates highlight the necessity for effective protective measures, emphasizing that non-coated tension clamps are unsuitable for use in aggressive environments.

Zn-Al coatings are an effective surface treatment technology used to protect steel surfaces against corrosion. The protective mechanism of these coatings is based on both physical and electrochemical processes. First, the Zn-Al coating forms an impermeable barrier between the metal surface and the environment, preventing oxygen and moisture from reaching the metal

Table 4. Rust type and scaling

Sample	Time (hour)	Percentage of surface rusted (%)	Type of rust (S, G, P) and rust scale (0–10)		
			Spot (S)	General (G)	Pinpoint (P)
Non-coated	0	0	10	10	10
	0.5	33–50	0–1	1–2	9
	1	50–100	0	0	6–7
ZnAl-coated	0	0	10	10	10
	48	0–0.01	9–10	9–10	10
	96	0.01–0.03	9	9	9–10
	144	0.01–0.03	9	9	9–10
	192	0.01–0.1	8–9	8	9
	240	0.01–0.1	8–9	8	9
	288	0.01–0.1	8–9	8	9
	336	0.03–0.3	7–8	7–8	8–9
	384	0.03–0.3	7–8	7–8	8–9
	432	0.03–0.3	7–8	7–8	8–9
	480	0.03–0.3	7–8	7–8	8–9
	528	0.1–1	6–7	7	7–8
	576	0.1–1	6–7	7	7–8
	624	0.1–1	6–7	7	7–8
	672	0.3–3	5–6	6	7
	720	1–3	5	6	6–7

surface. This barrier is strengthened by forming passive oxide layers such as ZnO and Al₂O₃, so the coating retains its durability even in high relative humidity and saline environments. Secondly, Zn–Al coatings provide galvanic protection; the Zn component is more anodic than the base metal and cathodically protects the base metal by oxidizing itself. In damaged areas, zinc forms protective products such as Zn(OH)₂ and ZnCO₃, while the Al component quickly stabilizes the area with an Al₂O₃ layer. This self-healing property increases the long-term durability of the coating. In addition, the synergistic effect of Zn and Al optimizes both the corrosion resistance and mechanical strength of the coating. The effectiveness of these protective mechanisms has been confirmed in several studies [43–45].

3.4. Rust type and scale analysis

Table 4 presents corrosion test durations, surface rust grades, corrosion types, and rust type scale information for non-coated and ZnAl-coated samples. For the non-coated samples, the initial rust grade is 10, with 0 % rust on the surface. The first signs of rust appeared at approximately 0.5 hours (30 minutes). The rust type and its corresponding scale were observed at this stage as 0–1S, 1–2G, and 9P. After 1 hour, nearly the entire surface of the non-coated sample was rusted. At this point, the rust type and its corresponding values were 0S, 0G, and 6–7P, with the rust coverage exceeding 50 %. These results indicate that the non-coated sample rapidly corroded at the very beginning

of the test. Furthermore, the swift onset and spread of corrosion suggest the absence of any protective barrier against rust. This highlights the non-coated metal surface's weak defense against environmental conditions. In the literature, this rapid degradation is primarily attributed to the exposure of iron-containing materials to moisture and oxygen, leading to iron oxide (rust) forming, quickly weakening the metal and degrading the surface [46, 47].

For the ZnAl-coated samples, the initial rust grade was 10, with 0 % rust on the surface. The first signs of rust appeared after approximately 92 hours. Between 0 and 240 hours, the rust type and corresponding values were observed as 8–9–10S, 8–10G, and 8–9P. Between 336 and 528 hours, the values were 7–8S, 7–8G, and 7–8P. At the end of 720 hours, the rust grade was recorded as 5S, 6G, and 6–7P, with rust covering only 1–3 % of the surface. These results demonstrate that the ZnAl coating exhibited high corrosion resistance throughout the test duration. Additionally, it provided effective protection against different types of rust. As a result, the coating significantly delayed rust formation, offering long-term corrosion protection.

3.5. Rust surface analysis

3.5.1. Non-coated sample

Figure 9 represents the corrosion test of the non-coated tension clamps at the initial stage, during the first appearance of rust, and after 1 hour of complete rust formation. Upon examination, at 0 hours (initial



Fig. 9. Corrosion test results showing the time-based deterioration of the non-coated sample.

stage), no rusting was observed on the sample. The rust scale rating was 10, and the rust percentage was 0 %. At this stage, the non-coated sample showed no signs of rusting. Furthermore, the metal surface appeared bright and passive, as it had not yet been exposed to the salt spray test.

After 0.5 hours, the rust type was identified as uniform corrosion, with a rust scale rating of 0–1, and approximately 33–50 % of the surface covered with rust, indicating that nearly half of the surface was rusted. In such a short period, rapid and aggressive corrosion occurred on the non-coated sample, with rust spreading over a large portion of the sample. This demonstrates that the non-coated 38Si7 sample is vulnerable as an unprotected metal in the salt spray test. The rust observed at this stage spread uniformly, indicating the presence of general corrosion.

After 1 hour, the rust type advanced to severe uniform corrosion, with the initiation of pitting corrosion. The rust scale rating dropped to 0, and over 90 % of the surface was covered with rust. By the end of the 1-hour test, nearly the entire sample was covered with a dense layer of rust. The rapid spread of rust underscores how sensitive non-coated metal is to environmental conditions when not protected by a coating. The rust on the surface quickly oxidized in the aggressive salt spray environment, leading to widespread uniform corrosion. Such rapid rusting also poses a significant threat to the structural integrity of the metal. This test further demonstrates that non-coated samples are highly susceptible to rust in harsh environmental conditions, particularly when exposed to corrosive substances such as chloride ions, and emphasizes the necessity of using effective protective coating for such materials.

3.5.2. ZnAl-coated sample

Figure 10 shows the corrosion test of the ZnAl-coated tension clamps at the initial stage, during the first appearance of rust, and after 720 hours of complete rust formation. Upon examining the rust type analysis, two main types of rust were observed on the ZnAl-coated sample: uniform (general) and pitting corrosion. Uniform corrosion was initially observed as slight surface discoloration between 0 and 96 hours and later as general rust spreading across the entire

surface. This type of corrosion affects a broad surface area evenly and gradually spreads throughout the sample. Pitting corrosion, a localized type of corrosion, was observed at later stages of the test (after 288 hours), where deep pits began forming on specific surface points, causing localized damage.

In terms of rust grade and rust percentage, no visible rust was observed on the surface between 0 and 96 hours, with nearly 0 % of the surface affected. During this period, the rust grade remained between 9 and 10. Between 192 and 288 hours, the first signs of rust, such as slight discoloration and surface oxidation, began to appear. Less than 0.1 % of the surface was affected, reducing the rust grade to the 8–9 range. From 336 to 528 hours, rust started spreading across the surface, affecting larger areas, and pitting corrosion became evident. During this stage, the rust grade dropped to between 6 and 7, indicating that around 1 % of the surface was rusted. From 576 to 720 hours, corrosion spread significantly, pitting deepened, and general corrosion became prominent. The rust grade dropped to around 5, showing that up to 3 % of the surface was rusted. Notably, rust coverage and corrosion rates peaked during the final hours (672–720).

In conclusion, the salt spray test conducted on the ZnAl-coated sample revealed the overall corrosion resistance of the sample. The coating effectively protected the surface during the early stages of the test (0–192 hours), preventing rust formation. However, after 240 hours, deterioration began at certain coating points due to the saline environment, and rust formation was observed. In the later stages (336–528 hours), pitting corrosion intensified, and rusting became more prominent on the surface. By the end of the 720-hour test, a significant portion of the surface was covered with deep pits and general rust. Particularly in the later stages, pitting corrosion caused deep damage to the sample. Additionally, these types of coatings may require improvements to provide long-term protection.

3.6. Correlation analysis

3.6.1. Non-coated sample

In this study, correlation analysis was applied to understand the corrosion behavior of the non-coated sample. The correlation matrix reveals the relation-



Fig. 10. Corrosion test results showing the time-based deterioration of the ZnAl-coated sample.

ships between test duration, surface rust percentage (%), spot rust (S), general rust (G), and pinpoint rust (P). The results are discussed in detail below and presented in Fig. 11.

The correlation between test duration and surface rust percentage was calculated as -0.98 . The correlation coefficient of -0.98 indicates a very strong negative relationship. This result suggests that the surface rust percentage rapidly rises as the test duration increases. Initially, the rust percentage was 0 %, but within the first 0.5 hours, 33–50 % of the surface exhibited rust, and after 1 hour, the rust percentage reached 50–100 %. This high correlation value confirms that the non-coated sample was completely corroded quickly. These findings demonstrate that the

uncoated steel surface, lacking a protective barrier, reacts swiftly to environmental conditions and deteriorates rapidly in an aggressive corrosion environment such as the salt spray test. Consequently, it is evident that corrosion initiates very rapidly in the non-coated sample and affects a significant portion of the surface within a short duration. Given that severe corrosion was observed within the first hour, the necessity of applying protective coatings is emphasized.

The correlation between spot rust (S) and general rust (G) was calculated as $+1.00$. The correlation coefficient 1.00 represents a perfect positive relationship, indicating that rust appearing at specific points on the sample surface quickly spreads across the entire surface. The fact that spot rust and general rust

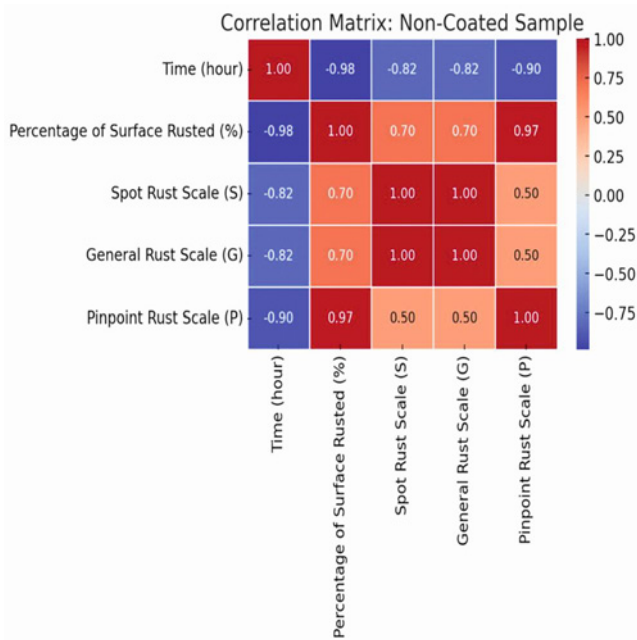


Fig. 11. Correlation matrix of non-coated sample.

are 100 % correlated suggests that corrosion on the non-coated steel sample does not occur randomly but starts at specific locations before expanding. During the first 0.5 hours, 33–50 % of the surface exhibited rust, and it was observed that this rust progressed in both spot and general forms. Consequently, corrosion initially starts as localized (spot) rust but rapidly spreads across the entire surface. This suggests that the microstructure of the steel may not be homogeneous, meaning that certain regions are more susceptible to corrosion than others.

The correlation between pinpoint rust (P) and test duration was calculated as -0.90 . The correlation coefficient of -0.90 indicates a strong negative relationship, meaning pinpoint rust formation decreases as the test duration increases. This is an unexpected result since pinpoint rusting is expected to increase over time. However, an inverse trend is observed here. The initial high levels of pinpoint rust suggest that corrosion initially forms at specific points but later spreads across the entire surface. As time progresses, localized corrosion points may merge, forming general rust. This result indicates that corrosion transitions from localized to affecting the entire surface over time, evolving into a general corrosion mechanism. It can be inferred that the pinpoint rust formations observed initially merge over time, forming larger rust patches.

The correlation between spot rust (S) and surface rust percentage was calculated as $+0.70$. The correlation coefficient of $+0.70$ represents a strong positive relationship, suggesting that as the surface rust percentage increases, the amount of spot rust also increases. Moreover, general rust formation follows a

similar trend as spot rust increases. Consequently, an increase in the rust percentage leads to the appearance of more rust spots on the surface. This result demonstrates that spot rust will inevitably spread if the surface is not protected with a coating, leading to increased material loss over time.

In conclusion, the correlation analysis confirms that the non-coated sample is highly corrosion resistant. A significant level of corrosion occurs within the first hour, verifying that the material deteriorates rapidly in the salt spray environment. The correlation analysis supports the observation that within the first 0.5 hours, the rust percentage reaches 33–50 %, indicating that the sample degrades at an accelerated rate. Corrosion begins as localized spots but quickly spreads across the entire surface. The fact that spot rust and general rust exhibit a perfect (100 %) correlation suggests that localized corrosion spots rapidly merge and affect large surface areas. Pinpoint rusting is initially prominent but decreases over time. This phenomenon indicates that pinpoint rust spots merge to form larger rust patches, ultimately leading to complete surface rusting. A strong correlation between spot rust and overall surface rust percentage is observed. As rust formation progresses, the number of rust spots increases proportionally.

3.6.2. ZnAl-coated sample

This analysis was conducted to understand the corrosion behavior of the ZnAl-coated sample by the ASTM D610-01 standard using a correlation matrix. The correlation analysis evaluates the relationship between test duration, surface rust percentage (%), spot rust (S), general rust (G), and pinpoint rust (P). The results are discussed in detail below and are presented in Fig. 12.

The correlation between test duration and surface rust percentage was calculated as -0.81 . The correlation coefficient of -0.81 indicates a strong negative relationship, meaning that while the rust percentage increases over time, its rate of increase slows down. Compared to the non-coated sample, the ZnAl-coated sample exhibits significantly higher resistance to corrosion over an extended period. The rust percentage remained relatively low up to 336 hours, after which corrosion increased slightly, reaching a surface rust percentage of 0.1–1 % at 576 hours and a maximum of 3 % at 720 hours. This correlation value confirms that ZnAl coating significantly delays corrosion and preserves most of the sample's surface. Consequently, while the non-coated sample undergoes rapid corrosion, the ZnAl-coated sample retains only 3 % rust coverage after 720 hours of testing. This result demonstrates that ZnAl coating provides a high level of protection for the steel, effectively slowing down the corrosion process.

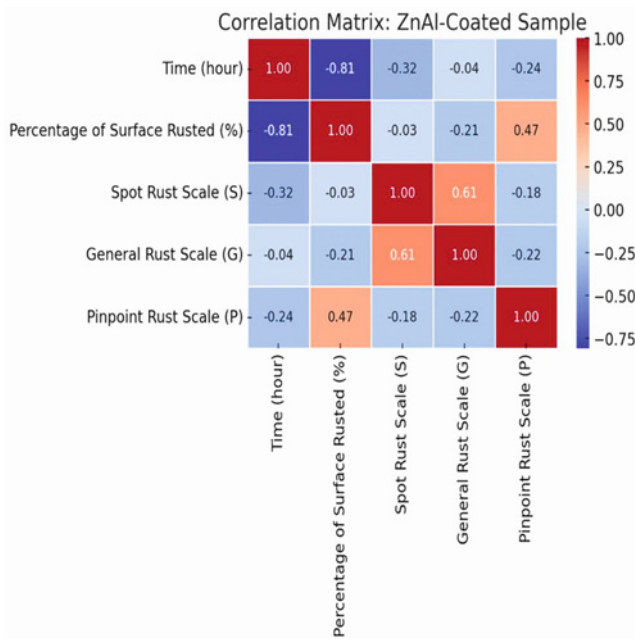


Fig. 12. Correlation matrix of ZnAl-coated sample.

The correlation between spot rust (S) and general rust (G) was calculated as +0.61. The correlation coefficient of 0.61 represents a moderate positive relationship. This indicates that ZnAl coating prevents spot rust from directly transitioning into general rust as quickly as in non-coated samples. While this correlation was 100 % in the non-coated sample, it is reduced to 61 % in the ZnAl-coated sample. This suggests that ZnAl coating limits the uncontrolled spread of rust across the surface and confines corrosion to localized regions. Unlike the non-coated sample, where rust propagates rapidly from a single point across the entire surface, rust in the ZnAl-coated sample remains more localized. In conclusion, there is no absolute relationship between spot rust and general rust in the ZnAl-coated sample. This confirms that ZnAl coating effectively slows down rust formation and prevents localized corrosion from developing into widespread corrosion.

The correlation between pinpoint rust (P) and test duration was calculated as -0.24 . The correlation coefficient of -0.24 indicates a weak negative relationship, suggesting that pinpoint rust percentage does not show a direct correlation with test duration. Unlike the non-coated sample, pinpoint rust does not steadily increase with exposure time. Instead, ZnAl coating prevents the formation of pinpoint rust and restricts localized corrosion. While pinpoint rust in the non-coated sample begins at a specific point and spreads, in the ZnAl-coated sample, it remains confined to localized areas without significantly expanding. In conclusion, ZnAl coating effectively suppresses pinpoint

rust formation. As the coating gradually wears down, rust formation begins in specific regions but does not spread across the entire surface.

The correlation between surface rust percentage (%) and pinpoint rust (P) was calculated as +0.47. The correlation coefficient of 0.47 represents a moderate positive relationship. This suggests that limited pinpoint rust formations appear as the ZnAl coating loses its corrosion resistance over time. While this correlation was 97 % in the non-coated sample, it is reduced to 47 % in the ZnAl-coated sample. This indicates that ZnAl coating prevents widespread rust formation and directs corrosion toward localized pinpoint areas, thereby reducing the likelihood of large-scale corrosion. In conclusion, ZnAl coating prevents full surface rusting and confines corrosion to specific localized areas. This suggests that the protective effect of the coating provides localized corrosion control, significantly safeguarding the sample from general rust formation.

Conclusion: The ZnAl-coated sample exhibits exceptional corrosion resistance. Considering that the non-coated sample reached 50–100 % rust coverage within the first hour, the fact that the ZnAl-coated sample maintains only 3 % rust coverage even after 720 hours of testing demonstrates its highly protective properties. ZnAl coating localizes corrosion and prevents complete surface rusting. The 61 % correlation between spot rust and general rust suggests that ZnAl coating slows the spread of rust across the surface. While rust initiates at a single point in the non-coated sample and rapidly spreads, rust remains localized in the ZnAl-coated sample. ZnAl coating effectively suppresses pinpoint rust formation. The coating prevents corrosion from forming at certain locations and limits localized corrosion development over time. This suggests that the ZnAl coating is a protective barrier, preventing pinpoint rust from becoming widespread corrosion. ZnAl coating provides long-term corrosion protection. Even after 720 hours of salt spray testing, the ZnAl-coated sample maintains a rust coverage of only 3 %, demonstrating the sustained effectiveness of the protective layer. This suggests that ZnAl coating is viable for materials exposed to harsh environmental conditions, such as railway fasteners and other structural components in corrosive environments. Consequently, the experimental corrosion results of both uncoated and ZnAl-coated specimens have been modeled and validated through correlation analysis.

4. Conclusions

In this study, the corrosion behavior of the SKL14 tension clamp, made from 38Si7 chemical composition and coated with ZnAl, was examined according to ASTM D610-01 standards using the salt spray test

conducted under the EN ISO 9227 standard. The following conclusions were drawn from the study:

- Approximately 50 % of the surface of the non-coated samples rusted within the first 30 minutes, and by the end of 1 hour, the entire surface was rusted.
- The first signs of rust on the ZnAl-coated samples appeared after 92 hours, and by the end of 720 hours, only about 3 % of the surface was rusted.
- The weight loss of the non-coated sample after 1 hour was 0.0137 g, while the weight loss of the ZnAl-coated sample after 720 hours was 1.23 g.
- The ZnAl coating reduced the corrosion rate of the base material by approximately 8 times and increased its corrosion resistance by more than 720 times.

Considering these results, the ZnAl coating significantly enhanced the corrosion resistance of the base material. However, to ensure better protection of the mechanical properties of tension clamps against corrosive effects throughout their service life, improving the ZnAl coating method or considering alternative coatings is recommended. This is particularly important for maintaining railway safety. Moreover, to better simulate the complex atmospheric conditions to which railway fastening systems are exposed, future investigations may consider using SO₂ or Na₂SO₃-based corrosion environments in addition to neutral salt spray testing.

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