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DEGRADATION IN A CORROSIVE ENVIRONMENT OF STEELS USED IN THE CONSTRUCTION OF METAL STRUCTURES

Florin CIOFU

Abstract: *This paper explores how atmospheric conditions affect the corrosion behavior of low-alloy steels S235JR and S355JR, commonly employed in industrial metal structures like harbor cranes and mining machinery. The investigation examines the impact of environmental parameters—including salinity, sulfur dioxide concentration, relative humidity, and temperature—on both the corrosion rate and the mechanical integrity of these materials. The experimental setup simulated polluted industrial atmospheres under controlled conditions. Corrosion was evaluated using gravimetric analysis, optical microscopy for microstructural characterization, and examination of corrosion products. Results revealed that certain iron oxyhydroxide phases, such as β-FeOOH, formed more readily in saline environments and contributed to surface degradation by promoting structural flaws like pores and cracks. These findings offer useful insights for optimizing anti-corrosion strategies, including protective coatings and inhibitor use, to enhance the durability of steel structures exposed to harsh atmospheric environments.*

Keywords: *corrosion, salinity, temperature, humidity, sulfur dioxide, corrosion rate,*

1. INTRODUCTION

Metallic materials exhibit varied responses when exposed to atmospheric conditions, often leading to notable deterioration in their physical and mechanical properties. Among these, low-alloy steels are frequently chosen for constructing metal structures due to their cost efficiency and mechanical robustness. Nonetheless, in service environments such as ports or mining operations, these materials are exposed to harsh elements—including elevated humidity, sulfur dioxide (SO_2) pollutants, and saline atmospheres—that significantly accelerate corrosion.

In polluted industrial settings, corrosion mechanisms intensify due to the formation of thin electrolytic films on steel surfaces. These films promote the infiltration of corrosive ions, while the presence of SO_2 enhances the electrical conductivity of the layer, thereby amplifying degradation processes [1].

While previous studies have examined atmospheric corrosion in general, the specific contribution of each individual factor (like salinity, SO_2, humidity, or temperature) remains insufficiently detailed. This study aims to address this gap by investigating the corrosion behavior of S235JR and S355JR steels under simulated environmental conditions using modern experimental techniques [2].

Corrosion in metals typically progresses via dissolution and mass loss or through the formation of oxide layers that alter surface integrity. Industrial zones with high levels of pollutants are particularly aggressive toward steel structures. Conditions such as rain, fog, elevated humidity, airborne particulates, heat, and oxygen exposure commonly found in open-pit mining operations or maritime environments contribute to an aggressive corrosive climate.

Under such circumstances, steel surfaces accumulate micro-droplets that form thin, conductive liquid layers. These facilitate ion transport, intensifying corrosion through mechanisms such as surface pitting, structural weakening, and depletion of key alloying elements [2].

Elevated sulfur levels further exacerbate this process by increasing the conductivity of surface films, allowing for deeper and faster penetration of corrosive agents. The complex interaction between these atmospheric elements and steel surfaces plays a critical role in determining the lifespan and structural stability of metallic infrastructure. Understanding these interactions is therefore vital for developing durable protective solutions and preventing premature structural failures [3].

Various research approaches have been employed to study atmospheric corrosion, including investigations into rust layer formation on carbon and weathering steels under specific humidity and temperature regimes. Predictive modeling based on environmental parameters has also emerged as a method to anticipate corrosion rates. Compared to prolonged field exposure studies, controlled laboratory tests offer a faster, more reproducible means of simulating and analyzing material degradation [4].

In particular, temperate-continental climates - characterized by wide temperature fluctuations, variable humidity, intense solar radiation, and atmospheric salinity—create especially aggressive environments for steel corrosion. In such conditions, corrosion rates may increase by a factor of three to five compared to standard climates. [2].

This study is designed to provide actionable insights for selecting appropriate construction materials, designing effective protective coatings, and estimating the expected service life of metal structures based on their exposure to environmental stressors.

2. MATERIALS AND METHODS

2.1. Materials

The metal structures of working equipment in ports or coal mining sites operate at temperatures ranging from -30°C to +40°C. These conditions create a favorable environment for the occurrence of creep phenomena. In this context, the results are useful for determining, for example, the load-bearing capacity of a structure under fire conditions, as well as for predicting its service life. The studied steels, S235JR and S355JR, were sampled from the metal structures of the ERC 2000 excavator and a port crane (fig. 1.a, b). The samples were cut to a size of 100 × 30 × 8 mm using a guillotine-type cutting machine (fig.2) [2].

a) ERC 2000

b) harbor crane

Fig.1. The metallic structure

Fig.2. Sample cutting

S235JR steel is commonly used in welded load-bearing structures of medium-tonnage equipment. The main mechanical properties and chemical composition of this steel are presented in Tables 1 and 2 [2].

S355JR steel is used in the construction of heavy-duty equipment, particularly for manufacturing load-bearing beams in the central area, tower, and arms. The main mechanical properties and chemical composition of this steel are presented in Tables 3 and 4 [2].

Table 1

Mechanical properties of S235JR steel (according to EN 10025)

Material	Mechanical characteristics		
	σ_r (N/mm^2)	σ_c (N/mm^2)	Elongation at fracture (%)
Steel S235JR	350	260	21

where: σr = tensile strength, σc = yield strength

Table 2

The chemical composition (weight %) of S235JR steel (according to EN 10025)

Chemical composition	**C**	**Si**	**Mn**	**P**	**S**	**Al**	**Ti**	**V**
(%)	0,18	0,09	0,85	0,045	0,045	0,022	0,004	0,04
Chemical composition	**Cu**	**Ni**	**Cr**	**Mo**	**Nb**	**B**	**Ca**	
(%)	0,015	0,015	0,018	0,002	0,04	0,0001	0,0001	

Table 3

Mechanical properties of S355JR steel (according to EN 10025)

Material	**Mechanical characteristics**		
	σ_r (N/mm^2)	σ_c (N/mm^2)	Elongation at fracture (%)
Steel S355JR	559	460	23

where: σ_r = tensile strength, σ_c = yield strength

Table 4

The chemical composition (weight %) of S355JR steel (according to EN 10025)

Chemical composition	**C**	**Si**	**Mn**	**P**	**S**	**Al**	**Ti**	**V**
(%)	0,19	0,28	1,5	0,018	0,008	0,03	0,004	0,06
Chemical composition	**Cu**	**Ni**	**Cr**	**Mo**	**Nb**	**B**	**Ca**	
(%)	0,01	0,01	0,01	0,002	0,04	0,0001	0,0001	

2.2. Preparation of test specimens

All samples (both S235JR and S355JR) were polished using abrasive paper. The samples were then cleaned using isopropanolo and distilated water for 15 minutes. For the study, four factors and parameters were considered, simulating the specific working environment conditions, as shown in Table 5.

First, corrosion tests were conducted by thermally decomposing sodium sulfite (Na_2SO_3) to study the influence of SO_2 on the corrosion of S235JR and S355JR steels at different concentrations. The tests were performed according to ISO 6988 and ASTM G8 standards [2].

Table 5

Factors and parameters used in experimental determinations

Factor	**Parameters**				
SO_2 (ppm)	100	150	200	250	300
Salinity (%)	1,00	2,00	3,00	4,00	5,00

First, corrosion tests were conducted by thermally decomposing sodium sulfite (Na_2SO_3) to study the influence of SO_2 on the corrosion of S235JR and S355JR steels at different concentrations. The tests were performed according to ISO 6988 and ASTM G8 standards.

The SO_2 exposure tests lasted 72 hours for each sample in a heat treatment oven (Therma, with heating up to 1280°C) [2,5].

During the tests, the humidity in the heat treatment oven was set to 75%, and the temperature was set to 40°C. The SO_2 content was set according to Table 5, individually for each test.

The corrosion tests in saline environment were conducted in accordance with ISO 9227:2006, by exposing the samples for 120 hours at a temperature of 40°C and a relative humidity of 80% [6].

The experiments were carried out under continuous conditions, without wet-dry cycles, in order to accelerate the corrosion process. Prior to testing, the samples were prepared by grinding with abrasive paper, followed by cleaning with ethanol and deionized water. Subsequently, they were exposed to controlled corrosive environments designed to simulate the specific conditions of a polluted industrial atmosphere [2].

2.3 Mass loss measurement

Mass loss determination was carried out in accordance with ISO 8407 [2,6].

The samples were weighed prior to exposure to the corrosive environment. After macroscopic inspection, they were rinsed with a water jet to remove soluble corrosion products. Subsequently, the samples were washed for 15 minutes in a cleaning solution composed of 300 ml deionized water, 10 g ammonium chloride (NH_4Cl), and 40 ml hydrochloric acid (HCl), in order to eliminate adherent corrosion products.

After cleaning, the samples were rinsed again under running water and then dried using warm air. Material loss was evaluated by comparing the sample weights before and after testing, using a precision electronic balance.

2.4 Characterization of corrosion products

The metallographic analysis of the corroded samples was performed using a KERN VIS optical metallographic microscope.

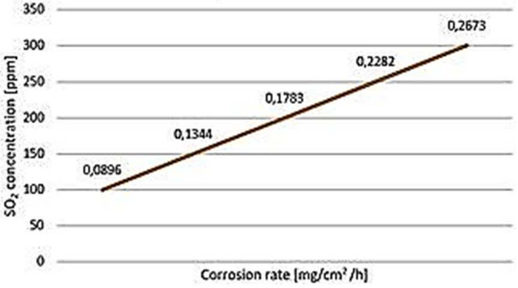
3. RESULTS AND DISCUSSION

3.1. Determination of mass loss

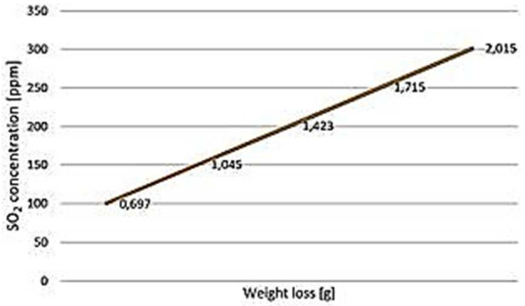
In the experimental study, the influence of sulfur dioxide (SO_2) concentration on the mass loss and corrosion rate (CR) of S235JR and S355JR steels, sampled from the structure of the ERC 2000 excavator, was analyzed. The evolution of these parameters was evaluated using the gravimetric method, and the results are illustrated in figure 3.a, b and figure 4.a, b. To quantify the impact of SO_2 on metallic degradation, the corrosion rate (CR) was calculated using the standard mathematical relation [2]:

$$CR = k \cdot C_{SO_2} \cdot f(T,U) \qquad (1)$$

Where: - k is a material- and working environment-specific coefficient; - C_{SO2} is the concentration of SO_2 (ppm); - f(T,U) is a temperature-humidity function [11].

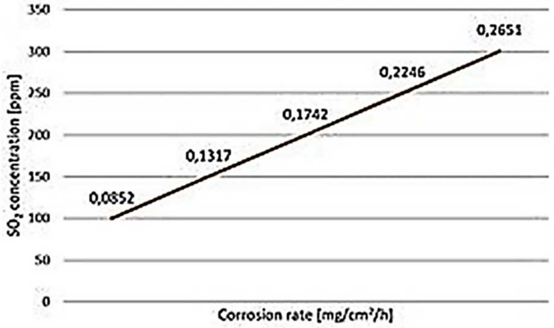


a) - corrosion rate

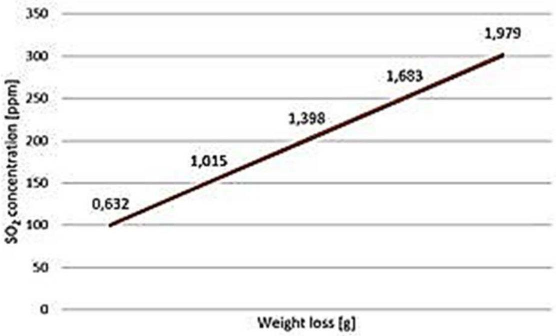


b) - weight loss

Fig.3. Corrosion rate and weight los for S235JR



a) - corrosion rate



b) - weight loss

Fig. 4. Corrosion rate and weight los for S355JR

This study examined the corrosion behavior of S235JR and S355JR steels, sourced from a port crane, with respect to changes in the environmental salinity. The findings, displayed in Figures 5 and 6, highlight both the corrosion rates and the mass loss experienced by the tested samples.

Corrosion Rate Trends Based on Salinity:

- Sharp initial increase: A marked rise in the corrosion rate was observed when the salinity level was below 2%.
- Subsequent decline: Beyond the 2% salinity threshold, the corrosion rate gradually decreased as salinity continued to increase.

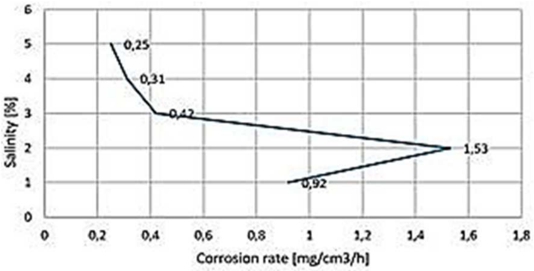
Two main factors govern the corrosion dynamics in saline environments:

- Salinity: Higher concentrations of chloride ions (Cl^-) in the solution enhance the electrical conductivity of the thin liquid film on the metal surface. These ions penetrate this film and react with the steel substrate, thereby accelerating corrosion processes [7].
- Dissolved oxygen content: As chloride concentration rises, the solubility of oxygen in the solution decreases progressively. Dissolved oxygen is vital for cathodic reduction reactions, and its reduction can alter the mechanisms of corrosion.

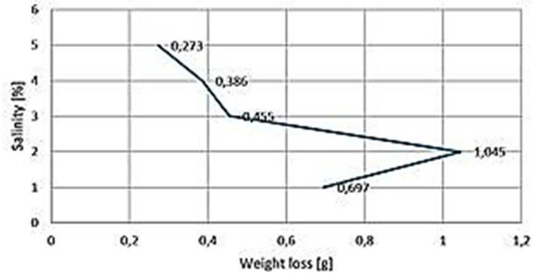
During the experiments, it was noted that the liquid film on the sample surfaces thickened over time, which promoted greater absorption of chloride ions. These ions, known for their aggressive corrosive effects, can disrupt protective passive films and infiltrate existing corrosion layers. This leads to substantial alterations of the metal surface and speeds up the corrosion process.

However, at high chloride concentrations, the solubility of oxygen in the liquid film decreases considerably, significantly reducing the intensity of the cathodic oxygen reduction reactions. Therefore, once the salinity exceeds the 2% threshold, the corrosion rate of the samples begins to decrease gradually. The data shown in figures 5.a and 6.a indicate a trend toward stabilization of the corrosion rate at salt concentrations above 3%, suggesting that under these conditions, the corrosion process is primarily controlled by oxygen diffusion rather than chloride concentration.

The analyses revealed a nuanced interplay between salinity levels and the corrosion rates of S235JR and S355JR steels. When salinity is below 2%, rising chloride ion concentrations exacerbate corrosion by enhancing electrical conductivity and damaging passive protective layers. However, at higher salinity levels, the reduced solubility of oxygen becomes the primary factor controlling corrosion, causing a gradual decline and eventual stabilization of the corrosion rate. This shift indicates a transition in the dominant corrosion mechanism—from one governed by salinity effects to one limited by the diffusion of oxygen [8].



a) - corrosion rate



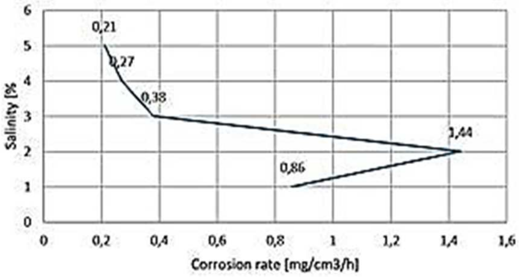
b) - weight los

Fig.5. Corrosion rate and weight los for S235JR

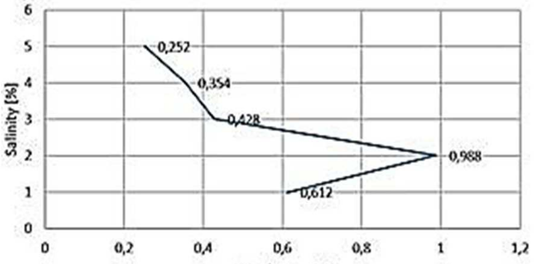
The main phases present in the rust formed at different salinity levels were γ-FeOOH, Fe_3O_4, $Fe_2O_3\cdot H_2O$, β-FeOOH, and α-FeOOH.

At the onset of corrosion, when the salinity content was 1%, Fe_3O_4 and $Fe_2O_3\cdot H_2O$ were identified on the surface of the steels, along with small amounts of γ-FeOOH and β-FeOOH.

As the salinity content increased, a larger quantity of β-FeOOH formed in the rust layer, suggesting that this phase forms more easily in environments with a high concentration of Cl^- ions.



a) - corrosion rate



b) - weight los

Fig.6. Corrosion rate and weight los for S355JR

An increased amount of β-FeOOH can introduce more defects into the rust, such as cracks and pores, thus facilitating the penetration of corrosive media and accelerating the oxidation of the sample [8].

3.2 Corrosion morphologies

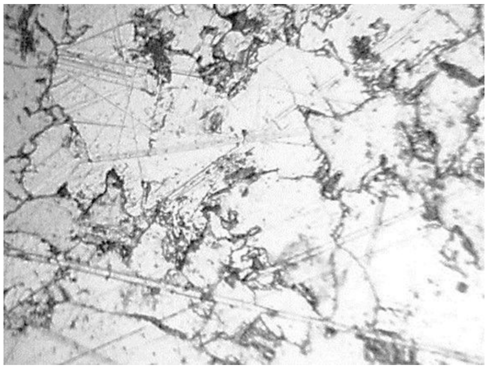
To assess how salinity affects the corrosion behavior of S235JR and S355JR steels, microstructural analyses were conducted using a KERN VIS optical metallographic microscope on samples exposed to saline solutions at concentrations of 1%, 3%, and 5% (see Figures 7.a, b, c). The resulting micrographs showed no notable differences between the two steel types, allowing for a generalized interpretation of the observations.

Microstructural findings:

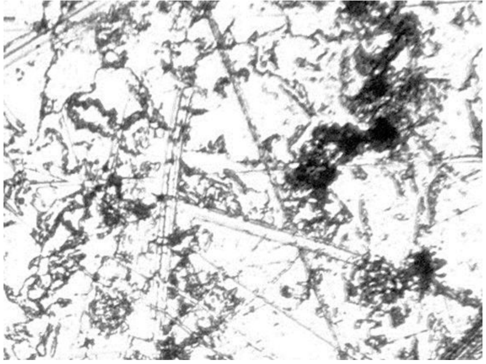
- Corrosion layer formation and growth: Across all salinity levels, the sample surfaces were consistently coated with corrosion products. Increasing salinity led to a gradual thickening and spread of the rust layer;
- Rust layer defects: Elevated salinity levels encouraged the development of cracks and pores within the corrosion layer. These flaws created microscopic pathways that enabled the corrosive solution to reach the underlying metal, thereby accelerating material degradation;
- Distinct features within the rust layer: At a 3% salinity level, honeycomb-like structures characteristic of the lepidocrocite phase (γ-FeOOH) were observed on the rust surface. Although this phase commonly occurs in corrosive environments, it is electrochemically unstable and fails to offer substantial protection against ongoing corrosion;
- Role of chloride ions: Chloride ions (Cl^-) in the saline solutions significantly influenced the corrosion process by penetrating through imperfections in the rust layer and interacting directly with the metal substrate. This resulted in a uniform corrosion pattern across the steel surface, without prominent localized attacks.

Exposure of S235JR and S355JR steels to environments with high salinity accelerates corrosion, as evidenced by the thickening of the rust layer and the development of structural defects that promote deeper ingress of corrosive agents.

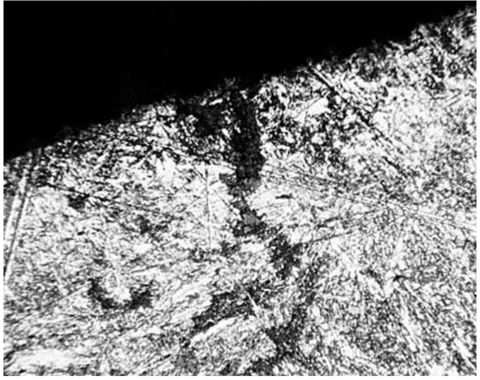
While γ-FeOOH is present in the corrosion products, its inability to effectively shield the metal underscores the necessity for additional protective strategies in such harsh conditions [8]. Steel samples exposed to an atmosphere contaminated with sulfur dioxide (SO_2) exhibited the uniform formation of a corrosion product layer, with moderate adherence to the substrate.



a) S235JR (400:1)



b) S355JR (400:1)



c) S235 JR (400:1)

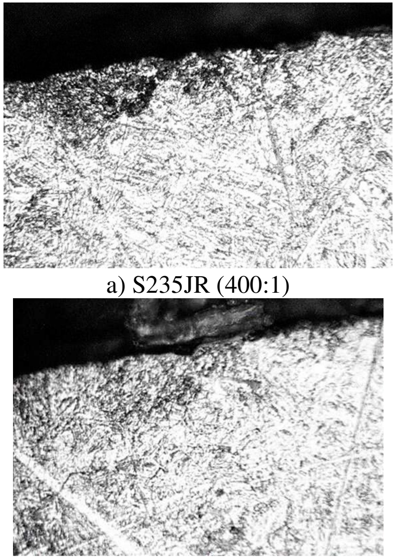
Fig.7. Microstructural analysis - the influence of salinity

Figure 8.a, b illustrates the morphological changes of the corroded surface under the influence of different SO_2 concentrations.

Evolution of the corrosion layer with Increasing SO_2 Concentration:

- Effect of SO_2 levels on corrosion: Rising concentrations of sulfur dioxide led to a gradual thickening of the rust layer along with noticeable enlargement of the corroded areas on the steel surface;
- Morphological alterations in the corrosion layer: The corrosion products exhibited significant structural changes, including the development of fine cracks and microcavities. These defects indicate an accelerated degradation process, likely linked to internal stresses formed during metal oxidation;
- Corrosion uniformity: The corrosion progressed steadily without indications of passivation, implying a uniform degradation of the steel substrate. The lack of localized severe damage, such as pitting, suggests that the corrosion was evenly distributed across the exposed surface.

These findings clearly demonstrate the direct impact of sulfur dioxide on atmospheric corrosion behavior, emphasizing the necessity for effective protective strategies like anti-corrosive coatings and vigilant monitoring of harsh industial environments;


a) S235JR (400:1)

b) S355JR (400:1)

Fig. 8. Microstructural analysis - the influence of SO_2

The microstructural analysis of the samples exposed to different concentrations of SO_2 and salinity revealed the presence of rust layers composed of γ-FeOOH, Fe_3O_4, $Fe_2O_3 \cdot H_2O$, β-FeOOH, and α-FeOOH.

The rust structures differ depending on the corrosion factors [9]:

- At high concentrations of SO_2, the rust layers exhibited cracks and pores, facilitating the penetration of corrosive agents;
- At high salinity concentrations, the formation of β-FeOOH led to an increase in structural defects.

4. CONCLUSIONS

This research investigated the individual effects of key atmospheric corrosion factors—namely sulfur dioxide (SO_2) concentration, relative humidity, and ambient temperature—on the corrosion behavior of S235JR and S355JR steels. The experiments were carried out under controlled conditions that simulated the typical atmospheric environment found in industrial zones where surface coal extraction equipment is used. The main findings are as follows:

- Effect of SO_2: The corrosion rate consistently increased with rising SO_2 levels, highlighting the critical role this pollutant plays in accelerating metal deterioration.
- Temperature influence: Higher temperatures led to increased corrosion rates, with S235JR steel exhibiting greater sensitivity in the 40–50°C range, indicating enhanced electrochemical activity at elevated temperatures.
- Relative humidity impact: A threshold of approximately 75% relative humidity was identified, beyond which a continuous water film formed on the metal surface, fostering oxidation reactions [10].

These results offer important insights for designing effective corrosion protection strategies, including optimizing coating techniques, selecting suitable corrosion inhibitors, and choosing materials with improved resistance for use in harsh atmospheric conditions. Such measures can substantially extend the service life of metal structures operating in industrial settings.

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Degradarea în mediu coroziv a unor oţeluri utilizate în construcţia structurilor metalice

Materialele metalice interacționează diferit cu mediul atmosferic, iar aceste interacțiuni pot duce la deteriorări fizico-mecanice semnificative. Oțelurile slab aliate sunt utilizate frecvent în structurile metalice datorită costului redus și proprietăților mecanice favorabile, dar sunt expuse unor factori agresivi precum umiditatea ridicată, atmosfera poluată cu SO_2 și mediile saline. Atmosfera industrială poluată accelerează coroziunea prin formarea unui film electrolitic subțire pe suprafața oțelului, favorizând pătrunderea ionilor agresivi. De asemenea, prezența SO_2 crește conductivitatea filmului coroziv, intensificând procesul de degradare.

Această lucrare analizează influența factorilor atmosferici de coroziune asupra comportamentului oțelurilor slab aliate S235JR și S355JR, utilizate în structuri metalice expuse la medii agresive, precum macaralele portuare și utilajele de extracție a cărbunelui. Studiul se axează pe analiza efectului salinității, concentrației de dioxid de sulf (SO_2), umidității relative şi temperaturii asupra ratei de coroziune și caracteristicilor fizico-mecanice ale acestor materiale. Testele experimentale au fost realizate în condiții controlate, simulând atmosfera industrială poluată. Pentru evaluarea comportamentului la coroziune s-au utilizat metode gravimetrice, analize microstructurale prin microscopie optică și caracterizarea stratului de coroziune format pe suprafața metalică.

Analiza microstructurală a probelor expuse la diferite medii corozive a evidențiat formarea fazelor γ-FeOOH, β-FeOOH și Fe_3O_4, cu impact diferit asupra rezistenței la coroziune. În special, formarea β-FeOOH în medii cu salinitate ridicată a fost asociată cu defecte structurale precum fisuri și pori, favorizând pătrunderea agenților corozivi. Astfel, cercetările oferă informații esențiale pentru dezvoltarea unor strategii eficiente de protecție anticorozivă a structurilor metalice utilizate în medii agresive. Rezultatele pot fi utilizate pentru optimizarea metodelor de acoperire, selecția inhibitorilor de coroziune și extinderea duratei de viață a componentelor metalice expuse în atmosferă industrială severă.

Florin CIOFU, Lecturer PhD. eng., ”Lucian Blaga” University of Sibiu, Engineering Faculty, Industrial Engineering and Management Department, Romania, E-mail: cristian.ciofu@ulbsibiu.ro, phone 0726317998