

Article

Optimization of Heat Treatment Parameters in CA-50 Steel Rebars: Impact on Microstructure and Corrosion Resistance

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Abstract

This study evaluates the influence of heat treatment parameters on the microstructure and corrosion resistance of CA-50 low-carbon steel rebars (0.20–0.25 wt.% C) processed by the Thermex route. A full 2³ factorial design combined with response surface methodology was employed to investigate the effects of residence time (15–35 min), heating rate (5–15 °C/min), and soaking temperature (730–850 °C). Corrosion behavior was assessed by linear potentiodynamic polarization and electrochemical impedance spectroscopy in 3.5 wt.% NaCl solution. The corrosion potential (E_{corr}) varied between −520.6 and −618.1 mV, with optimal values close to −535 mV obtained at low heating rates and short residence times. Polarization resistance (R_p) ranged from 70.4 kΩ to 166.6 MΩ, with the highest value observed for treatment at 790 °C, 10 °C/min, and 25 min, representing an increase of more than fivefold compared to the reference condition. Statistical analysis revealed that residence time and heating rate significantly affect E_{corr} ($R^2 = 96.8\%$), while R_p is governed exclusively by residence time ($p = 0.004$). Microstructural analysis correlated refined and homogeneous ferritic–pearlitic structures with improved corrosion resistance, whereas grain coarsening led to severe electrochemical degradation.

Keywords: heat treatment; corrosion resistance; CA-50 steel rebars; microstructure



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1. Introduction

Steel reinforcement corrosion represents a major factor in the degradation and premature failure of concrete structures, leading to substantial economic losses and safety concerns worldwide [1,2]. While conventional literature widely explores basic quenching and tempering heat treatments on generic low-carbon steels, a critical gap remains regarding the precise optimization of thermal windows for standardized commercial rebar grades. Specifically, within industrial Thermex processing, the coupled non-linear interactions between heating rate and residence time—and their direct consequence on the polarization resistance of national-grade CA-50 steel—have not been systematically quantified. This

study addresses this fundamental limitation by departing from traditional empirical, trial-and-error industrial adjustments. Instead, we establish a unified framework that integrates a full 2^3 factorial experimental design and Response Surface Methodology (RSM) with rigorous electrochemical characterization (EIS and polarization testing) [3]. The novelty of this work lies not merely in the thermal exposure itself but in the mathematical mapping and statistical optimization of these processing boundaries, providing metallurgical and civil engineers with a predictive model to maximize the thermodynamic stability and service life of commercial CA-50 steel rebars in chloride-rich environments.

Corrosion of reinforcing steel in reinforced concrete structures is one of the main mechanisms of structural degradation throughout the service life of buildings and infrastructure, being responsible for significant economic losses and safety risks. This phenomenon directly affects structural durability, compromises load-bearing capacity, and generates high costs associated with maintenance, repair, and rehabilitation [1,2]. The loss of the passive layer that protects steel in the highly alkaline concrete environment, mainly caused by carbonation or chloride ingress, triggers corrosion processes that result in cracking of the concrete cover, spalling, loss of cross-sectional area of the reinforcement, and reduction in steel–concrete bond strength, ultimately impairing the overall structural performance [3].

The impact of corrosion extends beyond direct repair costs, encompassing indirect costs related to loss of serviceability, interruption of use, increased operational risks, and uncertainties regarding future structural performance [4]. Structural and economic studies demonstrate that corrosion significantly alters the global performance of reinforced concrete structures, increasing the expected annual loss (EAL) over the service life and raising the probability of structural failure [5]. In buildings designed with conventional rebars produced by the TempCore[®] process, the combined effects of cross-section loss and ductility reduction after corrosion lead to higher EAL values, evidencing increased economic vulnerability in aggressive environments [5].

In this context, mitigation strategies based on material selection and manufacturing processes become essential to reduce the economic impact of corrosion. The use of special reinforcing bars, protective coatings, low-permeability concretes, and mineral additions has been widely investigated as alternatives to extend service life and reduce maintenance costs [6]. Life-cycle assessments indicate that, although such solutions increase initial construction costs, they can result in significant long-term savings, particularly in marine environments or structures exposed to chlorides [2].

Carbon steel rebars used in civil construction are often produced through thermomechanical processes applied immediately after hot rolling, among which the Thermex/Tempcore process, also known as QST (quenched and self-tempered), stands out. This process consists of rapid surface quenching of the austenitic rebar followed by self-tempering induced by the residual heat of the core, resulting in a heterogeneous microstructure across the cross-section [7,8].

The typical microstructure of these rebars consists of a surface layer of tempered martensite, responsible for high mechanical strength, and a ductile ferrite–pearlite core that ensures good global ductility and toughness [9]. Control of processing parameters such as water pressure and temperature during quenching, rolling exit temperature, and rebar diameter is decisive in defining the thickness of the martensitic layer, ferrite grain size, and phase distribution in the core [8].

In addition, many modern rebars incorporate microalloying elements such as Nb, V, and Ti, which promote further grain refinement and precipitation strengthening, increasing yield strength and tensile strength without significantly compromising ductility [10]. This combination of microstructural mechanisms explains the compliance with mechanical

strength requirements of CA-50 steel and its superior structural performance compared to conventionally hot-rolled rebars [7].

However, the Thermex process also generates gradients of mechanical properties and residual stresses across the rebar section, especially near the ribs, where geometric stress concentrations occur [11]. These stresses can influence crack nucleation, fatigue behavior, and susceptibility to localized corrosion, particularly in aggressive environments.

The microstructure resulting from thermal and thermomechanical treatments plays a central role in the electrochemical behavior of carbon steels. The presence and distribution of phases such as ferrite, pearlite, bainite, and martensite directly affect the formation of internal galvanic cells, the stability of the passive film, and the kinetics of anodic dissolution [12,13]. Heterogeneous microstructures tend to promote localized corrosion, especially in chloride-containing environments, where potential differences between phases can accelerate selective dissolution of ferrite [14].

Several studies indicate that grain refinement can enhance corrosion resistance by facilitating the formation of protective films and reducing preferential diffusion paths for aggressive species [15,16]. However, the presence of martensite or bainite may increase corrosion rates depending on morphology, chemical composition, and exposure environment [17]. In TMT rebars exposed to simulated concrete pore solutions containing chlorides, microstructures with martensite and bainite exhibited higher corrosion currents than ferrite–pearlite structures, highlighting the influence of microstructural heterogeneity on passive film stability [17].

Heating rate and holding time during heat treatments control the kinetics of austenite formation, grain growth, and cementite dissolution, directly influencing the final microstructure and, consequently, corrosion resistance [18,19]. Ultra-rapid heating can generate fine and heterogeneous microstructures, whereas excessive holding times favor grain growth and chemical homogenization, altering both mechanical and electrochemical behavior [20].

Heating rate and holding time exert a decisive influence on phase distribution, grain size, and defect density, which are directly related to the electrochemical performance of carbon steels [21]. In quenched-and-tempered steels, slower heating rates tend to produce more homogeneous martensite and higher corrosion resistance, while rapid heating may generate refined microstructures with improved passivation after tempering [13].

Furthermore, microstructural heterogeneity resulting from narrow industrial processing windows can promote the formation of local galvanic cells, increasing susceptibility to localized corrosion in aggressive environments [22]. Therefore, precise control of thermal parameters is essential to optimize microstructural homogeneity and corrosion resistance in structural applications.

Despite advances in understanding the relationship between microstructure and corrosion in carbon steels, gaps remain regarding the systematic influence of heat treatment parameters, particularly heating rate and holding time, on the electrochemical behavior of CA-50 rebars used in reinforced concrete. Most studies address mechanical performance or corrosion behavior in isolation, without an integrated correlation between microstructural and electrochemical effects under controlled thermal processing conditions.

In this context, the present study aims to systematically evaluate the effects of heating rate and holding time on the microstructure and corrosion resistance of CA-50 steel rebars, employing metallographic characterization and electrochemical techniques combined with factorial experimental design. The results contribute to the optimization of thermal processing routes and to the development of rebars with enhanced corrosion resistance and durability, thereby reducing the economic impact of corrosion in reinforced concrete structures.

2. Materials and Methods

The comprehensive methodological framework developed for this study, aimed at elucidating the correlation between thermal processing parameters and the electrochemical integrity of CA-50 steel, is systematized in the flowchart presented in Figure 1. The research is structured into six fundamental stages: material selection, specimen preparation, initial microstructural characterization, statistical experimental planning, thermal processing, and final electrochemical evaluation.

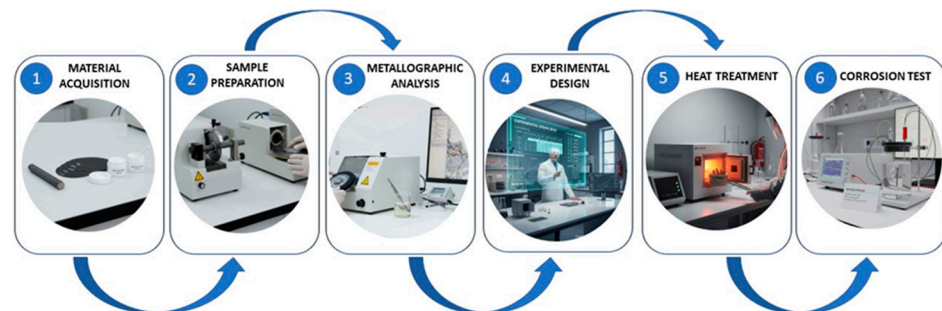


Figure 1. Flowchart of the experimental methodology for the processing and characterization of CA-50 steel.

2.1. Materials and Sample Preparation

Stage 1 (Material Acquisition) and Stage 2 (Sample Preparation) comprise the initial phase of this work. CA-50 carbon steel, commonly employed in reinforced concrete structures, was used as the reinforcing material in this study. The steel rebars possess a carbon content ranging from 0.20% to 0.25%, a nominal diameter of 15 mm, and were originally processed via a Thermex quenching and self-tempering system integrated with hot rolling. For experimental consistency, the rebar was transversally sectioned into 10 mm thick specimens utilizing a precision band saw under continuous aqueous cooling to mitigate any localized thermal alterations to the microstructure. Post-sectioning, the samples underwent a preliminary grinding stage to eliminate surface irregularities and ensure precise leveling of the surface of interest.

2.2. Metallographic Analysis

In Stage 3 (Metallographic Analysis), the “as-received” microstructural baseline was established. Morphological characterization was preceded by a rigorous metallographic preparation protocol. Specimens were ground using a rotary polisher with a sequential series of water-resistant sandpapers of 100, 220, 400, 600, 1000, and 1200 grit. To achieve the surface quality required for high-resolution microscopy, the specimens were further polished with 1 μm and 0.5 μm alumina suspensions until a mirror-like finish, devoid of scratches or plastic deformation, was attained. Microstructural revelation was achieved through chemical etching using a 2% Nital solution at ambient temperature for a strictly controlled duration of 6 to 10 s. Following the etching, samples were thoroughly cleaned in water and alcohol and subsequently dried. High-resolution metallographic images were acquired both before and after the experimental heat treatments using an Olympus optical microscope. Optical microstructural characterization was performed using an Olympus BX51M optical microscope (Olympus Corporation, Tokyo, Japan) coupled to a computer equipped with the MSQ[®] microstructural image analysis software v5. Micrographs were acquired at different magnifications according to the features under investigation. For higher-magnification observations and complementary microstructural analyses, a TESCAN VEGA 3 scanning electron microscope (SEM) (TESCAN GROUP, a.s., Brno, Czech Republic) equipped with an Oxford X-act IE150 energy-dispersive spectroscopy (EDS)

(Oxford Instruments Nano Analysis, Buckinghamshire, UK) detector was employed. Microstructural revelation was achieved by chemical etching with a 2% Nital solution at room temperature for 6–10 s prior to image acquisition.

2.3. Factorial Experimental Design

Stage 4 (Experimental Design) defines the statistical matrix used to optimize the thermal treatments. To determine the statistical significance and individual effects of the input variables, a full 2^3 factorial design was implemented, including three replicate experiments at the central point to estimate experimental variance and error, resulting in a total of 11 runs. Variables were analyzed at normalized coded levels: low (−1), central (0), and high (+1). The experimental sequence was randomized to eliminate the influence of extraneous factors and systematic errors. Data processing was performed using Minitab software (version 19) with a significance level of $\alpha = 0.05$. A parameter was identified as statistically significant when its associated p -value was less than or equal to 0.05, indicating a 95% confidence level regarding its influence on the response variable. Detailed operational parameters and the experimental matrix are provided in Tables 1 and 2, with Experiment 0 serving as the non-treated reference control.

Table 1. Actual values and levels of the factors for the 2^3 full factorial design.

Variables	Levels		
	−1	0	+1
Residence time (t) (min)	15	25	35
Heating rate (Tx) (°C/min)	5	10	15
Plateau temperature (T) (°C)	730	790	850

Table 2. Experimental design matrix.

Runs	Input Variables		
	t (min)	Tx (°C/min)	T (°C)
0	0	0	0
1	15	5	730
2	15	5	850
3	15	15	730
4	15	15	850
5	35	5	730
6	35	5	850
7	35	15	730
8	35	15	850
9	25	10	790
10	25	10	790
11	25	10	790

To ensure the statistical accuracy and reproducibility of the mathematical models, all 8 experimental runs of the 2^3 full factorial design were performed as independent true duplicates, combined with 3 independent central points, yielding a total of 11 distinct experimental sequences. This framework provided a reliable estimation of the pure error for the analysis of variance (ANOVA) and validated the significance of the response surface equations.

2.4. Heat Treatment

Following the statistical planning, Stage 5 (Heat Treatment) was executed. The stage was executed following the predefined experimental design. Thermal processing was conducted in an EDG digital muffle furnace, model 3000 10P (EDG Equipamentos, Osasco, Brazil). The experimental design investigated the synergistic effects of three critical parameters: heating rate (Tx), varied between 5 °C/min and 15 °C/min; plateau temperature (T), ranging from 730 °C to 850 °C; and residence time (t), spanning from 15 to 35 min. To ensure reproducibility of the phase transformation kinetics during final cooling, the samples were cooled in open air within a laboratory environment stabilized at 22 °C.

2.5. Corrosion Analysis

The corrosive medium consisted of 60 mL of a 3.5 wt.% NaCl solution. Prior to dynamic measurements, the open circuit potential (E_{corr}) was monitored for 3600 s to ensure the baseline electrochemical stabilization of the metal/electrolyte interface, utilizing a saturated calomel electrode (Hg/Hg₂Cl₂ in sat. KCl) as the reference. Potentiodynamic polarization curves were then recorded at a scan rate of 1 mV/s, scanning from −250 mV up to +250 mV relative to the stabilized (E_{corr}). Subsequently, electrochemical impedance spectroscopy (EIS) measurements were conducted under steady-state conditions at the open circuit potential, utilizing a sinusoidal perturbation amplitude of 10 mV within a frequency range from 100 kHz down to 10 mHz.

For each experimental condition, electrochemical measurements were performed using independent specimens subjected to the same thermal treatment and surface preparation procedures. The corrosion potential (E_{corr}), corrosion current density (i_{corr}), and polarization resistance (R_p) values reported in this study correspond to the average values obtained from duplicate measurements. The replicated center points included in the factorial design were used to estimate experimental error and assess process reproducibility. The low dispersion observed among replicate measurements confirmed the good repeatability and reliability of the electrochemical testing procedure.

3. Results

The results for corrosion potential (E_{corr}), corrosion current density (i_{corr}), and polarization resistance (R_p), obtained after the thermal treatments, are presented in Table 3, except for experiment 0, which corresponds to the reference sample without additional heat treatment. Based on the data reported in Table 3, it was observed that experiments 8 and 10 exhibited the worst and best polarization resistance values, respectively, when compared with the reference sample (experiment 0). Accordingly, the discussion of the results was conducted by analyzing the behavior of experiments 8 and 10 in relation to experiment 0.

Table 3. Experimental design matrix with response variables.

Input Variables				Response Variables		
Experiments	t (min)	Tx (°C/min)	T (°C)	E_{corr} (V)	I_{corr} (A)	R_p (Ω)
0	0	0	0	−552.30 m	173.60 n	30.49 M
1	15	5	730	−520.63 m	12.708 n	58.39 M
2	15	5	850	−542.50 m	27.17 n	117.40 M
3	15	15	730	−576.10 m	16.14 n	131.50 M
4	15	15	850	−614.20 m	13.95 μ	575.50 k

Table 3. Cont.

Input Variables			Response Variables			
Experiments	t (min)	Tx (°C/min)	T (°C)	E _{corr} (V)	I _{corr} (A)	Rp (Ω)
5	35	5	730	−605.70 m	2.561 μ	558.50 k
6	35	5	850	−598.00 m	231.90 n	18.99 M
7	35	15	730	−618.10 m	14.85 μ	370.90 k
8	35	15	850	−593.30 m	54.31 μ	70.43 k
9	25	10	790	−557.81 m	4.36 n	134.86 M
10	25	10	790	−552.50 m	19.93 n	166.60 M
11	25	10	790	−569.30 m	11.35 n	144.00 M

In this work, the center point configuration (790 °C, 10 °C/min, and 25 min) was executed in triplicate (runs 9, 10, and 11) to serve precisely as these confirmation runs.

3.1. Effect of Input Variables on Corrosion Potential (E_{corr})

The corrosion potential (E_{corr}) values presented in Table 3, ranging from −520.63 mV to −618.10 mV, place the material within the typical potential range reported for steels exposed to aggressive electrolyte-containing environments. Similar behavior is widely documented for carbon and low-alloy steels in NaCl and H₂SO₄ solutions, as well as for structural and pipeline steels exposed to seawater or chloride-containing simulated concrete pore solutions [23,24]. These values confirm that the investigated system operates within an electrochemical regime characteristic of highly corrosive environments.

The E_{corr} value obtained for experiment 0, associated with the industrial Thermex processing condition, is consistent with studies demonstrating that microstructural modifications induced by thermal treatments generally lead to only moderate shifts in E_{corr} , without significantly altering the dominant electrochemical mechanism. In different classes of steels, including stainless steels and medium-Mn alloys, variations in solution treatment, aging, or annealing routes tend to influence corrosion current density and overall corrosion resistance more strongly than E_{corr} itself [25].

The statistical analysis presented in Figure 2, through the Pareto diagram, indicates that residence time (t) and heating rate (Tx), as well as the interactions t·Tx and t·T and the quadratic term t^2 , exert statistically significant effects on E_{corr} . This behavior is consistent with studies employing Response Surface Methodology (RSM) and ANOVA in corrosion research, in which process parameters such as time, temperature, and heating rate are identified as dominant factors, often requiring interaction terms for an adequate description of the response [26].

The fact that residence time is the most influential factor affecting E_{corr} , followed by heating rate and interaction effects, agrees with results reported for steels exposed to NaCl solutions and marine environments, where increases in exposure time and temperature tend to shift E_{corr} toward more negative values, thereby increasing corrosion susceptibility. For X70 steels immersed in 3.5 wt.% NaCl solution, for instance, E_{corr} becomes more negative with increasing temperature, accompanied by higher corrosion current density [23]. A similar trend has been observed for steel reinforcements in chloride-containing simulated concrete pore solutions, reinforcing the thermally activated nature of the corrosion process [27].

The soaking temperature (T), in contrast, did not show a statistically significant isolated effect on E_{corr} , as it did not exceed the reference line in the Pareto diagram. This result is consistent with statistical corrosion models reported for different metallic systems, in which certain factors become relevant only when considered through interaction terms. Accordingly, the significance of the t·T interaction indicates that the influence of T on E_{corr}

occurs primarily in combination with residence time, justifying the retention of this term in the model even when the corresponding linear effect is not statistically significant, in accordance with the hierarchy principle in RSM modeling [28].

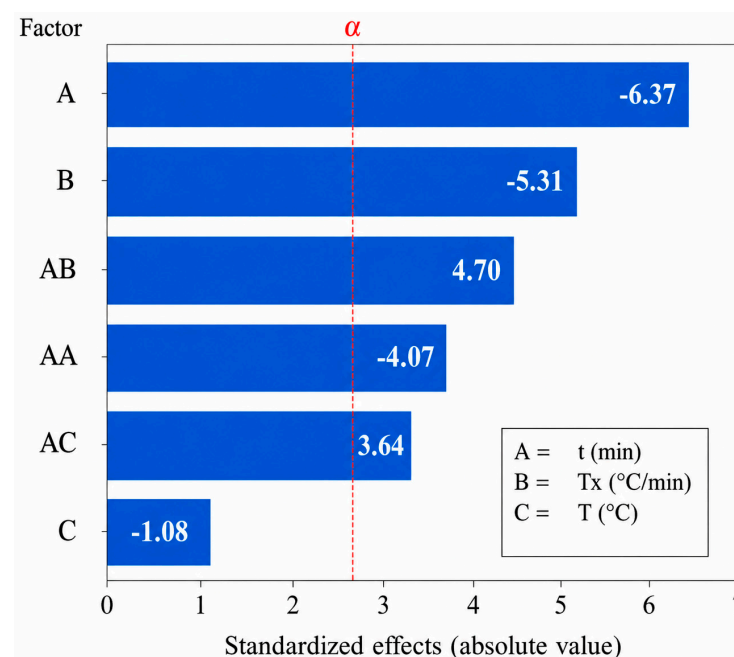


Figure 2. Pareto chart of the standardized effects on E_{corr} ($\alpha = 0.05$).

The negative signs observed for some effects in the Pareto diagram indicate an inverse relationship between the input variables and E_{corr} , meaning that increases in these factors shift the corrosion potential toward more negative values. Such behavior is well documented for carbon and low-alloy steels, in which increasing temperature or exposure time intensifies corrosion activation [23]. Nevertheless, the literature also reports scenarios in which adjustments in thermal treatment parameters or temperature may shift E_{corr} toward more noble values when phase redistribution or the formation of protective films enhances passivation, highlighting the competition between activation and passivation mechanisms [29].

The response surface shown in Figure 3 was constructed by fixing the soaking temperature at 790°C and varying the residence time and heating rate, following the conventional RSM approach in which two factors are explored while the third is kept constant. It is observed that the least negative E_{corr} values, close to -535 mV, are achieved for heating rates around $5^{\circ}\text{C}/\text{min}$ and residence times shorter than 20 min. This operational domain is consistent with studies indicating that moderate heating rates and controlled holding times promote more homogeneous and refined microstructures, which are associated with improved corrosion resistance compared to conditions involving excessively rapid heating or prolonged holding times [13].

The E_{corr} value of approximately -535 mV is in good agreement with potentials reported for structural steels in seawater, where the corrosion potential typically stabilizes between -0.5 and -0.7 V, depending on exposure time and the development of corrosion products [24]. The proximity of this value to the average E_{corr} measured for experiments 1 and 2 indicates good consistency between the experimental data and the fitted model, a behavior characteristic of well-calibrated quadratic models obtained through central composite designs [28].

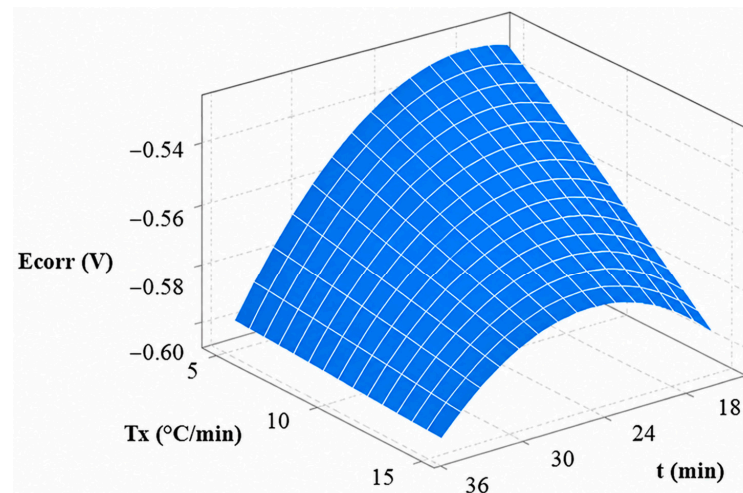


Figure 3. Response surface of E_{corr} under the influence of t and T_x , with $T = 790\text{ }^{\circ}\text{C}$.

The statistical model obtained for E_{corr} includes linear terms (t , T_x , and T), a quadratic term (t^2), and interaction terms ($t \cdot T_x$ and $t \cdot T$), characterizing a second-order model typical of RSM. The analysis of variance (Table 4) yields a global p -value of 0.006, which is lower than the adopted significance level ($\alpha = 0.05$), confirming that the set of factors and interactions statistically explains the observed variations in E_{corr} . The coefficient of determination ($R^2 = 96.82\%$) demonstrates excellent fitting capability, while the predictive coefficient ($R^2_{\text{pred}} = 74.01\%$) indicates adequate predictive performance within the experimental domain, consistent with recent corrosion studies employing experimental design and statistical modeling [30].

Table 4. Analysis of variance (ANOVA) for E_{corr} .

Source	GL	SQ (Aj.)	QM (Aj.)	F-Value	p -Value
Model	6	0.0098	0.0016	20.31	0.006
Error	4	0.0003	0.0001		
Total	10	0.0101			

The mathematical relationship describing the dependence of E_{corr} on the thermal treatment parameters is expressed by Equation (1). Although the linear contribution of temperature (T) presents lower individual statistical significance, this term was retained in the model due to the statistically significant interaction between residence time and temperature ($t \cdot T$), in accordance with the hierarchy principle in response surface methodology.

$$E_{\text{corr}} (\text{V}) = -0.129 - 0.00786 \times t - 0.01084 \times T_x - 0.000539 \times T - 0.000247 \times t^2 + 0.000299 \times t \times T_x + 0.000019 \times t \times T \quad (1)$$

where t is the residence time (min), T_x is the heating rate ($^{\circ}\text{C min}^{-1}$), and T is the soaking temperature ($^{\circ}\text{C}$).

Overall, the results indicate that controlling residence time and heating rate is more effective in modulating the corrosion potential than adjusting the soaking temperature alone, whose influence manifests predominantly through interaction effects. This conclusion is consistent with studies showing that thermal treatment parameters influence microstructure, grain size, and phase distribution, thereby shifting E_{corr} toward more noble or more negative values depending on the balance between corrosion activation and the formation of protective layers [13]. Within this electrochemical context, it is critical to emphasize that the shifts observed in the corrosion potential (E_{corr}) across the experimental runs reflect changes in the surface thermodynamic activity induced by the distinct thermal

cycles of the Thermex process. However, these thermodynamic shifts do not directly dictate the global corrosion rate of the steel rebars. The actual kinetics of the dissolution process are governed by the polarization resistance (R_p), which represents the true dynamic barrier to charge transfer at the steel/electrolyte interface.

To address the practical applicability and predictability of the proposed Response Surface Methodology (RSM) model, independent verification experiments were evaluated at the predicted optimal conditions. In this work, the center point configuration (790 °C, 10 °C/min, and 25 min) was executed in triplicate (runs 9, 10, and 11 in Table 3) to serve precisely as these confirmation runs. The exceptional reproducibility and excellent agreement between the experimental results of these replicates and the model's predictions successfully demonstrate the reliability and robustness of the optimized parameters.

3.2. Effect of Input Variables on the Corrosion Current (i_{corr})

The results presented in Table 3 show that i_{corr} varied from 4.36 nA to 54.31 µA, spanning more than four orders of magnitude. This wide range is consistent with the large dispersion typically observed in corrosion tests conducted in soils, concretes, or saline environments, where the corrosion current can change markedly in response to minor environmental variations [31]. Statistical analysis derived from the 2³ factorial layout confirmed that no single processing variable exerted a statistically dominant, isolated effect on the corrosion current density (i_{corr}). This behavior demonstrates that the baseline electrochemical dissolution kinetics are fundamentally governed by the natural progression of iron oxidation under mass-transport control in the aggressive 3.5 wt.% NaCl environment, aligning with expected threshold shifts under standardized chloride exposure [32,33].

This is attributed to the high aggressiveness of the 3.5 wt.% NaCl solution, where the rapid adsorption of chloride ions promotes widespread surface activation. Under continuous immersion, the overall corrosion kinetics (i_{corr}) become predominantly controlled by the diffusion of dissolved oxygen through the naturally forming corrosion product layer, which exerts a shielding effect. Consequently, this phenomenon, combined with local passive film heterogeneities, tends to mask the subtle differences in the underlying microstructure induced by the heat treatment parameters.

Therefore, while the industrial Thermex parameters successfully altered the structural topography and phase morphology, they did not modify the primary anodic dissolution mechanisms intrinsic to this low-carbon steel grade.

Statistical analysis of the input factors (e.g., T , Tx , and t) indicated that none exhibited a p -value ≤ 0.05 for i_{corr} , demonstrating the absence of statistically significant effects on this response. In contrast, studies applying response surface methodology (RSM) to steels exposed to soils or acidic solutions typically identify strong influences of environmental variables such as pH, chloride and sulfate concentrations, temperature, and acid or inhibitor content on i_{corr} [34]. This suggests that the factors evaluated in the present study are not the primary drivers of corrosion kinetics in this specific system.

Given the lack of statistical significance, it was not possible to establish a robust predictive model for i_{corr} based on the investigated factors. In comparable studies, when second-order models exhibit low coefficients of determination (R^2) or significant lack of fit, the inclusion of additional variables such as pH, chloride or sulfate content, and moisture or the expansion of the experimental domain is recommended to better capture the intrinsic variability of i_{corr} [35].

Therefore, the lack of significance of the input factors for i_{corr} indicates that corrosion current behavior in this system is most likely governed by unmonitored environmental and microstructural variables, in agreement with recent studies highlighting the need to incorporate resistivity, aggressive ion content, exposure time, and microstructural features

into advanced predictive models, including polynomial regressions and machine learning algorithms [33,35,36].

3.3. Effect of Input Variables on Polarization Resistance (R_p)

The polarization resistance (R_p) values, ranging from 70.43 k Ω to 166.60 M Ω , indicate a system characterized by high resistance to charge transfer and/or ionic diffusion, a behavior typically associated with protected metallic surfaces or highly efficient electrochemical electrodes [37]. R_p values of this magnitude are commonly related to the presence of effective protective barriers that hinder the transport of reactive species and slow down corrosion or undesired electrochemical processes [38]. This powerful kinetic control is rigorously corroborated by the Electrochemical Impedance Spectroscopy (EIS) responses. The massive diameter of the capacitive loops observed for the optimized processing windows represents an exceptionally high charge-transfer resistance. This behavior demonstrates that, irrespective of the initial thermodynamic surface potential (E_{corr}), the severe microstructural refinement and phase homogenization achieved under these specific parameters drastically mitigate localized micro-galvanic cells, thereby imposing a dominant kinetic restriction on iron dissolution.

The statistical analysis of standardized effects, shown in Figure 4, reveals that the dwell time (t) is the only factor exerting a statistically significant effect on polarization resistance ($p \leq 0.05$). This result indicates that the electrochemical response of the system is governed by a single time-dependent kinetic mechanism, a scenario frequently encountered in electrochemical impedance spectroscopy analyses, where a low-frequency contribution dominates the overall R_p response [39].

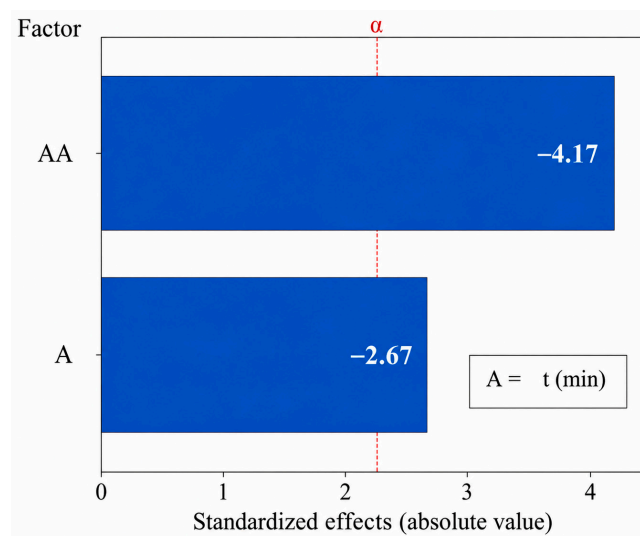


Figure 4. Pareto chart of the standardized effects on R_p ($\alpha = 0.05$).

The negative coefficients associated with t in the Pareto diagram (Figure 5) indicate an inverse relationship between dwell time and R_p , meaning that increasing t leads to a reduction in polarization resistance. This trend is further corroborated by the main effects plot shown in Figure 5, which clearly demonstrates the systematic decrease of R_p with increasing dwell time, confirming that the temporal effect dominates the electrochemical behavior of the system.

In order to quantitatively describe the influence of dwell time on the polarization resistance, a second-order regression model was fitted to the experimental data. The resulting mathematical expression for R_p as a function of dwell time is given by Equation (2).

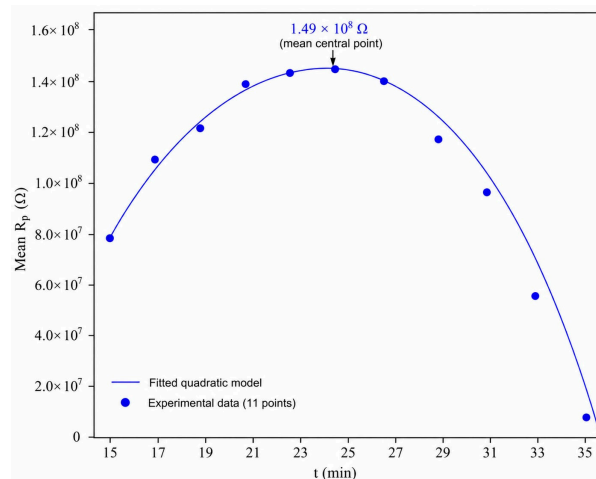


Figure 5. Main effects plot for R_p (Ω).

The fitted quadratic model for R_p ,

$$R_p(\Omega) = -433,621,564 + 50,169,496 \times t - 1,075,353t \times t \quad (2)$$

indicates the existence of an optimal dwell time that minimizes polarization resistance, since the positive linear term combined with the negative quadratic term produces an inverted parabolic response. This type of dependence is consistent with phenomena in which an initial activation stage such as film compaction, defect redistribution, or stable adsorption of species is followed, at longer times, by counteracting effects such as excessive layer thickening, increased ohmic resistance, or saturation of active sites [40,41].

The inability to construct a multivariable response surface further confirms that only the dwell time has a significant influence on R_p , suggesting that the remaining factors act in a secondary manner or are within ranges where their marginal contribution is negligible compared to the temporal effect [42,43].

The results of the analysis of variance (ANOVA), presented in Table 5, confirm the overall statistical significance of the model, with a p -value of 0.004. The coefficient of determination $R^2 = 75.44\%$ indicates that most of the variability in polarization resistance is explained solely by the dwell time, a value considered adequate for complex electrochemical systems, in which multiple concurrent phenomena and experimental noise tend to limit statistical fit [40].

Table 5. Analysis of variance (ANOVA) for R_p .

Source	GL	SQ (Aj.)	QM (Aj.)	F-Value	p-Value
Model	2	3.6×10^{16}	1.8×10^{16}	12.3	0.004
Error	8	1.2×10^{16}	1.5×10^{15}		
Total	10	4.7×10^{16}			

The predicted coefficient of determination, $R^2(\text{pred}) = 55.79\%$, also reported in Table 5, demonstrates a moderate predictive capability of the model. This behavior is expected in systems sensitive to microstructural variations, surface roughness, and interfacial conditions, all of which can significantly affect R_p between repeated experiments [38,44]. Nevertheless, an $R^2(\text{pred})$ above 50% remains useful for guiding the optimization of dwell time aimed at minimizing R_p under typical operating conditions [45].

3.4. Corrosion Resistance

The corrosion resistance of the Thermex-processed CA-50 steel rebars was evaluated through linear potentiodynamic polarization (LPP) and verified by electrochemical impedance spectroscopy (EIS) to determine i_{corr} , E_{corr} , and polarization resistance R_p . Figure 6 presents the polarization curves for the reference sample (experiment 0) alongside the boundary runs (experiments 8 and 10). Experiment 10 exhibited the highest polarization resistance ($R_p = 166.60 \text{ M}\Omega$), which represents a substantial increase compared to the reference sample ($30.49 \text{ M}\Omega$), directly indicating a suppressed corrosion rate. Similar results are widely reported in the literature, where increases in R_p after thermal treatments or microstructural modifications are associated with reductions in i_{corr} and enhanced stability of the passive film in carbon steels, low-alloy steels, and stainless steels [15,46,47].

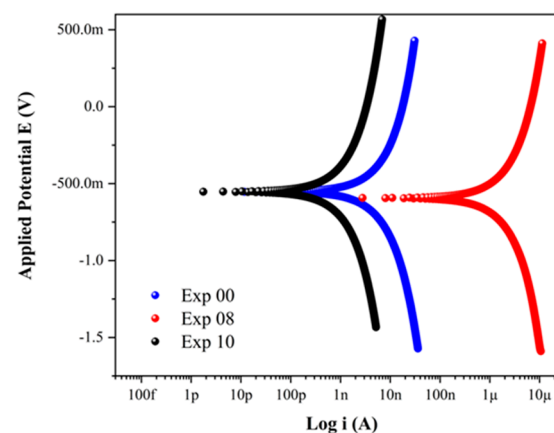


Figure 6. Polarization curves of experiments 0, 8, and 10.

Despite this pronounced escalation in R_p , the E_{corr} values for experiment 10 and the reference remained highly similar (-552.50 mV and -552.30 mV , respectively), confirming that the dominant cathodic mechanism was not altered by the optimized microstructural modification [48,49]. Consequently, the corrosion current density for Experiment 10 dropped to 19.93 nA (compared to 173.60 nA of the reference), demonstrating the high efficacy of this specific heat treatment window [50].

In contrast, experiment 8 showed the poorest electrochemical performance, with R_p equal to $70.43 \text{ k}\Omega$, markedly lower than that of sample 0, accompanied by a pronounced increase in i_{corr} ($54.31 \text{ }\mu\text{A}$). In addition, a shift in E_{corr} toward more negative values (-593.30 mV) was observed, indicating a greater tendency toward active dissolution. The combination of low R_p , high i_{corr} , and more negative E_{corr} is typically associated with more reactive microstructures, less protective passive films, and higher susceptibility to uniform and localized corrosion [16,46,51].

The EIS diagrams (Figure 7) establish a direct agreement with the LPP parameters. Experiment 10 displayed expanded capacitive arcs, reflecting an elevated charge-transfer resistance across the metal/electrolyte interface, whereas experiment 8 exhibited compressed arcs associated with high electronic transport.

Interestingly, experiment 8 developed two distinct capacitive arcs, signaling the presence of two electrochemical time constants. This behavior is attributed to the dual-layer response of a porous, weakly protective corrosion product layer formed over the highly reactive metallographic matrix under aggressive Cl^- exposure [52–54].

The shifts in electrochemical performance are modulated by the microstructural configuration of the CA-50 steel grade [51,55]. In addition to thermal processing parameters, the chemical composition of CA-50 steel also plays an important role in defining phase stability and corrosion behavior. Carbon acts as an austenite stabilizer and directly in-

fluences the ferrite–pearlite balance, while Mn contributes to austenite stabilization and pearlite refinement [56,57]. Previous studies demonstrated that increasing carbon content promotes the transition from ferritic to ferritic–pearlitic microstructures, increasing electrochemical heterogeneity and susceptibility to localized corrosion in chloride-containing environments [58]. In pearlitic regions, galvanic coupling between ferrite and cementite accelerates localized anodic dissolution, particularly in NaCl media [58–60].

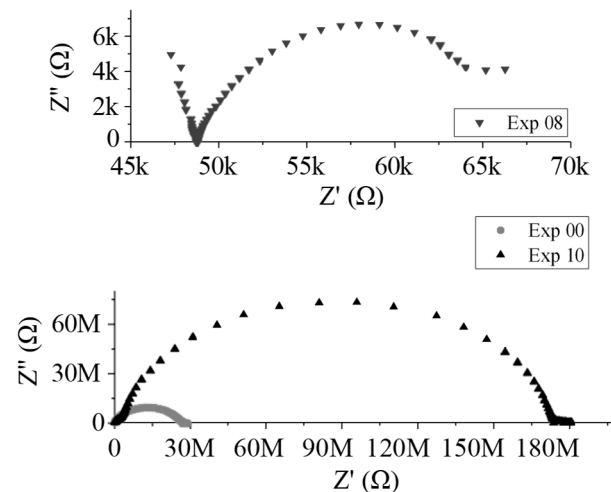


Figure 7. Impedance curves of experiments 0, 8, and 10.

Microalloying elements such as Nb, V, and Ti contribute to grain refinement and precipitation strengthening through the formation of carbides and carbonitrides, promoting more homogeneous microstructures [61,62]. Previous studies have reported that Ti–Nb microalloyed steels may exhibit enhanced passive-film stability and improved corrosion resistance due to grain refinement and reduced galvanic heterogeneity [63,64]. Therefore, the electrochemical differences observed between experiments 8 and 10 may be associated not only with the applied thermal parameters but also with their influence on phase distribution, grain refinement, and local microstructural heterogeneity.

The refined ferritic–pearlitic matrix obtained in experiment 10 minimizes the potential difference between the constituent phases, suppressing the driving force for micro-galvanic cell acceleration [50]. Conversely, the thermal parameters of experiment 8 generated structural heterogeneities and unfavorable phase distributions, triggering the selective dissolution of ferrite around the continuous pearlite lamellae, leading to the observed drop in R_p and acceleration of $i_{(corr)}$ [58]. Rather than acting as isolated features, the grain size reduction and localized phase optimization operate in an integrated manner with stress relief to dictate the final barrier properties [65]. Therefore, the industrial Thermex window applied in experiment 10 achieved an optimized microstructural balance, favoring a continuous and stable electronic barrier against uniform and localized attack.

Although the electrochemical tests were conducted in a 3.5 wt.% NaCl solution, the observed microstructural effects are expected to remain relevant in reinforced concrete environments, since phase distribution, grain refinement, and microstructural heterogeneity also influence passive-film stability and localized corrosion processes in chloride-contaminated concrete pore solutions [66,67]. Nevertheless, the present experimental condition does not fully reproduce the highly alkaline chemistry and transport conditions of real reinforced concrete systems, which should be considered a limitation of the study.

3.5. Initial Characterization of the CA-50 Reinforcing Steel

Before evaluating the influence of the Thermex processing parameters on the corrosion behavior and microstructural evolution of the CA-50 reinforcing steel, the as-received material was characterized by optical microscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS).

The optical micrograph presented in Figure 8a reveals the typical ferritic-pearlitic microstructure commonly reported for low-carbon reinforcing steels. The ferrite phase appears as the lighter regions, whereas the pearlite colonies are observed as darker areas, which is consistent with previous studies on CA-50 and AISI 1020 steels [3,24]. To support the microstructural interpretation obtained by optical microscopy, XRD analysis was performed, and the diffraction pattern is shown in Figure 8b. The diffractogram exhibits characteristic diffraction peaks at approximately 44.7° and 65.0° , corresponding to the (110) and (200) crystallographic planes of α -Fe with a body-centered cubic (BCC) structure. The predominance of α -Fe reflections confirms that ferrite is the main crystalline phase present in the steel. Combined with the optical microscopy observations, these results provide complementary evidence supporting the ferritic-pearlitic microstructure adopted throughout this study.

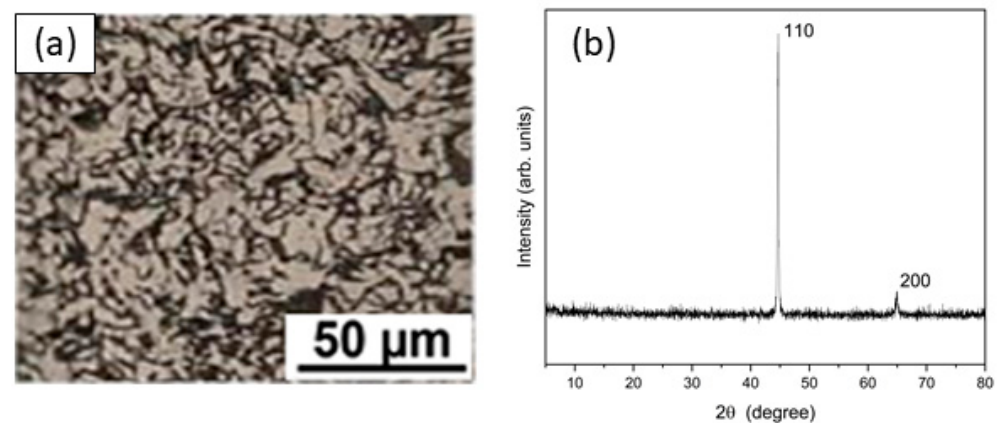


Figure 8. Initial microstructural characterization of the as-received CA-50 reinforcing steel: (a) optical micrograph showing the ferritic-pearlitic microstructure; (b) X-ray diffraction pattern obtained using Cu K α radiation ($\lambda = 1.5418 \text{ \AA}$).

Additional chemical and microstructural characterization was performed using SEM coupled with EDS analysis, as presented in Figure 9. The EDS spectrum and quantitative analysis (Figure 9a) revealed that the analyzed region is predominantly composed of iron, containing approximately 99.7 wt.% Fe and 0.3 wt.% Si. The intense Fe peaks observed at approximately 0.7 and 6.4 keV confirm that iron is the major constituent of the metallic matrix. The low silicon content detected is associated with the steel manufacturing process, since silicon is commonly employed as a deoxidizing element during steel refining and may remain dissolved in the matrix or be associated with non-metallic inclusions [1].

The SEM image shown in Figure 9b was used as the reference area for elemental mapping. The elemental distribution maps presented in Figure 9c reveal a homogeneous distribution of Fe throughout the analyzed region, while Si is detected only in trace amounts. Furthermore, the absence of significant amounts of alloying elements such as Cr, Ni, Mo, and V indicates that the material corresponds to a low-alloy carbon steel, which is consistent with the typical composition of CA-50 reinforcing bars used in reinforced concrete structures. No evidence of significant chemical segregation was observed within the analyzed area, indicating a relatively homogeneous metallic matrix.

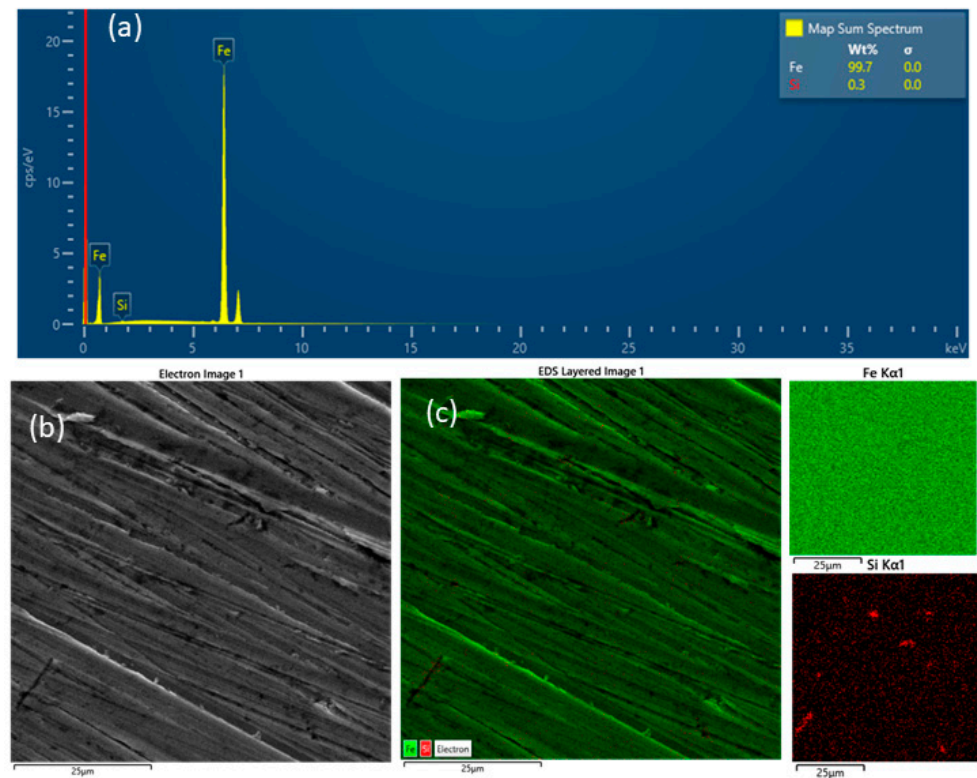


Figure 9. SEM–EDS characterization of the as-received CA-50 reinforcing steel: (a) EDS spectrum and quantitative elemental analysis; (b) SEM micrograph of the analyzed region; (c) elemental mapping showing the distribution of Fe and Si within the analyzed area.

The combined results obtained from optical microscopy, XRD, SEM, and EDS provide complementary evidence supporting the identification of the ferritic-pearlitic microstructure and chemical homogeneity of the CA-50 reinforcing steel. These findings establish the initial microstructural condition of the material and provide a reliable basis for interpreting the microstructural and electrochemical changes discussed in the subsequent sections.

3.6. Surface Characterization After Electrochemical Exposure

To further investigate the surface condition after electrochemical testing, scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) was performed on sample 6 after exposure to the 3.5 wt.% NaCl solution. The results are presented in Figure 10.

The EDS spectrum and quantitative elemental analysis shown in Figure 10a revealed that the analyzed surface region was predominantly composed of iron (97.6 wt.%), together with minor amounts of oxygen (1.9 wt.%) and silicon (0.5 wt.%). The predominance of Fe confirms that the metallic substrate remained exposed within the analyzed area, whereas the presence of oxygen indicates the formation of oxidized surface regions associated with corrosion products generated during electrochemical exposure.

The SEM micrograph presented in Figure 10b reveals the morphology of the analyzed surface after testing. Localized surface irregularities and oxidized regions can be observed, suggesting the development of corrosion products on specific areas of the steel surface. Such features are commonly reported for carbon steels exposed to chloride-containing environments and may influence local electrochemical activity.

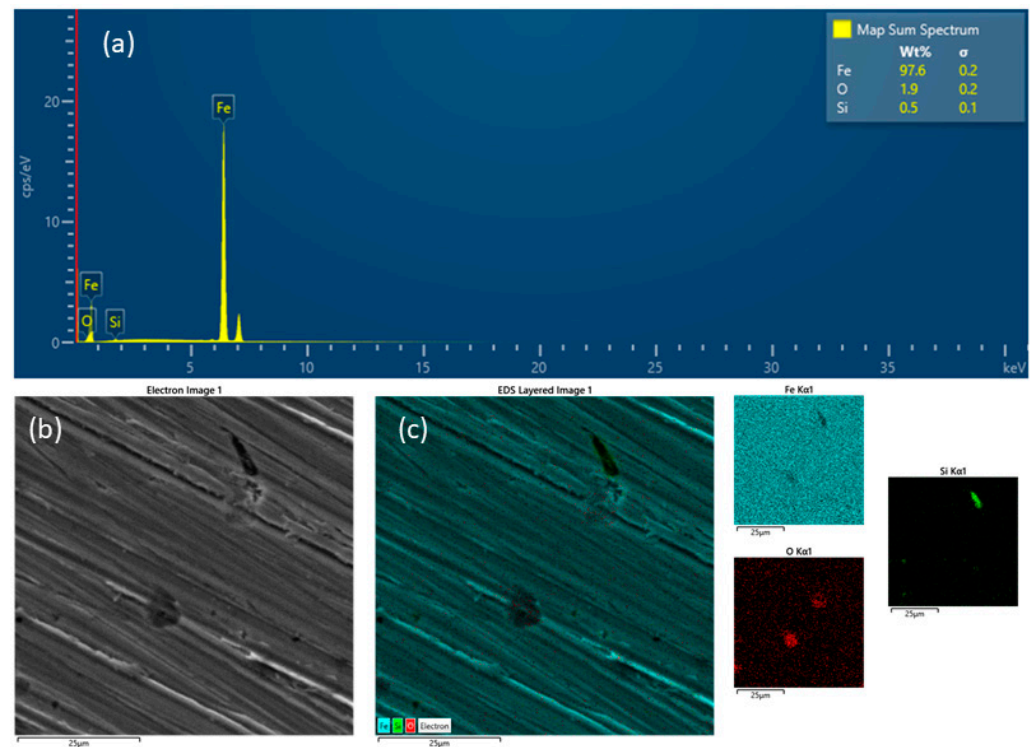


Figure 10. Surface characterization of sample 6 after electrochemical exposure in 3.5 wt.% NaCl solution: (a) EDS spectrum and quantitative elemental analysis; (b) SEM micrograph of the analyzed surface region; (c) elemental distribution maps of Fe, O, and Si.

The elemental distribution maps shown in Figure 10c reveal a relatively homogeneous distribution of Fe throughout the analyzed region, whereas oxygen and silicon are concentrated in localized areas. The localized enrichment of oxygen is consistent with the formation of corrosion products containing iron oxides and oxyhydroxides. In contrast, silicon was detected only in trace amounts and appears associated with isolated regions, possibly related to residual inclusions originating from the steel manufacturing process.

These observations provide additional evidence that corrosion-product films formed during exposure may partially cover the steel surface and contribute to the shielding effect discussed in Section 3.2. Furthermore, the heterogeneous distribution of oxygen-containing regions highlights the localized nature of the corrosion process, which may not be fully captured by electrochemical parameters representing the average response of the exposed surface.

3.7. Morphological Characterization

The microstructural characterization of the CA-50 reinforcing bar (AISI 1020 steel) reveals a strong correlation between thermal processing, the radial core–surface microstructural gradient, and the resulting mechanical and electrochemical performance. This behavior is consistent with that widely reported for TMT/Thermex rebars and low-carbon steels, in which controlled thermomechanical processing produces heterogeneous yet functionally optimized microstructures [68]. In the industrial condition (sample 0), the microstructure exhibits the characteristic gradient associated with the Thermex process, as evidenced in Figure 11(A1–A3), comprising a ferritic–pearlitic core formed under slower cooling conditions (Figure 11(A1)), a transitional region containing bainite and pearlite (Figure 11(A2)), and a refined surface layer with probable lath martensite and/or acicular bainite generated by rapid surface quenching (Figure 11(A3)). This heterogeneous architecture, frequently documented in TMT rebars, combines a hard, wear-resistant outer shell with a more ductile

ferritic–pearlitic core, thereby ensuring a favorable balance between strength and toughness [69]. Optical and scanning electron microscopy studies of normalized and tempered TMT rebars corroborate the presence of fine ferrite–pearlite colonies in the core and refined martensitic matrices at the periphery, in close agreement with the radial microstructural features observed in the CA-50 steel investigated here (Figure 11(A1–A3)) [70]. Numerical and experimental models of hot-rolled bars further support this radial phase distribution, which originates from deformed austenite transforming into martensite or bainite at the surface and ferrite–pearlite in the interior during differential cooling [71].

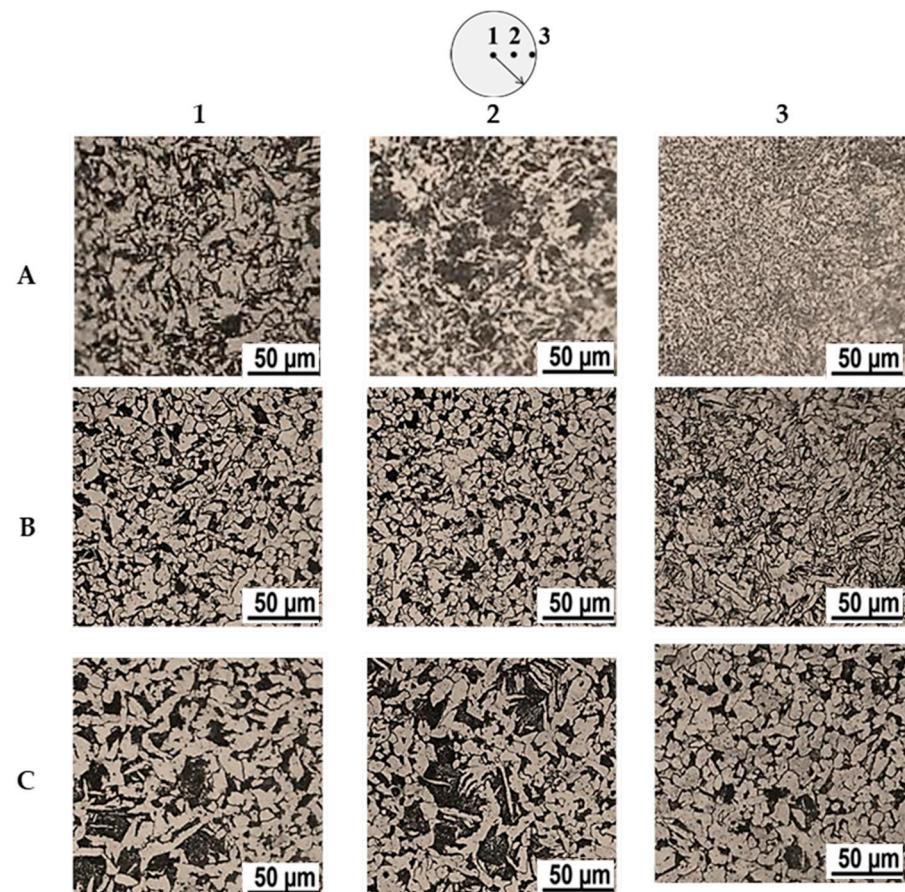


Figure 11. Optical micrographs of CA-50 steel: (A1–A3) industrial condition (experiment 0); (B1–B3) heat-treated sample under experiment 10 conditions ($10\text{ }^{\circ}\text{C min}^{-1}$, $790\text{ }^{\circ}\text{C}$, 25 min); (C1–C3) heat-treated sample under experiment 8 conditions ($15\text{ }^{\circ}\text{C min}^{-1}$, $850\text{ }^{\circ}\text{C}$, 35 min), showing the radial microstructural variation from core (1) to surface (3).

Following thermal treatment under the conditions of experiment 10 ($10\text{ }^{\circ}\text{C min}^{-1}$, $790\text{ }^{\circ}\text{C}$, 25 min), the microstructure evolves toward a more homogeneous morphology across the cross-section, as shown in Figure 11(B1–B3). An increased fraction of equiaxed ferrite, a marked reduction in martensitic and bainitic constituents, and a more uniform grain size distribution from core (Figure 11(B1)) to surface (Figure 11(B3)) are observed. Heating in the range of $780\text{--}800\text{ }^{\circ}\text{C}$ in low-carbon steels promotes partial re-austenitization of pearlite, bainite, and martensite, while the moderate heating rate and limited holding time restrict excessive grain growth. Upon cooling, this results in ferritic–pearlitic microstructures with controlled grain sizes, as widely reported for AISI 1020 and related steels subjected to intercritical annealing or normalization treatments [72]. Similar trends have been documented for TMT rebars normalized at temperatures between 800 and $900\text{ }^{\circ}\text{C}$, where partial homogenization of the core–shell gradient occurs without complete loss of microstructural refinement [68]. Studies on duplex and dual-phase steels further demon-

strate that moderate intercritical treatments can yield ferritic matrices with limited amounts of dispersed martensite or nearly full ferrite–pearlite structures, depending on carbon redistribution and cooling severity [73,74]. The microstructural state achieved in experiment 10 (Figure 11(B1–B3)), characterized by neither excessively fine nor overly coarse grains, is therefore consistent with these findings and provides a plausible explanation for the improved corrosion resistance observed, since relatively homogeneous ferritic–pearlitic microstructures tend to mitigate internal micro-galvanic coupling [75].

In contrast, the microstructure obtained under the conditions of experiment 8 ($15\text{ }^{\circ}\text{C min}^{-1}$, $850\text{ }^{\circ}\text{C}$, 35 min), illustrated in Figure 11(C1–C3), is dominated by markedly coarse and, in some regions, coalesced grains throughout the cross-section. The combination of a higher heating rate, elevated temperature, and prolonged holding time promotes near-complete austenitization, dissolution of precipitates that pin grain boundaries, and accelerated growth of prior-austenite grains, followed by diffusional transformation into coarse ferrite and pearlite during cooling [76]. Numerous studies on low- and medium-carbon steels indicate that above approximately $850\text{--}900\text{ }^{\circ}\text{C}$, grain growth becomes pronounced, leading to increased average grain size and reduced grain boundary density, which adversely affects both mechanical performance and corrosion behavior [77]. In reinforcing steels, post-TMT heat treatments conducted at temperatures close to or above the A_3 line for extended times are known to suppress the beneficial core–shell gradient and produce a relatively uniform yet coarse ferritic–pearlitic microstructure, often associated with reduced strength and increased susceptibility to localized corrosion [68]. The microstructural features observed in experiment 8 (Figure 11(C1–C3)) closely reproduce this behavior.

Taken together, the microstructures of the industrial CA-50 steel (sample 0) and those obtained after the thermal treatments applied in experiments 10 and 8, as evidenced in Figure 11(A1–C3), follow the trends widely reported in the literature for TMT rebars and low-carbon steels. Moderate heating rates, lower intercritical temperatures, and intermediate holding times promote ferritic–pearlitic microstructures with controlled grain size and partial homogenization, whereas higher temperatures and longer residence time lead to extensive grain coarsening and loss of the beneficial radial gradient. These microstructural differences provide a consistent and mechanistically sound explanation for the variations in mechanical properties and corrosion resistance observed in the present study.

Beyond the statistical boundaries, these findings carry significant practical implications for materials and structural engineering. By establishing a data-driven map of the industrial Thermex-processing window for commercial CA-50 steel rebars, this study provides a predictive framework that transcends traditional empirical trial-and-error practices in steel manufacturing plants. Metallurgical engineers and structural designers can utilize these optimized parameters to systematically tailor refined ferritic–pearlitic microstructures. Consequently, this precise microstructural control yields a substantial increase in polarization resistance, directly translating into a slowed thermodynamic degradation rate when these reinforcing bars are embedded in aggressive environments.

4. Conclusions

The results of this study clearly demonstrate the relationship between the evaluated heat-treatment parameters and the corrosion resistance of a low-carbon steel containing approximately 0.2–0.25 wt.% carbon. Complementary characterization by optical microscopy, XRD, SEM, and EDS confirmed the predominance of a ferritic–pearlitic microstructure and the chemical homogeneity of the as-received CA-50 steel. The electrochemical analysis revealed that variations in thermal processing conditions significantly influence the corro-

sion behavior, highlighting the strong coupling between processing, microstructure, and electrochemical response.

Statistical analysis indicated that the residence time (t) and the heating rate (T_x) are the main factors affecting the corrosion potential (E_{corr}), both exhibiting an inverse relationship. Specifically, lower values of residence time and heating rate resulted in more noble E_{corr} values, suggesting enhanced thermodynamic stability of the steel surface under these conditions. This behavior may be associated with the microstructural changes observed after heat treatment, which can influence localized electrochemical activity.

Regarding polarization resistance (R_p), the results showed that residence time (t) is the only statistically significant variable influencing R_p . An inverse relationship was observed, indicating that when the residence time exceeds approximately 25 min, the corrosion resistance tends to decrease. This finding suggests the existence of an optimal temporal window in which the observed microstructural features favor higher resistance to charge transfer and mass transport processes. The empirical modeling demonstrated high predictability, confirming that fine-tuning these processing variables directly dictates the structural and electrochemical performance of the CA-50 steel.

Significant differences in corrosion resistance were observed between the thermally treated samples corresponding to experiments 8 and 10, which presented the worst and best electrochemical performance, respectively. These differences are directly related to their distinct microstructures, reinforcing the role of microstructural morphology in governing corrosion mechanisms. In agreement with literature reports, the results indicate the existence of an optimal grain size distribution range that maximizes corrosion resistance by balancing diffusion pathways, phase stability, and electrochemical homogeneity.

Overall, the findings emphasize the importance of optimizing heat-treatment parameters to improve the control and predictability of corrosion resistance in low-carbon steels. The combined use of electrochemical testing and statistical modeling proved to be an effective approach for identifying dominant factors and establishing reliable structure–property–performance relationships.

From an engineering perspective, the integration of factorial design, Response Surface Methodology (RSM), and electrochemical testing provides a practical, data-driven framework for steel manufacturing plants, enabling the precise optimization of Thermex-processing variables to maximize the service life of CA-50 steel rebars in chloride-rich environments.

From an industrial perspective, the results demonstrate that relatively small adjustments in Thermex-processing parameters, particularly residence time, can substantially affect the corrosion performance and long-term durability of CA-50 steel rebars. The identification of optimized thermal windows may contribute to reducing premature degradation in reinforced concrete structures exposed to chloride-rich environments, potentially lowering maintenance demands and lifecycle costs in civil infrastructure applications.

Although the present study successfully established statistically significant relationships between processing variables and electrochemical behavior, some limitations remain. The investigation was conducted under controlled laboratory conditions using a 3.5 wt.% NaCl solution, which does not fully reproduce the complexity of real reinforced concrete environments. Future studies should incorporate long-term exposure tests, mechanical performance evaluation, residual stress analysis, and simulated concrete pore solutions to further validate the proposed optimization framework under practical service conditions.

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