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Effect of Electrolyte pH Level on the Surface Uniformity of Zinc Electroplating Coatings on AISI 1020 and 1070 Steels

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Abstract

Metal is one of the most frequently found materials in daily life and carbon steel is the most repeatedly used one. Carbon steel is a material that has the main elements in the form of iron and carbon, as well as supporting elements in the form of silicon, phosphorus, sulfur, and manganese. This study will compare the performance of zinc coating on high carbon steel (AISI 1070) and low carbon steel (AISI 1020), which research variables are electrolyte pH and coating quality testing with the corrosion rate method. It concluded that the reduction in the mass of the control specimen (which was not coated with Zn) was 2.83 g for AISI 1070 and for AISI 1020 was 2.69 g. The pH level in the electrolyte did not have a significant effect on the coating process, as evidenced by the Gr1P1S1 specimen (20 minutes, 40°C, pH 4) having an average thickness of 42.8 µm and Gr2P2S1 (20 minutes, 40°C, pH 3) having an average thickness of 43 µm. The electrolyte temperature and process time had a significant effect on the process. The lower the carbon content in carbon steel as a workpiece, the more difficult it would be to accept atoms from the anode/coating metal, as evidenced by the average increase in the mass of high carbon specimens of 0.70556 g compared to low carbon of 0.85333 g. In the test results using the average corrosion rate method, AISI 1070 showed a greater reduction in mass with an average figure of -0.1933 g compared to AISI 1020 at -0.098 g.

Keywords: corrosion; electroplating; pH; Zn; AISI.

1. Introduction

Steel is one of the most widely used metallic materials in industrial applications due to its favorable mechanical properties and cost effectiveness, particularly low and high carbon steels such as AISI 1020 and 1070, which are commonly applied in automotive, marine, and structural components [1]. However, exposure to aggressive environments often leads to corrosion, resulting in material degradation and reduced service life, especially in applications directly interacting with atmospheric and marine conditions [2].

To mitigate corrosion and improve surface performance, various surface engineering techniques have been developed, among which electroplating is widely adopted due to its simplicity, economic feasibility, and effectiveness in enhancing corrosion resistance and surface quality [3]. Zinc (Zn) electroplating has been extensively studied for carbon steels, with previous studies focusing on the effects of process parameters such as plating time, temperature, current density, and anode–cathode distance on coating thickness, adhesion strength, and corrosion resistance [4]-[10]. These studies consistently report that plating time and temperature significantly influence coating characteristics, while substrate material properties also affect Zn deposition behavior. Nevertheless, only limited attention has been given to the role of electrolyte pH, particularly in relation to surface roughness and corrosion performance on steels with different carbon contents. Moreover, comparative investigations between low carbon and high carbon steels under controlled electrolyte pH conditions remain scarce. Therefore, this research focuses on analyzing the effect of electrolyte pH on the surface quality and corrosion behavior of Zn electroplated AISI 1020 and 1070 steels. The objectives of this study are to evaluate coating thickness uniformity, surface quality, and corrosion resistance using gravimetric mass loss measurements

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under controlled electroplating parameters, thereby providing insight into the influence of carbon content and electrolyte pH on Zn electroplating performance.

2. Experimental Methods

2.1. Research Design and Experimental Flow

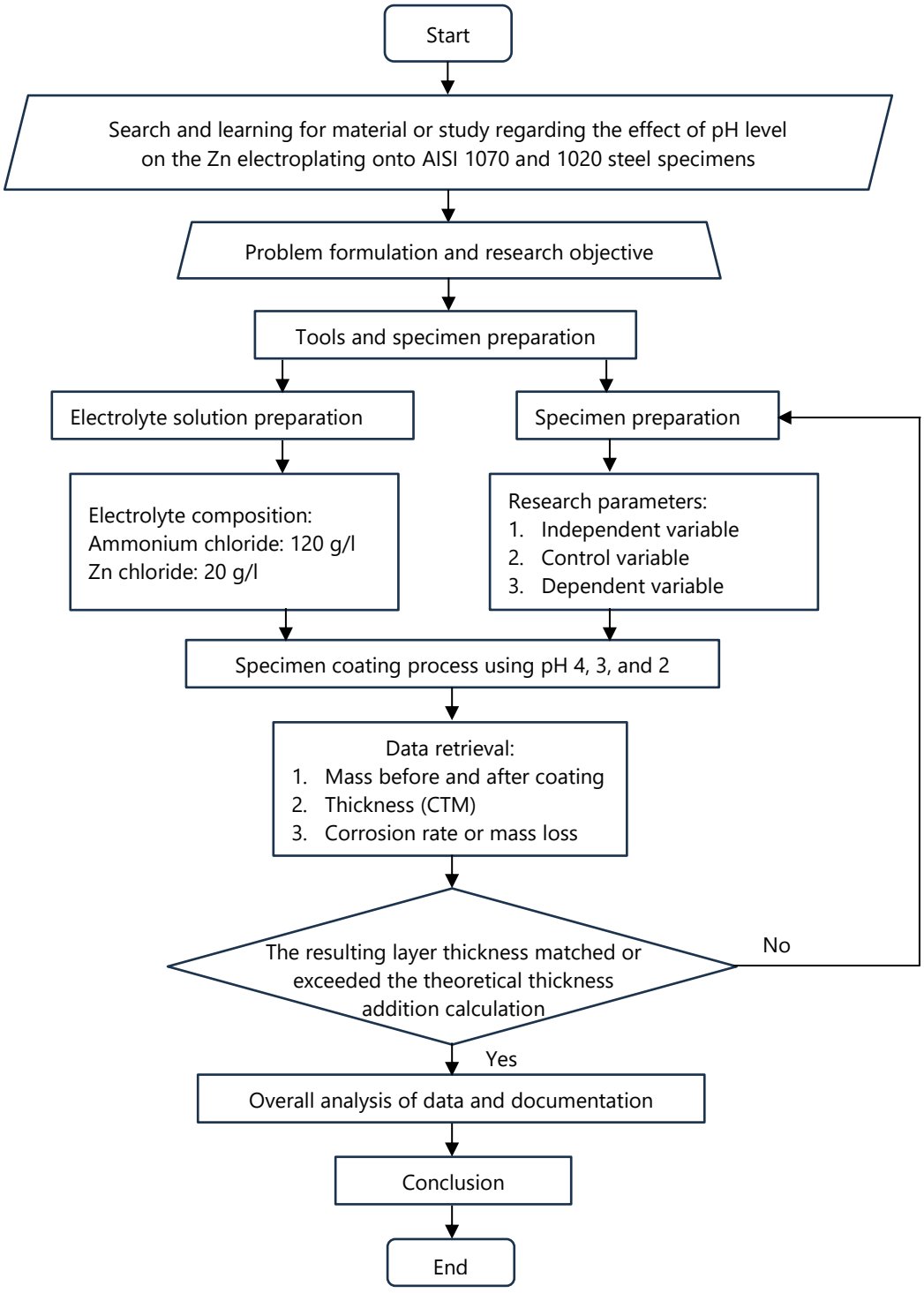

Figure 1. Research flow diagram of electrolyte solution pH effect on the Zn electroplating process

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This research employed an experimental laboratory method to investigate the effect of electrolyte pH on the quality of Zn electroplating layers applied to carbon steel substrates. The experimental workflow consisted of specimen preparation, electrolyte preparation, electroplating process with controlled parameters, coating thickness measurement, and corrosion rate testing. The overall experimental procedure is illustrated in Figure 1, which presents the flow diagram of the research stages.

2.2. Materials and Specimen Preparation

Two types of carbon steel were used as substrate materials, namely AISI 1070 (high carbon steel) and AISI 1020 (low carbon steel). The AISI 1070 specimens were cut into rectangular plates with dimensions of 60±1×40±1×7±1 mm, while the AISI 1020 specimens were prepared with dimensions of 50±1×53±1×5±1 mm. Each specimen was assigned a unique identification code based on the experimental parameters.

Prior to electroplating, all specimens underwent surface preparation procedures, including degreasing using an alkaline degreaser and pickling to remove corrosion products and surface impurities. These procedures were conducted in accordance with ASTM G1 standard. After cleaning, the specimens were rinsed, dried, and weighed to obtain the initial mass (D1).

2.3. Electroplating System and Materials

Figure 2. Conceptual design of the electroplating research apparatus

The electroplating setup consisted of a Zn chloride bath system powered by a direct electric current (DC) adjustable power supply. A conceptual design of the electroplating apparatus is presented in Figure 2. Zn plates were used as the anode, while the steel specimens acted as the cathode.

The electrolyte composition was maintained as follows: ammonium chloride at a concentration of 120 g/L and Zn chloride at 20 g/L, with hydrochloric acid added to adjust the pH of the electrolyte. The materials and equipment used in this study are summarized in Table 1.

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Table 1. Research apparatus and materials

No.	Apparatus	Amount
1	Computer/laptop	1 Device
2	AISI 1070 steel specimens	9 Pcs
3	AISI 1020 steel specimens	9 Pcs
4	Zn plate (40x40 mm)	6 Pcs
5	Zn chloride	2 kg
6	Ammonium chloride	3 kg
7	Distilled water	10 L
8	Solvent (isopropyl alcohol)	3 L
9	Hydrochloric acid 30% (HCl)	1 L
10	Alkaline degreaser	500 mL
11	Tissue	2 Pack
12	Digital balance (0.1 g resolution)	1 Pcs
13	Plastic container	450 mL
14	Plastic tank (4L)	1 Pcs
15	Control panel	1 Set
16	Heating element 450W	1 Pcs
17	Thermocouple type K	1 Pcs
18	DC adjustable power supply (30V 10A)	1 Pcs
19	Coating thickness gauge	2 Pcs
20	Digital vernier caliper	1 Pcs

2.4. Experimental Parameters

The electroplating process was conducted under controlled experimental parameters. The independent variables included immersion time (20, 40, and 60 minutes), electrolyte temperature (40, 50, and 60°C), and electrolyte pH values (4, 3, and 2). The electric current was maintained constant at 3.16 A, and the electrolyte composition was kept unchanged throughout the experiments.

Table 2. Research parameters and unique specimen codes

Immersion time (minutes)	Electrolyte temperature (°C)	Electrolyte pH	Unique specimen code
20	40	4	Gr1P1S1
40	50	4	Gr1P1S2
60	60	4	Gr1P1S3
20	40	3	Gr2P2S1
40	50	3	Gr2P2S2
60	60	3	Gr2P2S3
20	40	2	Gr3P3S1
40	50	2	Gr3P3S2
60	60	2	Gr3P3S3

The dependent variables evaluated in this study were coating thickness and corrosion rate, while the substrate material (AISI 1020 and 1070) served as a comparative parameter. The detailed parameter combinations and specimen coding system are presented in Table 2.

2.5. Electroplating Procedure

The electroplating process was carried out by suspending the steel specimens at the cathode (negative terminal) and the Zn plates at the anode (positive terminal) of the DC power supply. The electrolyte bath temperature and pH were adjusted according to the predetermined parameters. After completion of the electroplating process, the specimens were rinsed with distilled water, dried, and weighed to obtain the post-plating mass (D2).

Konversi Energi dan Manufaktur
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Coating thickness measurements were conducted at five different points on each specimen surface using a coating thickness gauge. The measurement locations for AISI 1070 and 1020 specimens are illustrated in Figure 3 (a) and (b), respectively.

(a) (b)

Figure 3. Thickness measurement points on: (a) AISI 1070 steel and (b) AISI 1020 steel

2.6. Corrosion Testing Method

To evaluate coating quality, corrosion testing was performed using a gravimetric mass loss method. The specimens were exposed to a salt mist spray environment using seawater collected from a coastal pier to accelerate the corrosion process. The exposure was conducted for six days with spraying intervals of approximately five hours.

After completion of the corrosion test, the specimens were cleaned and weighed to obtain the final mass (D3). The corrosion rate was determined based on mass loss measurements, following ASTM G85 standard for coating quality evaluation.

2.7. Data Processing and Analysis

Data processing and analysis were conducted to evaluate the effect of electrolyte pH on coating uniformity, thickness, and corrosion resistance of Zn electroplated layers on AISI 1020 and 1070 steels. The collected data consisted of specimen mass, dimensions, coating thickness, and mass loss before and after corrosion testing. Measurements were performed at several stages, including after pickling and degreasing, after electroplating, and after corrosion exposure.

The electrical parameters used during the electroplating process were determined using Ohm's law to ensure a stable and controlled current supply [1]. The applied current was calculated based on the measured voltage and electrical resistance of the system, as expressed in the following equation [1].

$$I = \frac{V}{R} \tag{1}$$

where I is the electric current (A), V is the applied voltage (V), and R is the electrical resistance (Ω).

The electroplating process was further analyzed using current density, which represents the distribution of electric current over the effective surface area of the specimen [1]. Current density is a critical parameter influencing coating thickness and uniformity. The current density was calculated using the following equation [1].

$$J = \frac{I}{A} \tag{2}$$

where J is the current density (A/cm^2), I is the applied current (A), and A is the effective surface area of the specimen (cm^2). The effective surface area of the specimen was determined based on its geometric dimensions using the following equation [1].

$$A = 2(lw + lt + wt) \tag{3}$$

where l is the length (cm), w is the width (cm), and t is the thickness of the specimen (cm).

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The average coating thickness was initially evaluated using the mass difference method, which considers the increase in specimen mass after electroplating and the density of the coating material [11]. This method provides a representative estimation of the deposited Zn layer over the specimen surface. The average coating thickness was calculated using the following equation [11].

$$\delta_{avg} = \frac{\Delta m}{\rho \cdot A} \quad (4)$$

where δ_{avg} is the average coating thickness (cm), Δm is the mass difference before and after electroplating (g), ρ is the density of Zn (g/cm^3), and A is the surface area of the specimen (cm^2).

To support the thickness analysis, the volume of the deposited Zn layer was calculated using the following equation [11].

$$V = \frac{\Delta m}{\rho} \quad (5)$$

where V is the coating volume (cm^3), Δm is the mass increase due to electroplating (g), and ρ is the density of Zn (g/cm^3). The theoretical coating thickness was then determined by correlating the coating volume with the surface area of the specimen, as expressed in the following equation [11].

$$\delta = \frac{V}{A} \quad (6)$$

Corrosion resistance of the electroplated specimens was evaluated using the gravimetric mass loss method. This method assesses the degradation of material by measuring the mass reduction after immersion in a corrosive medium for a specified duration. The corrosion rate was calculated using the following equation [6].

$$CR = \frac{\Delta m}{A \cdot t} \quad (7)$$

where CR is the corrosion rate (g/cm^2·h), Δm is the mass loss after corrosion testing (g), A is the exposed surface area (cm^2), and t is the immersion time (h). The corrosion rate results were used to compare the protective performance of Zn coatings formed under different electrolyte pH conditions on AISI 1020 and 1070 steels.

3. Results and Discussion

This section presents and discusses the experimental results obtained from Zn electroplating on AISI 1020 (low carbon steel) and AISI 1070 (high carbon steel). The discussion integrates coating thickness, coating uniformity, mass gain during electroplating, and corrosion rate performance under varying electrolyte pH conditions.

3.1. Effect of Electrolyte pH on Zn Coating Thickness

The specimen, after coating, is further illustrated in Figure 4. It can be seen that these specimens are fully coated with Zn.

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Figure 4. Specimen conditions after the coating process (Left: AISI 1020; Right: AISI 1070)

The coating thickness measurements obtained using a coating thickness gauge for AISI 1070 and 1020 specimens are summarized in Tables 3 and 4. The coating thickness values were measured at multiple points (see Figure 3) on each specimen under different electrolyte pH conditions.

Table 3. Coating thickness measurement results (AISI 1020 steel)

Sample	Spot thickness (µm)					Average (µm)
	1	2	3	4	5	
Gr1P1S1	50	57	39	57	11	42.8
Gr1P1S2	43	15	35	0	0	18.6
Gr1P1S3	172	148	269	50	199	167.6
Gr2P2S1	39	47	41	43	45	43
Gr2P2S2	94	93	55	76	14	66.4
Gr2P2S3	63	92	114	95	11	75
Gr3P3S1	41	31	10	41	6	25.8
Gr3P3S2	37	0	30	20	19	21.2
Gr3P3S3	125	130	80	153	111	119.8

Table 4. Coating thickness measurement results (AISI 1070 steel)

Sample	Spot thickness (µm)					Average (µm)
	1	2	3	4	5	
Gr1P1S1	36	28	35	28	34	32.2
Gr1P1S2	113	19	77	69	38	63.2
Gr1P1S3	116	94	91	147	116	112.8
Gr2P2S1	14	21	15	9	14	14.2
Gr2P2S2	46	43	104	0	33	45.2
Gr2P2S3	42	51	78	72	64	61.4
Gr3P3S1	19	26	0	83	30	31.6
Gr3P3S2	132	152	111	118	157	134
Gr3P3S3	58	51	59	161	15	68.8

According to Tables 3 and 4, generally, an increase in plating time and temperature leads to an increase in Zn film thickness. Mascenik et al. [12] have found that increasing Zn plating time leads to an increase in film thickness. Moreover, Pratiwi et al. [10] have stated that increasing the plating bath temperature promotes an increase in Zn film thickness. Both conditions influence ion movement more rapidly; therefore, the film thickness increases [13].

At an electroplating temperature of 40°C and a processing time of 20 minutes, the coating thickness values obtained at pH 3 and 4 are comparable, indicating that electrolyte pH does not play a dominant role in controlling coating thickness under these conditions. This finding is consistent with previous studies reporting that

Konversi Energi dan Manufaktur
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Jurnal Konversi Energi dan Manufaktur
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Website : http://journal.unj.ac.id/unj/index.php/jkem
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deposition time and current density have a stronger influence on Zn layer growth than moderate variations in electrolyte pH [10], [14].

3.2. Coating Uniformity Analysis

Coating uniformity was evaluated using the average coating thickness data calculated from multiple measurement points on each specimen. The average thickness values for high-carbon and low-carbon steels after electroplating (D2 condition) are presented in Tables 5 and 6.

Table 5. Average coating thickness of high-carbon steel (D2)

Specimen thickness (µm)								
Gr1P1S1	**Gr1P1S2**	**Gr1P1S3**	**Gr2P2S1**	**Gr2P2S2**	**Gr2P2S3**	**Gr3P3S1**	**Gr3P3S2**	**Gr3P3S3**
32.2	63.2	112.8	14.6	45.2	61.4	31.6	134	68.8

Table 6. Average coating thickness of low-carbon steel (D2)

Specimen thickness (µm)								
Gr1P1S1	**Gr1P1S2**	**Gr1P1S3**	**Gr2P2S1**	**Gr2P2S2**	**Gr2P2S3**	**Gr3P3S1**	**Gr3P3S2**	**Gr3P3S3**
42.8	18.6	167.6	43	66.4	75	25.8	21.2	119.8

Visual inspection of the coated specimens, as shown in Figure 5, indicates that AISI 1070 specimens tend to exhibit a more uniform surface appearance compared to AISI 1020 specimens under identical electroplating conditions.

Figure 5. Specimen conditions after the pickling process (Left: AISI 1020; Right: AISI 1070)

The higher uniformity observed on AISI 1070 steel may be attributed to differences in surface reactivity and carbon content, which influence Zn ion adsorption during the electroplating process. Similar observations have been reported by Ansari et al. [14], who highlighted the role of substrate properties in determining coating morphology.

3.3. Mass Gain After Electroplating

The mass changes of the specimens before and after electroplating were measured using a digital balance and are presented in Tables 7 and 8.

Table 7. Mass increase of high-carbon steel specimens (D2)

Specimen mass (g)								
Gr1P1S1	**Gr1P1S2**	**Gr1P1S3**	**Gr2P2S1**	**Gr2P2S2**	**Gr2P2S3**	**Gr3P3S1**	**Gr3P3S2**	**Gr3P3S3**
+0.06	+0.96	+1.14	+0.24	+0.18	+1.13	+0.25	+1.16	+1.24

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Table 8. Mass increase of low-carbon steel specimens (D2)

Specimen mass (g)								
Gr1P1S1	**Gr1P1S2**	**Gr1P1S3**	**Gr2P2S1**	**Gr2P2S2**	**Gr2P2S3**	**Gr3P3S1**	**Gr3P3S2**	**Gr3P3S3**
+0.05	+0.92	+1.36	+0.1	+1.1	+1.31	+0.46	+0.89	+1.49

The results indicate that AISI 1020 specimens experienced a higher average mass gain compared to AISI 1070 specimens. This suggests that low-carbon steel tends to accumulate a greater amount of Zn during electroplating. However, a higher mass gain does not necessarily imply better coating uniformity, as discussed in Sub-section 3.2.

To further clarify the distribution of mass gain across different electroplating conditions, the comparative results are needed. Figure 6 illustrates the variation in mass increase for both high-carbon steel (AISI 1070) and low-carbon steel (AISI 1020) specimens under identical process parameters, represented by specimen codes Gr1PS, Gr2PS, and Gr3PS. This representation enables a clearer comparison of Zn deposition behavior as a function of processing time and temperature.

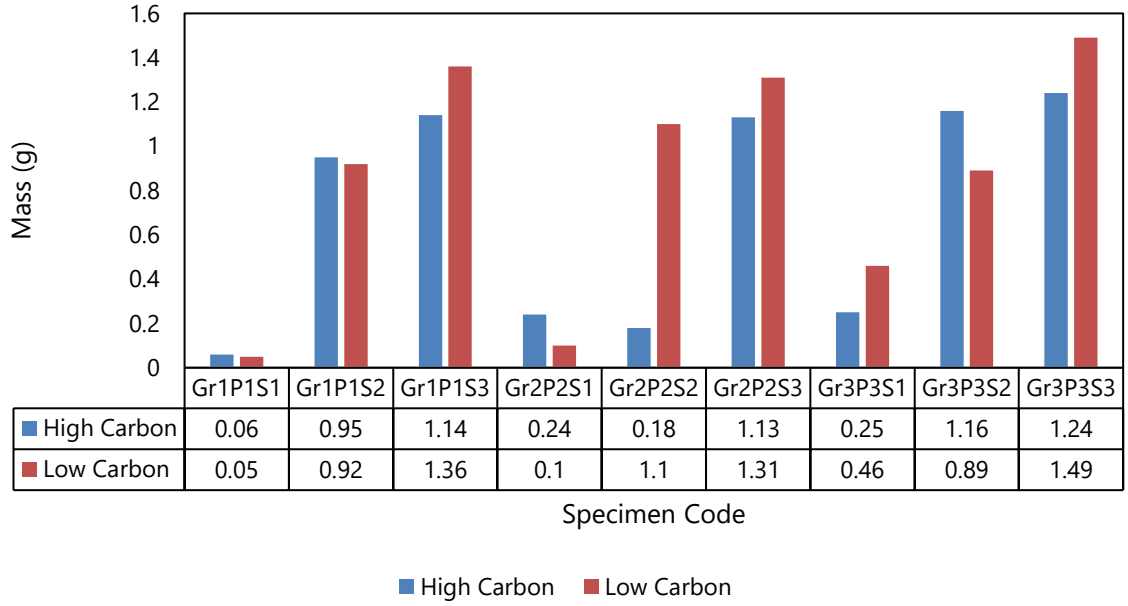

Figure 6. Mass gain of high-carbon and low-carbon steel specimens after electroplating under various process conditions

The observed mass gain trends are consistent with the current density and surface area calculations performed during data processing, where mass increase is directly related to the amount of Zn deposited on the cathode surface, as expressed by Faraday-based deposition principles [11].

3.4. Corrosion Rate Performance

The corrosion resistance of the electroplated and uncoated specimens was evaluated using the gravimetric mass loss method using equation (7). The mass values of the specimens after corrosion testing are summarized in Tables 9 and 10.

Table 9. Mass (W_t) of AISI 1070 (high-carbon steel) specimens after corrosion rate testing

Specimen mass (g)								
Gr1P1S1	**Gr1P1S2**	**Gr1P1S3**	**Gr2P2S1**	**Gr2P2S2**	**Gr2P2S3**	**Gr3P3S1**	**Gr3P3S2**	**Gr3P3S3**
136.83	134.27	131.67	133.38	131.22	142.05	128.1	134.66	132.28

Konversi Energi dan Manufaktur
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Jurnal Konversi Energi dan Manufaktur
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Table 10. Mass (W_t) of AISI 1020 (low-carbon steel) specimens after corrosion rate testing

Specimen mass (g)								
Gr1P1S1	**Gr1P1S2**	**Gr1P1S3**	**Gr2P2S1**	**Gr2P2S2**	**Gr2P2S3**	**Gr3P3S1**	**Gr3P3S2**	**Gr3P3S3**
86.65	91.04	88.28	90.24	90.2	91.52	91.71	92.18	89.78

Figure 7. Specimen conditions after the pickling process (Left: AISI 1020; Right: AISI 1070)

The visual condition of the specimens before and after corrosion testing is shown in Figure 7. To provide a clearer comparison of corrosion behavior between high-carbon and low-carbon steel specimens under different electroplating conditions, the calculated mass loss results need to be visualized. Figure 8 presents the corrosion-induced mass reduction of both AISI 1020 and 1070 specimens across all specimen codes, enabling direct evaluation of the effectiveness of Zn electroplating and the influence of material composition on corrosion performance.

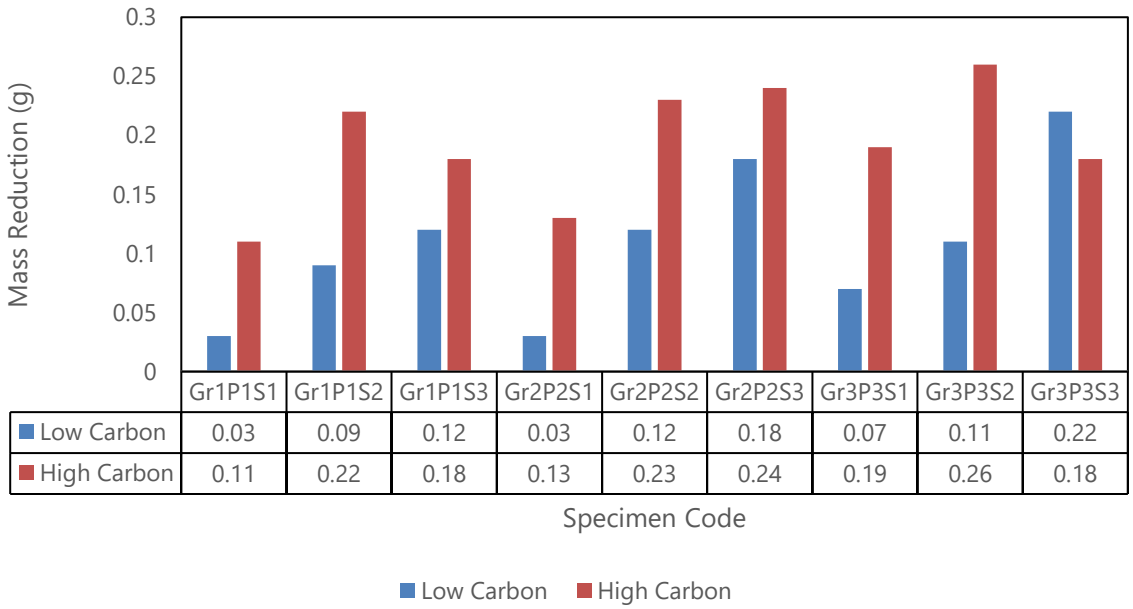

Figure 8. Corrosion-induced mass loss of Zn-coated AISI 1020 and 1070 specimens under various electroplating conditions

As shown in Figure 8, AISI 1070 consistently shows greater mass loss compared to AISI 1020, indicating a higher corrosion rate. This behavior is associated with the higher carbon content of AISI 1070, which influences microstructural heterogeneity and promotes localized corrosion [15]-[18]. The observed trends align well with previous studies reported by Sandi et al. [19] and Lintang et al. [20], confirming the protective role of Zn electroplating and the material-dependent nature of corrosion performance.

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4. Conclusion

This study clarifies the relative influence of electrolyte pH, process parameters, and base material characteristics on Zn electroplating performance for low carbon steel (AISI 1020) and high carbon steel (AISI 1070). The results demonstrate that within the acidic pH range investigated, electrolyte pH does not significantly affect coating thickness uniformity compared to immersion time and electrolyte temperature, which are identified as the dominant parameters governing Zn deposition and mass gain. It was proven that by Gr1P1S1 specimen (20 minutes, 40°C, pH 4) has an average thickness of 42.8 µm and Gr2P2S1 (20 minutes, 40°C, pH 3) has an average thickness of 43 µm.

The findings further show that low carbon steel exhibits a greater tendency to accept Zn ions during electrodeposition. Higher average mass gain was proven by the average increase in mass of high carbon specimens is 0.70556 g compared to low carbon 0.85333 g. Meanwhile, gravimetric corrosion testing confirms that Zn electroplating effectively improves corrosion resistance for both materials, with observable differences linked to carbon content. The average corrosion rate of high carbon steel (AISI 1070) has a greater mass reduction with an average figure of -0.1933 g compared to low carbon steel (AISI 1020) at -0.098 g. Suggestions for further study are expanding the range of research variables, for example, the pH of basic electrolytes (more than 7) compared to acidic ones (less than 7) and using a scanning electron microscope (SEM) method that can be applied to observe the thickness and evenness of the coating on a microscale.

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