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Influence of current density in Cu-Mn electroplating of AISI 1020 steel corrosion rate

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ABSTRACT

AISI 1020 steel is widely applied as the primary material for construction and piping systems on ships. This research was conducted to investigate the effect of electroplating Cu-Mn current density on the corrosion rate of AISI 1020 steel in a 3% NaCl corrosive medium. Corrosion rate testing was carried out using the weight loss method with the immersion of samples in a corrosive NaCl medium for 168 h and variations in current densities of 35, 45, 55, 65, and 75 mA/cm^2. The results showed that the higher current density applied to the lower corrosion rate. This is because an increase in electroplating current density will also increase Cu and Mn ions deposited in steel, where deposits of these ions will improve the corrosion resistance of steel. The lowest corrosion rate was obtained at 0,053 mm/y at a current density of 75 mA/cm2. XRD characterization results showed that peaks formed at current densities of 35 mA/cm^2 are almost the same as the results of steel characterization after electroplating current density of 75 mA/cm^2 a lower intensity. The metallurgical microscope analysis results showed that the formed layer is thicker with increasing electroplating current density.

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1. Introduction

Steel is a significant factor that is very important for the development of a nation's industry. All aspects of life, ranging from household equipment, necessary materials in industrial equipment, bridge construction, buildings, and ships using steel as the main basic material [1]. However, steel has a very reactive weakness and has a high tendency to be attacked by corrosion when in the air, aqueous environment, or acidic media [2]. Corrosion or better known as rust is an event of damage to a metal that occurs due to metallurgical factors and the result of environmental influences to reduce the quality of the metal material [3]. Electroplating is a method of coating the surface of a material that occurs in an electrolyte solution by an electric current flowing through the anode to the specimen that functions as a cathode [4]. The advantages of this method include: the process that occurs is quite simple, has high selectivity, and has a good throwing power [5]. One type of metal coating that can be done is by using a sacrificial anode [6]. Manganese metal has a minimal standard reduction potential so that it can be used as a sacrificial anode from steel. Manganese metal has several advantages, which are environmentally friendly, have a low coefficient of friction, excellent mechanical properties, and relatively cheap [7]. However, chemically pure manganese has high reactivity and brittle properties [8]. It needs to be combined with other metals such as zinc [9] copper or tin to reduce internal stress and improve corrosion resistance [2].

Gong and Zangari's research [7] shows that Mn's brittle nature is the result of changes in the manganese deposition phase at room temperature, from γ-Mn ductile to the α-Mn brittle phase. This phase change can be prevented effectively by the addition of copper (Cu) [8]. Copper (Cu) and its alloys are widely used in many environments and applications because of their excellent stability and corrosion resistance [9]. The addition of a small amount of copper to the manganese electroplating process can inhibit the rate of oxidation in the corrosive medium of 3% NaCl, thereby increasing the corrosion resistance of the manganese layer [10]. Triastuti and Purwanto (2012) [11] examined the effect of adding tartrate

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ions to Cu-Mn electrodeposition in carbon steel pipes. The results showed that the corrosion rate of Cu-Mn by electrodeposition results with tartrate ions was lower than without the addition of tartrate ions used a potassium periodate base solution in the Cu-Mn electrodeposition process to minimize galvanic corrosion at the interface layer [12]. Research on manganese's physical characteristics and corrosion from coatings on low carbon steel shows that steels with manganese coatings have decreased corrosion rates by 68–81%. In comparison, steels with manganese and copper coatings can reduce corrosion rates from 92 to 98% [13].

In this research, the steel used is AISI 1020 steel, widely applied as the primary material of construction and piping systems for ships. AISI 1020 steel was electroplated with variations in current density and electroplating time using an electrolyte solution containing Cu^{2+} and Mn^{2+} ions to form a Cu-Mn layer. Then the steel was immersed in 3% NaCl corrosive medium with a soaking time of 168 h. Electroplating steel samples and corrosion tests will be characterized by X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD).

2. Methods

The work procedure of Cu-Mn electroplating process as well as carrying out experimental procedures to see the rate of corrosion of steel that has been electroplated.

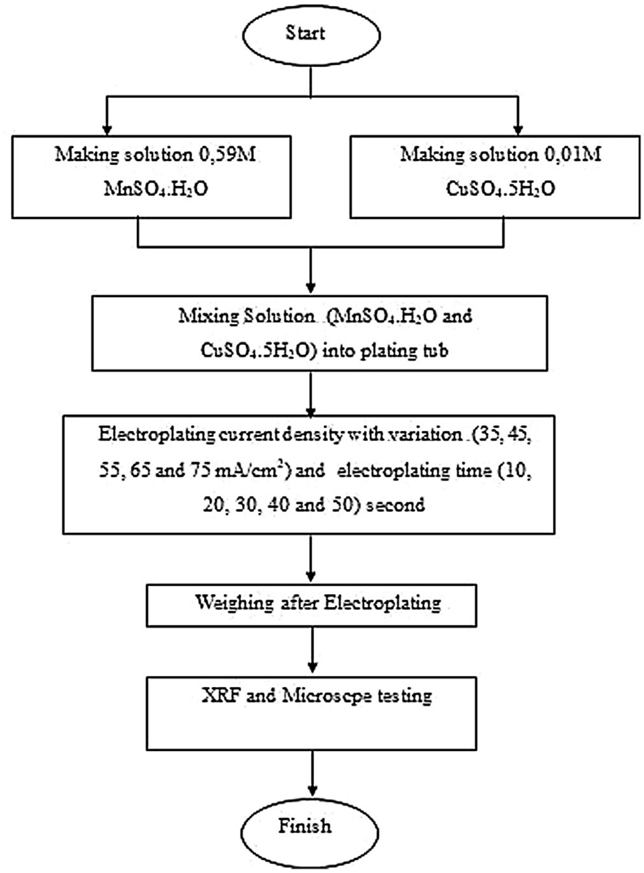

Fig. 1. Methods to Determine the corrosion rate.

3. Results and discussions

Electroplating steel will also experience changes in the contents of its constituent elements. This change can be known by using portable XRF. The following Table 1 shows the change in content in the form of percentage weight (% wt) of the steel constituent elements before and after electroplating the results of the portable XRF analysis.

Electroplating with variations in current density conducted to determine the effect of electroplating current density on the elements contained in steel after electroplating and the corrosion rate of steel. The electroplating process is carried out with variations in the current density of 35, 45, 55, 65, and 75 mA/cm^2 for 50 s. Data on the results of AISI 1020 steel electroplating with variations in current density are presented in Table 1.

Deposit weight increases in steel weight after electroplating, i.e., the difference in weight of steel after electroplating with the weight of steel before electroplating. The relationship between electroplating current density and the weight of sludge produced is shown in Fig. 1.

Fig. 2 shows the effect of current density and the weight of the sediment. As shown in Fig. 2, the weight of sludge produced in steel after electroplating increases with increasing current density applied to the electroplating process. The most massive sediment weight was obtained at a current density of 75 mA/cm^2, which was 0.0381 gr. The research results of Supriadi et al. [10] also showed similar results. His research on the copper electroplating

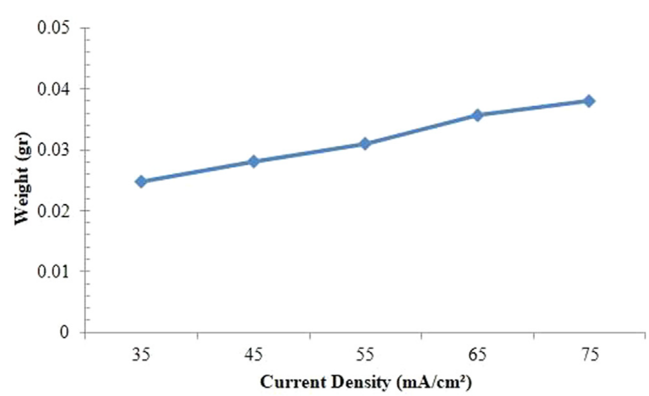

Fig. 2. The effect of current density on sediment weight.

Table 1
Electroplating research data with variations in current density.

No	Current Density (mA/cm2)	Initial Weight (gram)	Final Weight(gram)	Sediment Weight(gram)
1	35	78.9509	78.9757	0.0232
2	45	77.2423	77.2704	0.0281
3	55	85.9888	86.0198	0.0310
4	65	79.3968	79.4325	0.0357
5	75	81.1417	81.1798	0.0381

Table 2
XRF analysis of steel before and after electroplating with variation in current density.

No	Current Density(mA/cm2)	Before electroplating (%wt)			After electroplating (%wt)				
		Fe	Si	Mn	Fe	Si	Mn	S	Cu
1	10	99.51	0.33	0.15	87.78	0.015	2.58	5.77	0.28
2	20	99.51	0.34	0.14	87.92	0.20	2.66	8.69	0.30
3	30	99.48	0.39	0.13	86.5	0.16	3.03	9.78	0.31
4	40	99.47	0.38	0.14	85.8	0.25	3.20	10.2	0.32
5	50	99.44	0.41	0.14	88.46	0.08	3.25	7.59	0.325

Table 3
The research data is corrosion rate with variations in electroplating current density.

Current Density(mA/cm2)	A(cm^2)	Initial Weight(gram)	Final Weight(gram)	Δm (gr)	Corrosion rate(mmpy)
35	27.90	78.9757	78.9344	0.0413	0.098
45	27.92	77.2704	77.2315	0.0389	0.092
55	27.87	86.0198	85.9878	0.032	0.076
65	27.80	79.4325	79.4047	0.0278	0.066
75	28.04	81.1798	81.1571	0.0227	0.053

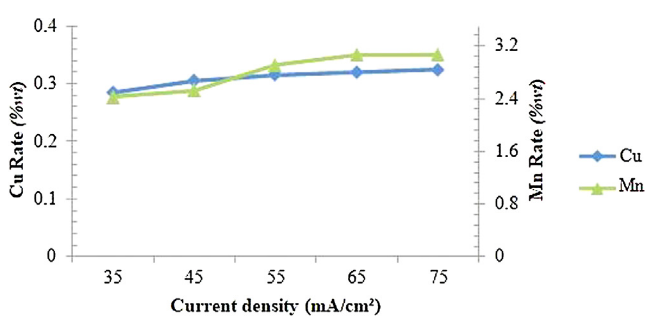

Fig. 3. Effect of electroplating current density on Cu and Mn contents.

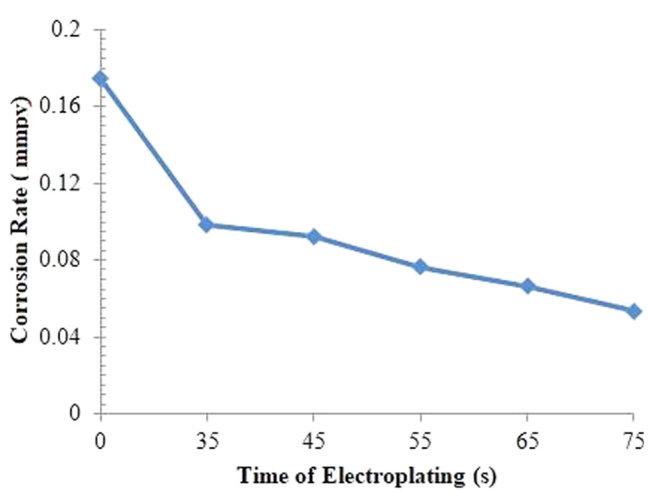

Fig. 4. Effect of electroplating current density on the rate of corrosion.

process was carried out with variations in current density on medium carbon steel. His research results showed that the higher the density of electroplating currents applied would result in the weight of the steel after electroplating had increased. According to Ndariyono [14], this happens because the increasing current density used in the coating process increases in energy, accelerating the release of electron ions. This condition accelerates the movement of electrons from positive ions to negative ions so that the ions that settle on the surface of the steel will increase and subsequently have an impact on increasing the weight of sludge produced on the steel surface.

After the electroplating process, the steel is then analyzed using XRF portable to determine changes in the levels of the constituent elements of steel after electroplating. The results of the analysis of AISI 1020 steel elements before and after electroplating with variations in current density using portable XRF are shown in Table 2.

Table 2 shows the change in contents of the AISI 1020 steel constituent elements after the electroplating process with variations in current density. Based on Table 3, it can be said that after the electroplating process, Mn contents have increased. In addition, it is the same as in the electroplating process with time variations. In the electroplating process with variations in current density, there is also the Cu element in the electroplating steel. This is because the electrolyte solution used contains copper ions (Cu^{2+}); therefore, during the electroplating process, Cu ions settle to the cathode in this case steel. The effect of current density used in the electroplating process on increasing contents of Cu and Mn steel can be seen in Fig. 2.

Fig. 3 displays a graph of the relationship of current density to increase the contents of Cu and Mn in steel after the electroplating process. Fig. 3 shows that the contents of Cu and Mn increase with increasing current density used in the electroplating process. This is because an increase in current density will also increase energy, which will accelerate the movement of ions toward the surface of the cathode (steel) so that the Cu and Mn ions that settle on the surface of the cathode will be even higher (Ndariyono, 2011). According to Gong and Zangari (2004), in the electroplating process of manganese and copper, an electron transfer mechanism occurs. The reaction that occurs in the manganese and copper coating process is as follows.

$$\tfrac{1}{2}\,O_2 + 2H_2O + 2e^- \rightarrow 2OH \quad (1)$$

$$Mn^{2+} + 2OH^- \rightarrow Mn(OH)_2 \quad (2)$$

$$Cu^{2+} + 2OH^- \rightarrow Cu(OH)_2 \quad (3)$$

Based on reactions (1)-(3), it can be seen that oxygen reacts with water to form hydroxyl ions (OH^-). Then these hydroxyl ions react with Mn^{2+} and Cu^{2+} ions from the electrolyte solution used to form the $Mn(OH)_2$ and Cu $(OH)_2$ layers at the cathode. Based on voltaic series, Cu metal has a more positive reduction potential than Mn metal so that Cu metal is more easily reduced and

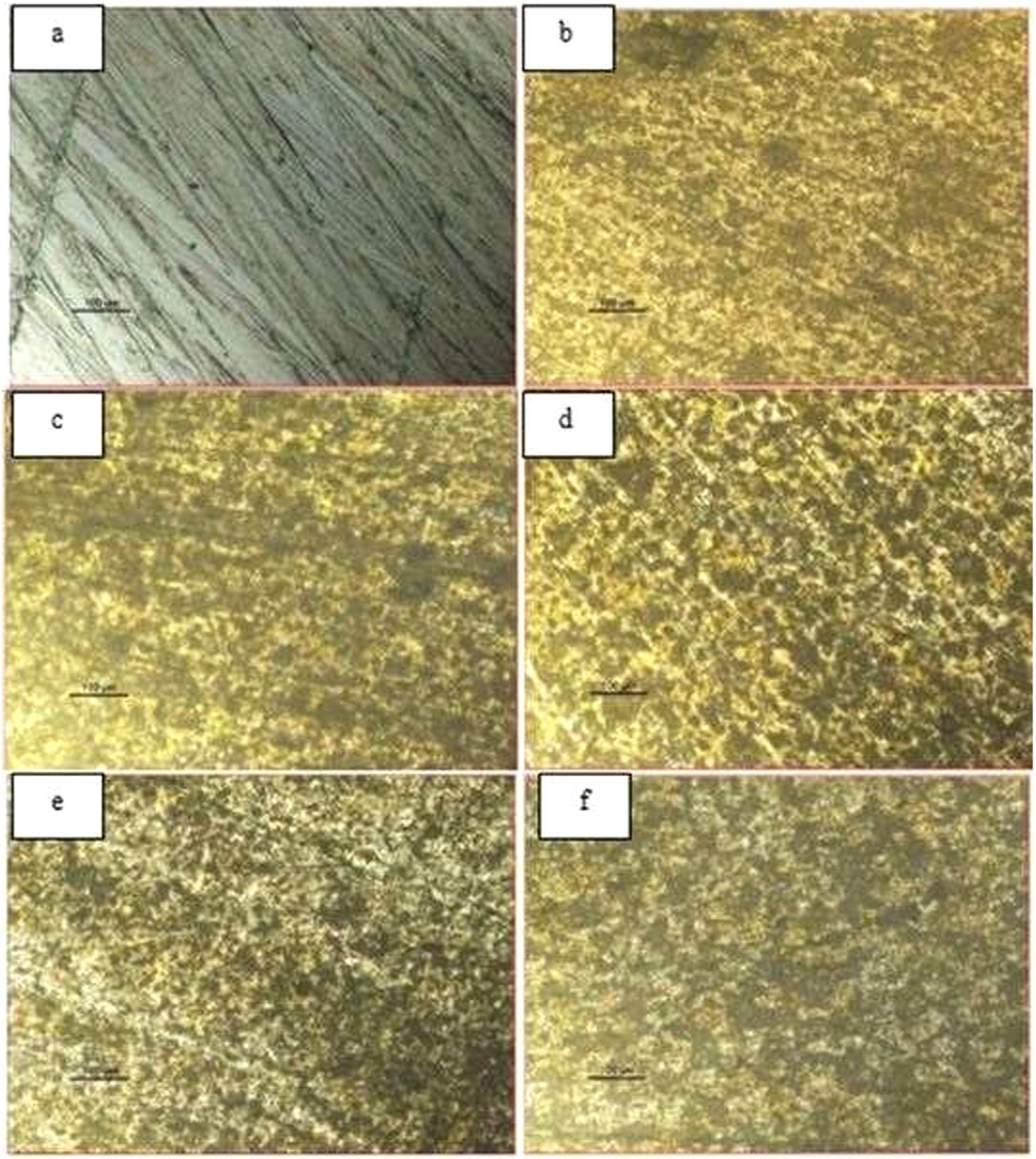

Fig. 5. Analysis of AISI 1020 steel metallurgical microscopy results from electroplating at 50 s and current density (a) 0; (b) 35; (c) 45; (d) 55; (e) 65; and (f) 75 mA/cm^2 with a magnification of 100x.

attaches to the cathode. Electroplating current density also affects the rate of corrosion of the coating steel. The research data on corrosion rates for coating results with variations in the electroplating current density are presented in Table 3.

Table 3 presents research data on corrosion rates for AISI 1020 steel resulting from electroplating with variations in current density. In Table 3, it can be seen that an increase in electroplating current density results in a decrease in sample weight (Δm). This weight reduction occurs due to erosion of the steel layer after being immersed in a corrosive medium. The reduction in steel weight reduction will impact the rate of steel corrosion, which will also be lower. The effect of electroplating current density on the rate of steel corrosion can be seen in Fig. 4.

Fig. 4 shows that increasing the electroplating current density will result in a decreased steel corrosion rate. This is because an increase in electroplating current density will also increase the Cu and Mn ions deposited on the steel. The deposition of these ions will improve the corrosion resistance of the steel. In Fig. 4 it can be seen that the rate of corrosion of steel for each current density of 35, 45, 55, 65, and 75 mA/cm^2 are 0.098 mmpy, 0.092 mmpy, 0.076 mmpy, 0.066x10^{-4} mmpy, and 0.053 mmpy, respectively. Gong and Zangari (2004) conducted Cu-Mn electroplating research on SS304 steel with various current densities. The results showed that increasing current density would improve corrosion resistance and mechanical properties of the electroplating steel. The corrosion rate of AISI 1020 steel results in electroplating decreases

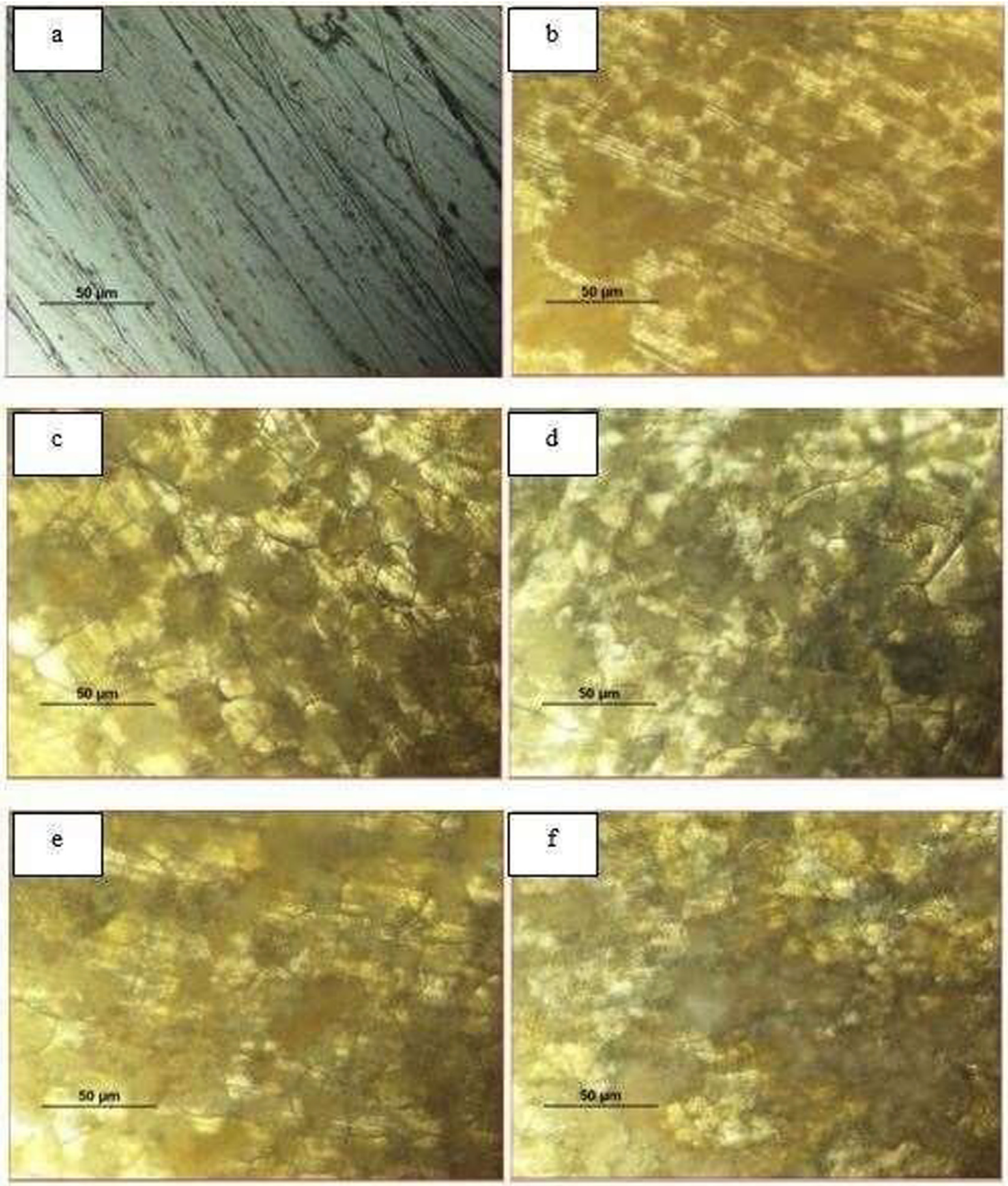

Fig. 6. Analysis of AISI 1020 steel metallurgical microscopy results from electroplating at 50 s and current density (a) 0; (b) 35; (c) 45; (d) 55; (e) 65; and (f) 75 mA/cm^2 with 400x magnification.

due to the presence of Cu^{2+} additives, which improve the manganese coating results' corrosion resistance. Adding a small amount of Cu^{2+} to the manganese electroplating process will affect the deposit's chemical state and improve its mechanical properties and corrosion resistance. In manganese electroplating, Cu^{2+} ions can inhibit the inclusion that occurs in the manganese layer during electroplating. In addition, Cu^{2+} ions can also inhibit the rate of oxidation in solution.

Fig. 5 and Fig. 6 show the results of the AISI 1020 steel metallurgical microscope analysis after electroplating with variations in current density with magnifications of 100x each in Fig. 5 and 400x in Fig. 6. The results of the metallurgical microscope analysis show different results at each current flow. Just as in the results of the analysis of metallurgical microscopes with time variations, the results of metallurgical microscopes with variations in current density also show the results of layers that are getting thicker with the greater current density applied to the electroplating process. Electroplating steel with variations in current density was also tested for corrosion rates by immersing the sample in 3% NaCl solution for 168 h. Then the corrosion test sample is also analyzed using a metallurgical microscope. The results of the metallurgical microscope analysis of samples after this corrosion test are shown in Fig. 7 and Fig. 8. Fig. 7 and Fig. 8 present the results of the analysis of metallurgical steel microscopes after being tested for corrosion at magnifications of 100x and 400x. Fig. 7 shows that the electroplating steel appears black and there are cracks in the layer after being immersed in 3% NaCl solution.

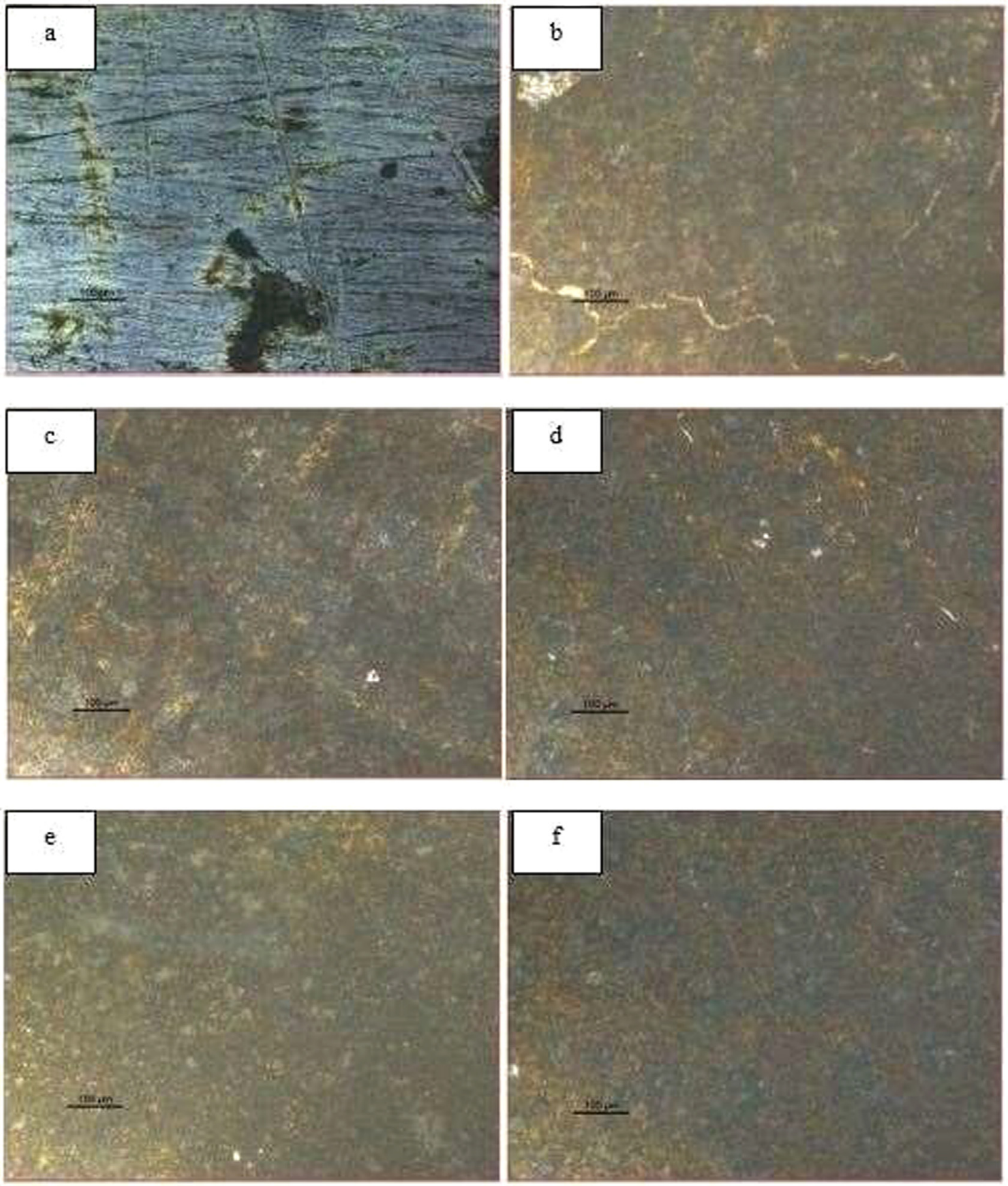

Fig. 7. The results of the metallurgical steel microscope after corrosion test on time electroplating 50 s and current density (a) 0; (b) 35; (c) 45; (d) 55; (e) 65; and (f) 75 mA/cm^2 with a magnification of 100x.

Cracked layers are clearly seen in Fig. 7 (a) steel sample electroplated with a time of 50 s and a current density of 35 mA / cm2. Furthermore, Fig. 7 also shows that the cracks in the layer decrease with increasing electroplating current. While in Fig. 8 with 400x magnification, damage to the steel layer after being immersed in a corrosive medium is more clearly seen which indicates the steel has been corroded.

4. Conclusions

From the results of the study, it can be obtained that the greater the current density applied to the steel will reduce the corrosion rate of the steel. The Cu and Mn ions which settle to the cathode are increasing with increasing time and electroplating current density. The lowest corrosion rate was obtained at an electroplating time of 50 s and a current density of 75 mA/cm2 of 0.053 mm/y. The results of the metallurgical microscope analysis show that the layer is thicker with increasing time and electroplating current density.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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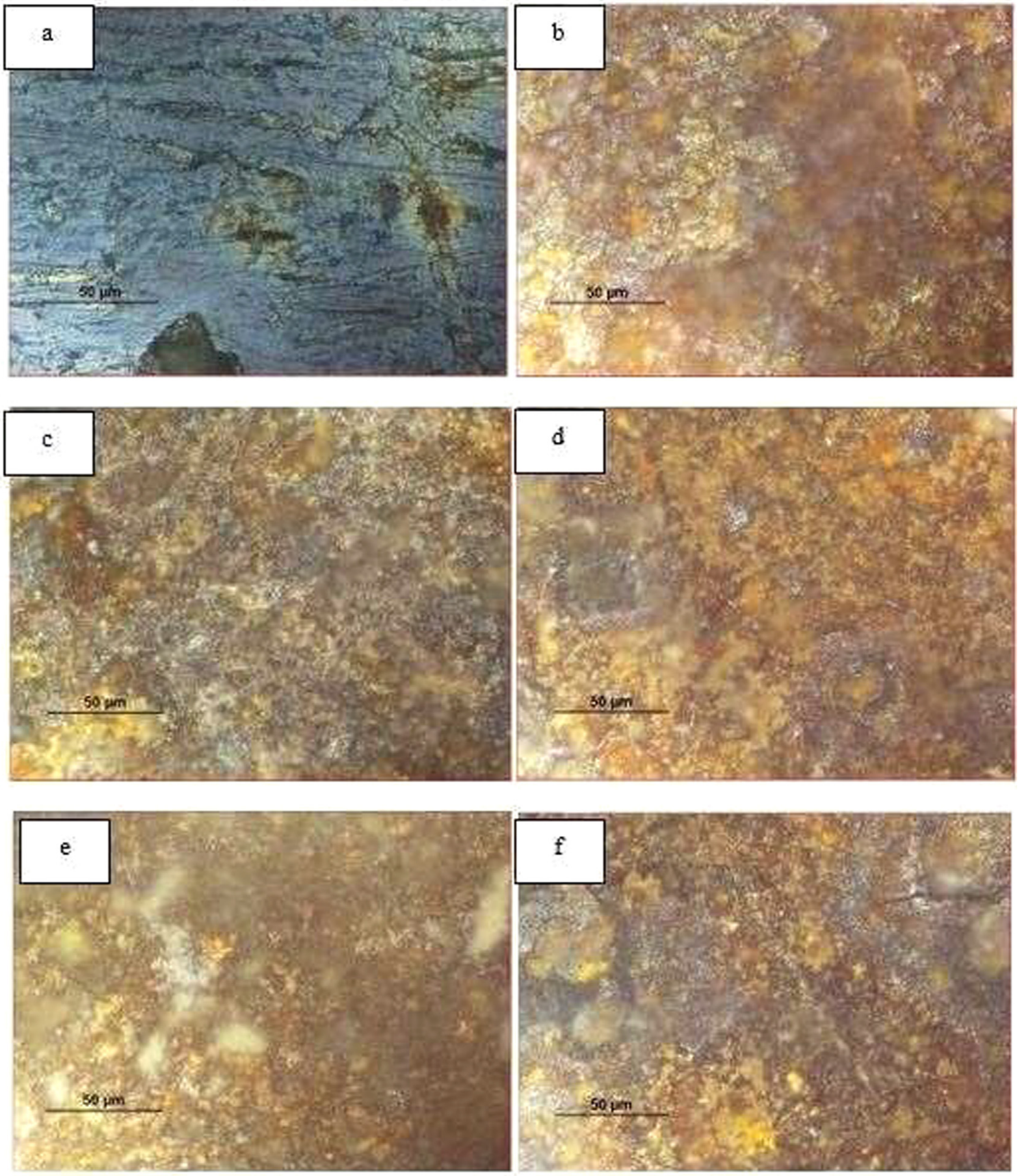

Fig. 8. The results of the metallurgical steel microscope after corrosion test on time electroplating 50 s and meeting (a) 0; (b) 35; (c) 45; (d) 55; (e) 65; and (f) 75 mA/cm^2 with 400x magnification.

References

[1] T. Surdia, S. dan Saito. Pengetahuan Bahan Teknik. Pradnya Paramita. Jakarta. Pp. 69-72.
[2] J. Gong, G. Wei, J.A. Barnard, G. Zangari, Electrodeposition and Characterization of Sacrificial Copper-Manganese Alloy Coatings: Part II. Structural, Mechanical and Corrosion-Resistance Properties, Metal. Mater. Trans. 36 (1) (2005) 2705–2715.
[3] D.A. Bayliss, D.H. Deacon, Steelwork Corrosion Control, Second Edition., Spon Press, London, 2002, pp. 18–24.
[4] M.S. Saleim, A.M. Ahmed, A.F. El Adl, Electroplating in Steel in Presence of Isopropanol-Water Mixture, Int. J. Electrochem. Sci. 9 (2) (2014) 2016–2028.
[5] D. Landolt, Electrodeposition Science and Technology in Last Quarter of Twentieth Century, J. Electrochem Soc. 149 (3) (2002) 9–20.
[6] F. Afriani, Komalasari dan Zultiniar., Proteksi Katodik Metode Anoda Tumbal untuk Mengendalikan Laju Korosi, Jurnal FTEKNIK 1 (2) (2014) 1–12.
[7] J. Gong, Z. Giovanni, Electrodeposition and Characterization of Manganese Coatings, J. Electrochem. Soci. 149 (4) (2002) 209–217.
[8] J. Gong, Z. Giovanni, Increased Metallic Character of Electrodeposited Mn Coatings using Metal Ion Additives, Electrochem. Solid-State Lett. 7 (9) (2004) 91–94.
[9] Z.I. Ortiz, P.D. Arista, Y. Meas, R.O. Borges, G. Trejo, Characterization of the Corrosion Products of Electrodeposited Zn, Zn- Co and Zn-Mn Alloys Coatings, Corrosion Sci. 51 (2009) 2703–2715.
[10] H. Supriadi, F.Pengaruh Rapat Arus dan Temperatur Elektrolit Terhadap Ketebalan dan Efisiensi Katoda Pada Elektroplating Tembaga Untuk Baja Karbon Sedang, J. Mech. 4 (1) (2013) 30–37.
[11] W.E. Triastuti, B.P.Efek Penambahan Ion Tartrate Terhadap Elektrodeposisi Mn-Cu Pada Pipa Baja Karbon, J. KAPAL. 9 (3) (2012) 167–170.
[12] A.M. Chockalingam, U.R.K. Lagudu, S.V. Babu, Potassium Periodate-Based Solutions for Minimizing Galvanic Corrosion at the Cu-Mn Interface and for Polishing the Associated Cu Interconnect Structures, J. Solid State Sci. Technol. 2 (4) (2013) 160–165.
[13] W.E. Triastuti, S.Karakter Fisik dan Korosi Mangan Hasil Pelapisan pada Baja AISI 1020, J. KAPAL. 9 (1) (2013) 1–7.
[14] Ndariyono. 2011. Pengaruh Temperatur Larutan Elektrolit dan Rapat Arus Katoda Terhadap Ketebalan dan Adhesivitas Lapisan Pada Proses Elektroplating Tembaga-Nikel-Khrom. Skripsi. Universitas Sebelas Maret. Surakarta. Pp. 21-22.