Analysis of the Effect of Voltage and Zinc Plating Duration on Low Carbon Steel A36 by Electroplating Process on Corrosion Rate

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(Received: 02 May 2024 / Revised: 14 May 2024 /Accepted: 26 May 2024)

Abstract— **Corrosion is a significant issue in steel constructions, and zinc coating (electroplating) is one of the methods used to protect steel from corrosion. This research aims to analyze the effect of voltage and duration of zinc coating on low carbon steel A36 through the electroplating process on the corrosion rate and coating thickness. An experimental method was employed, varying the voltage (6, 8, and 10 Volts) and coating duration (10, 20, and 30 minutes) during the electroplating process using a ZnO solution. The corrosion rate was tested electrochemically in a 3.5% NaCl solution. The results showed a significant correlation between voltage, coating duration, corrosion rate, and coating thickness. Higher voltages and longer durations produced thicker zinc coatings and reduced the corrosion rate. The optimal conditions were found at 10 Volts for 30 minutes, producing a 160 µm thick coating and the lowest corrosion rate of 0.00318 mmpy. The minimal coating condition, 6 Volts for 10 minutes, resulted in a 30 µm thick coating and a corrosion rate of 0.050120 mmpy.**

Keywords— electroplating, a36 steel, thickness, corrosion rate

I. INTRODUCTION

.Along with the rapid technological advancements today, various human products have developed significantly. Many of these products are made from metal materials. It is essential to provide the appropriate finishing touch or surface treatment to these metal products, both to enhance their aesthetic appearance and durability. Steel, as one of the most common types of metal in the engineering industry, has various grades with different characteristics. The use of steel is widespread and covers various fields, one of which is the shipping industry.

One of the challenges often faced by steel is corrosion. Damage due to corrosion impacts the depreciation of quality and efficiency of use and causes losses from a maintenance cost perspective. Corrosion can occur when metal comes into contact with its surrounding environment. Corrosion can damage a metal due to the chemical reactions that occur. This causes the steel on ships to experience a decrease in quality, which can ultimately disrupt the ship's voyage. Although corrosion is an unavoidable phenomenon, it can be controlled. One strategy to increase corrosion resistance is through strengthening the corrosion resistance of low carbon steel, which is done by applying a protective coating on its surface using a mixture of metals with superior resistance to environments that tend to cause corrosion [1].

Electroplating is one method useful in improving surface appearance by providing a protective coating that can increase hardness, thickness, and resistance to friction and corrosion processes. The coating process is carried out through immersing the component in a solution containing metal ions, which will then form a protective layer.

Electroplating is a process of depositing metal atom ions on the cathode electrode (negative) by electrolysis using a DC electric current. This process takes place until the metal layer is eventually deposited and firmly adheres, forming a protective layer on the surface of the base metal. [2] The electroplating method serves as a defensive step to prevent corrosion attack on metal objects by applying a specific metal coating, such as nickel, chromium, copper, or zinc, as a protective coating. The part to be electroplated needs to have conductive properties, i.e., able to conduct electric current. The core of the metal electroplating process is to protect the steel surface from the threat of corrosion that could damage it. The electroplating method is a relatively easy procedure to implement, involving simple equipment, and requiring a minimal amount of labor. The electroplating method has seen significant advancements in the industrial sector and has become a superior alternative to various coating application techniques, particularly because of its straightforward process, affordable cost, and more easily accessible raw materials [3].

Previous research discussed the effect of time and temperature variations during zinc electroplating. Testing was carried out through the electroplating process of AISI 1020 steel. The analysis results showed that the highest thickness dimension recorded was around 28.1333 µm, achieved at a temperature variation of 35°C and a duration

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of 15 minutes. Meanwhile, the highest adhesive strength reached around 15.595 MPa, occurring at a temperature variation of 25°C with a duration of 9 minutes. In terms of corrosion resistance, the lowest recorded value was around 0.0097 mmpy, found at a temperature variation of 35°C and a duration of 15 minutes [4].

In addition, the current strength in the electroplating process also has an influence on the coating thickness. Previous research discussed the effect of parameters on the nickel coating process on the thickness of the layer, investigating the effect of nickel electroplating coating on copper material with parameters such as coating duration of 5, 10, and 15 minutes, current strength of 0.28, 0.35, 0.42 A and temperatures of 40, 50, 60 °C, resulting in the finding that the thickness of the nickel layer will increase with increasing current strength, coating duration, and temperature. From the test results, the highest value for layer thickness was 82 μm at 0.42 amps with a coating time of 15 minutes and a coating temperature of 60°C [5].

Then, previous research discussed the effect of current density on coating using Zn-Mn in the electroplating process. The test results showed that current density had a significant influence on the corrosion rate. Testing was carried out through the electroplating process of AISI 1020 steel against zinc with current densities of 55, 70, 80, 90, and 100 mA/cm2 for 50 seconds. The research results showed that the higher the electroplating current density, the more deposits on the steel increased the steel mass and the content of steel element constituents, thereby reducing the corrosion rate. The lowest corrosion rate of 0.29 x 104 mm/y was obtained at a current density of 100 mA/cm2 [6].

Other research showed that the thickness of a coating layer does not guarantee that the coating can protect perfectly. The thicker a coating is, the greater the risk of coating failure, such as reduced flexibility or shrinkage. This research discussed the comparison of corrosion rates with different coating thicknesses. The results showed that the specimen with a thickness of 248 μm had a corrosion rate of 0.020262 mmpy, while the specimen with a thickness of 229 μm had a corrosion rate of 0.011891 mmpy [7].

In research discussing the use of Cr and Sn electroplating on the electrochemical corrosion resistance of low carbon steel specimens, it was concluded that the coating elements resulted in a decrease in corrosion rate compared to uncoated metal. Chromium caused a greater decrease in corrosion rate than tin. Chromium had the lowest corrosion rate of 5.18 mm/y, while tin had a corrosion rate of 9.57 mm/y [8].

Previous research studied the effect of Cu-Mn electroplating 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 by immersing samples in a corrosive NaCl medium for 168 hours and varying the current density of 35, 45, 55, 65, and 75 mA/cm2. The research results showed that higher applied current density resulted in lower corrosion rates, with a corrosion rate of 0.053mm/y [9].

Previous research discussed palladium films with good adhesive strength deposited on 316L stainless steel with non-electroplating and electroplating coatings. In a 0.01 M NaCl solution, the palladium-coated samples also showed better corrosion resistance. 316L steel coated with palladium had a thickness of 2 μm, while the uncoated steel had a thickness of 1μm. This made the electroplated 316 steel have better corrosion resistance than the non-electroplated steel [10].

Further research discussed the comparison of coatings between Cr-C (chromium sulfate bath), Cr-C (chromium chloride bath), Ni-P, and Ni-B using the electroplating method on AISI 4140 steel. The experimental results showed that the Ni-B coating had the highest hardness of around 951 Hv and the best adhesive strength of around 11 MPa. These two excellent properties caused the Ni-B coating to have the lowest wear rate of around 0.66×10-6 mm3/Nm [11].

In this research, a comparison was made between electroplating with nickel (Ni) and nickel molybdenum (Ni-Mo). To compare the corrosion behavior of the coatings, polarization tests and electrochemical impedance spectroscopy (EIS) were performed in 3 v/v% HCl and 3.5 wt.% NaCl solutions. The results showed that the Ni-Mo coating had higher corrosion resistance than the pure Ni coating in general, and Ni-15 wt.% Mo had the highest polarization resistance of 21 kΩ.cm2 after immersion for 24 hours in 3 v/v% HCl solution, while the resistance of the pure Ni coating in the same medium was only 0.3 kΩ.cm2 [12].

Based on several previous studies, the longer the electroplating process, the increase in the protective layer of the material occurs. However, the thickness of a material's protective layer does not guarantee that the layer can protect perfectly. Additionally, not all electroplating processes with prolonged durations will increase the layer thickness. An excessively long electroplating process will cause the solution to become saturated, resulting in a decrease in thickness. Therefore, in this research, the authors want to develop the previous research by using influential parameters, namely voltage and duration, to find the most effective value.

II. METHOD

A. Data Collection

Steel becomes one of the types of metals that has a very broad application. Steel basically consists of a combination of iron and carbon with the addition of small amounts of additional elements, often referred to as carbon steel. If this steel contains additional elements in larger proportions, causing changes in its characteristics, then this type of steel is known as alloy steel [13].

ASTM A36 steel is one variant of low carbon steel. This steel differs from alloy steel which mixes additional metals with specific concentrations to improve mechanical properties and corrosion resistance. In contrast, this steel has minimal weld crack sensitivity characteristics when compared to other types of carbon steel. Specifically, the composition of ASTM A36 steel has a carbon content of less than 0,3%, with details of 0,26% carbon, 0,04% phosphorus, 0,05% sulfur, and 0,4% silicon as shown in Figure 1 and Table 1 [14].

TABLE 1.
CHEMICAL COMPOSITION ASTM A36

No	*Element*	*Value (%)*
1	C	0,25-0,29
2	Cu	0.20
3	Fe	98.00
4	Mn	1.03
5	P	0.04
6	Si	0.38
7	S	0.050

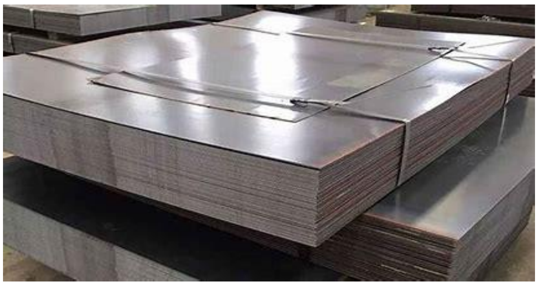

Figure. 1. ASTM A36 Steel

B. Specimens

The specimens in this study were cut according to the size dimensions shown in Figure 2 and divided according to variations as listed in Table 2.

Gage Length (G) : 50 mm
Width (W) size : 50 mm
Thickness (T) : 3 mm

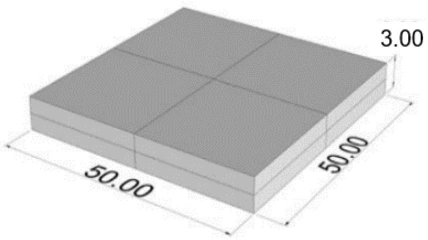

Figure. 2. Specimen Dimension

TABLE 2.
SPECIMEN REQUIREMENTS

Volt	6 V			8 V			10 V			RAW
Time (minutes)	10	20	30	10	20	30	10	20	30	
Thickness	1	1	1	1	1	1	1	1	1	1
Corrosion Rate	1	1	1	1	1	1	1	1	1	1
Total					20					

C. Electroplating

Electroplating is a method of depositing a metal coating onto the surface of an object (cathode) through an electrolysis process. The deposition in this process occurs due to the transfer of charged metal ions from the electrode through the electrolyte. The electrolyte result then deposits on the other electrode (cathode). During the deposition process, chemical reactions occur on both electrodes and the electrolyte, either in the form of reduction reactions consistently moving in a certain direction. Therefore, a stable direct current voltage source is required for the electroplating process to take place.

D. Surface Preparation

The surface preparation stage is the stage to prepare the test specimen in order to meet applicable standards to obtain maximum results. The standard used is ASTM B633 - 19 concerning Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel.

E. Specimen Preparation

The samples to be coated with the electroplating technique were taken from low carbon steel. Based on the composition analysis, it was known that the steel contained 0.23% carbon. The samples were cut to dimensions of 50 mm x 50 mm x 3 mm, where the center of one end was drilled to serve as a hole for hanging the sample, acting as the cathode.

E.1 Pre Treatment

In this process, it is ensured that the surface of the workpiece to be coated is in a truly clean condition, free from various types of contaminants. The cleaning was carried out in two stages. The first stage was mechanical cleaning, which aimed to smoothen the surface and remove scratches and traces that were still adhering to the workpiece Figure 3.

Figure. 3. Mechanical Cleaning

The second stage was solvent cleaning. This step was performed to clean the specimens from dust, grease, oil, salts, and particles that had undergone corrosion prior to the coating process by using organic solvents, alkalis, and immersion in acid solutions as shown in Figure 4.

Figure. 4. Solution Cleaning

E.2 Electroplating Process

After the workpiece was completely free from contaminants, it could be prepared for the coating process as shown in Figure 5. In carrying out the coating, it was crucial to pay special attention to the operational conditions. These conditions played a very significant role in determining the success and quality of the resulting coating. During the coating process, several factors needed to be considered, such as voltage, solution pH, current density, and solution temperature.

Figure. 5. Electroplatinc Procces

E.3 Post Treatment

The workpieces that have undergone the electroplating process are generally cleaned using water and then dried. In the context of the role of water, it is important to understand the required water quality. For example, tap water is utilized for rinsing and cooling processes, while mineral-free water, such as deionized water, is specifically used for solution preparation, analysis, and the addition of calcium and magnesium. This is because calcium and magnesium tend to react with compounds such as copper cyanide, silver cyanide, and cadmium cyanide. Generally, water contains elements like bicarbonate salts, sulfates, chlorides, and nitrates.

F. Thickness Measurement

Thickness measurement is the calculation of the difference in thickness of the steel before and after the electroplating process to obtain the thickness of the zinc coating on A36 steel. This process utilizes a micrometer device to measure the extent to which the specimen has dimensions in the direction perpendicular to its surface. In this process, the standard used is BKI part 1 Vol X on "Implementation of Hull Construction Thickness Measurement Standards". The maximum thickness criteria according to the regulations is 250 μm.

G. Corrosion Rate

Corrosion rate refers to the rate of material degradation or deterioration over time. In measuring the corrosion rate, the unit commonly used is mm/y (according to international standards) or mils per year (mpy, which is the British standard). The resistance of a material to corrosion is often measured within a corrosion rate range of 1 to 200 mpy. The Table 3 classifies material resistance based on corrosion rate levels [14].

TABLE 3.
CORROSION RATE

Relative Corrotion Resistance	Approximate Metric Equivalent				
	mpy	mm/year	μm/yr	nm/yr	pm/sec
Outstanding	<1	<0,02	<25	<2	<1
Excellent	1-5	0,02-0,1	25-100	2-10	1-5
Good	5-20	0,1-0,5	100-500	10-50	5-20
Fair	20-50	0,5-1	500-1000	50-100	20-50
Poor	50-200	42125	1000-5000	150-500	50-200
Unexceptable	200+	5+	5000+	500+	200+

III. RESULTS AND DISCUSSION

The obtained data will then be analyzed to obtain results and discussion. The following are the results and discussion based on the analysis conducted in this study.

A. Surface Preparation

This process aims to ensure optimal surface conditions, so that the electroplating coating can be carried out effectively. Therefore, this step must be executed in accordance with established standards to achieve a coating level that complies with applicable standards.

In this process, the standard used is ASTM B633 - 19 on "Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel". A36 steel must undergo mechanical cleaning and cleaning using an acid solution, which is a mixture of water and HCl.

B. Electroplating

In this process, several things need to be considered before the metal coating process is carried out on the material. The first thing that needs to be considered is the provision regarding the electrolyte solution used. The electrolyte solution must consist of zinc oxide. In addition, during the electroplating process, something that must not be forgotten is the temperature of the electroplating solution. The solution temperature must be kept not exceeding 50°C in order to comply with the BKI Vol G regulations on Guidance for the Corrosion Protection and Coating Systems. After these two things are met, the electroplating process can be carried out using voltage variations of 6 V, 8 V, 10 V and time durations of 10 minutes, 20 minutes, and 30 minutes with the results shown in the figure 6.

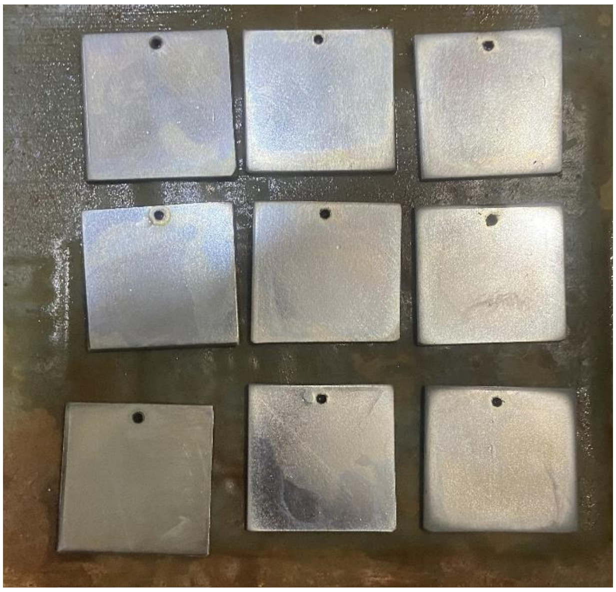

Figure. 6. Specimens After Electroplatinc

C. Thickness Measurement

One of the important parameters that need to be characterized after the electroplating process is the thickness of the layer formed on the substrate surface. Thickness measurement aims to validate whether the deposited layer is in accordance with the initial design before coating. Then the thickness data is also useful for analyzing the growth rate of the layer against the electroplating process variables themselves. In addition, thickness measurement is also useful to validate that the electroplating results have met the BKI part 1 Vol X

In this study, the thickness of the zinc layer resulting from electroplating on a carbon steel substrate was measured using a micrometer screw with an accuracy of 0.01 mm. The working principle of this tool is that the screw rotation is used to linearly move the measuring jaws and the physical contact between the tip of the jaws and the specimen surface is utilized to read the vernier scale on the micrometer screw barrel.
6 V: 10 minutes = 30 µm, 20 minutes = 100 µm, 30 minutes = 115 µm, 8 V: 10 minutes = 40 µm, 20 minutes = 110 µm, 30 minutes = 125 µm, 10 V: 10 minutes = 50 µm, 20 minutes = 125 µm, 30 minutes = 160 µm

TABLE 4.
THICKNESS MEASUREMENT

Voltage	Time (Minutes)	Electroplating Thickness
6 V	10	30 µm
	20	100 µm
	30	115 µm
8 V	10	40 µm
	20	110 µm
	30	120 µm
10 V	10	50 µm
	20	125 µm
	30	160 µm

Based on the Table 4 electroplating thickness test results according to HES D 2003-17, which is a minimum of 8 µm, in this study, based on the voltage and temperature variables, the following electroplating layer thickness test results shown in Figure 7.

of metal deterioration can be calculated. The application of this electrochemical method is generally widely applied in the industrial sector to evaluate the corrosion resistance of materials and design materials with better corrosion resistance.

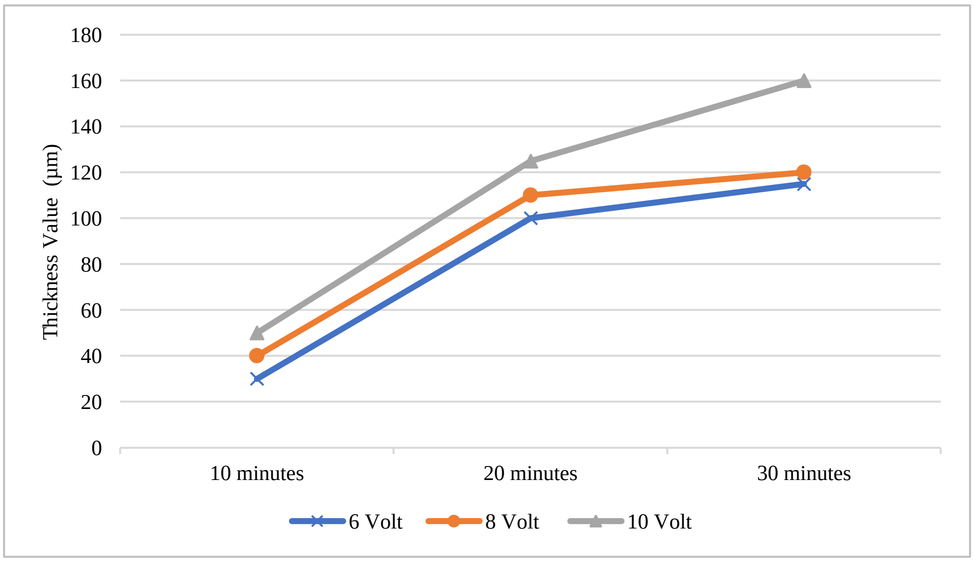

Figure. 7. Electroplating Thickness

D. Corrosion Rate Test

Electrochemical corrosion rate measurement is a testing technique used to assess the deterioration rate of metals or metal alloys by analyzing the electric current arising from the electrochemical reaction between the metal and the electrolyte. This procedure involves measuring the electric potential on the corroded metal surface and measuring the electric current flowing through the electrolyte. From the collected data, the rate standard on "Implementation of Hull Construction Thickness Measurement Standards". The maximum thickness criteria according to the regulation is 250 µm.

This test was carried out at the Corrosion and Material Failure Laboratory, Metallurgical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya. The results of the corrosion rate test are as follows:

TABLE 5.
VALUE OF CORROSION RATE

Voltage	Time (Minutes)	Icorr (μA/cm²)	Corrosion Rate (mm/year)	Category
RAW	-	2.83×10^{-5}	0.329	Good
6 V	10	4.31×10^{-6}	0,050	Excellent
	20	2.42×10^{-6}	0,027	Excellent
	30	1.75×10^{-6}	0,020	Excellent
8 V	10	2.82×10^{-6}	0,032	Excellent
	20	2.12×10^{-6}	0,024	Excellent
	30	1.46×10^{-6}	0,017	Outstanding
10 V	10	2.48×10^{-6}	0,028	Excellent
	20	1.20×10^{-6}	0,014	Outstanding
	30	2.37×10^{-7}	0,003	Outstanding

The Table 5 and Figure 8 shows the corrosion rate results for the material without any treatment, obtaining a corrosion rate of 0.32935 mmpy.

Based on the corrosion rate graph at 6 V variation with 10 minutes time, it shows a corrosion rate of 0.050120 mmpy, 20 minutes time shows a corrosion rate of 0.027932 mmpy, and at 30 minutes time, it shows a corrosion rate of 0.020470 mmpy.

Furthermore, at 8 V with 10 minutes time, it shows a corrosion rate of 0.032786 mmpy, 20 minutes time shows a corrosion rate of 0.024661 mmpy, and 30 minutes time shows a corrosion rate of 0.017030 mmpy.

At 10 V with 10 minutes time, it shows a corrosion rate of 0.028992 mmpy, 20 minutes time shows a corrosion rate of 0.014002 mmpy, and at 30 minutes time, it shows a corrosion rate of 0.003181 mmpy.

After observing the comparison on the graph above, it is found that the highest corrosion rate value of all specimens is at the specimen with 6 V voltage and 10 minutes time of 0.050120 mmpy. While the lowest corrosion rate is found in the specimen with 10 V voltage and 30 minutes time with a value of 0.003181 mmpy.

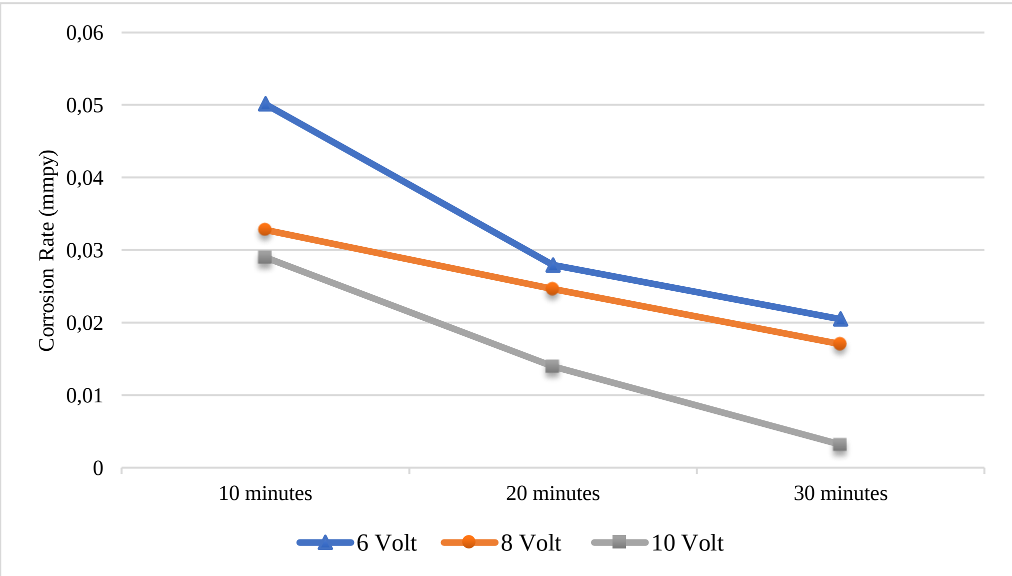

Figure. 8. Corrosion Rate

IV. CONCLUSION

Then, the greater the voltage and duration of time during electroplating on the test material, the greater the thickness of the layer. This can be observed in each material tested at the same time duration and voltage but with different layer thicknesses. As in the case of the test material with 6 Volt voltage for 10 minutes, it only has a thickness of 30 μm. While the test material with 10 Volt for 30 minutes has the highest layer thickness of 160 μm.

Furthermore, the thickness of the electroplating layer greatly affects the material's corrosion rate value. The higher the layer thickness, the lower the corrosion rate value that occurs on the material. This is evidenced by the results of the test material testing carried out. On the material that has the smallest thickness of 30 μm, it has the highest corrosion rate of 0.050120 mmpy. While the test material with the highest layer thickness of 160 μm has the lowest corrosion rate of 0.003181 mmpy. Zinc electroplating on materials as an effort to reduce corrosion rate is an efficient step.

REFERENCES

[1] F. Gapsari, Pengantar Korosi, Malang: UB Press, 2017.

[2] I. A. A. Saleh, Elektroplating Teknik Pelapisan Logam dengan Cara Listrik. Margaasih: Yrama Widya, 2014.

[3] S. Harnowo, "Studi Eksperimental Tentang Pengaruh Variasi Rapat Arus Pada Hard Chrome Electroplating Terhadap Karakteristik Permukaan Baja Karbon Rendah", *MECHANICAL, vol. 1, no. 1,* 2010

[4] V. M. Pratiwi, S. Sulistijono, M. I. P. Hidayat, and H. Zuniandra, "Pengaruh Variasi Waktu dan Temperatur Elektroplating Seng Terhadap Ketebalan, Kekuatan Lekat dan Ketahanan Korosi pada Baja," *Jurnal Teknik ITS*, vol. 8, no. 2, 2020.

[5] B. Santosa and M. Syamsa, "Pengaruh Parameter Proses Pelapisan Nikel Terhadap Ketebalan Lapisan," *Jurnal Teknik Mesin Universitas Kristen Petra*, vol. 9, no. 1, pp. 25–30, Jul. 2007.

[6] A. P. Sandi, E. G. Suka, Y. I. Supriyatna, and S. Sumardi, "The Influence of Zn-Mn Electroplating Current Density To AISI 1020 Steel Corrosion Rate," *AIP Conference Proceedings*, 2020.

[7] Y. K. Afandi, I. S. Arief, and A. Amiadji, "Analisa Laju Korosi Pada Pelat Baja Karbon Dengan Variasi Ketebalan Coating," *DOAJ (DOAJ: Directory of Open Access Journals),* 2015.

[8] Ameen and F. M. Hassan, "The Effect Of Electroplating Of Cr And Sn On Corrosion Resistance Of Low Carbon Steel (CK15)," *American Journal of Scientific and Industrial Research*, vol. 1, no. 3, pp. 565–572, . 2010.

[9] Y. I. Supriyatna, R. Noviyana, E. G. Suka, B. N. H. Kambuna, S. Sumardi, and Sudibyo, "Influence Of Current Density In Cu-Mn Electroplating Of AISI 1020 Steel Corrosion Rate," *Materials Today: Proceedings*, vol. 44, pp. 3289–3295, 2021.

[10] J. Tang and Y. Zuo, "Study On Corrosion Resistance Of Palladium Films On 316L Stainless Steel By Electroplating And Electroless Plating," *Corrosion Science*, Vol. 50, No. 10, Pp. 2873–2878, 2008.

[11] H. Sheu, "A Comparison Of The Corrosion Resistance And Wear Resistance Behavior Of CR-C, NI-P And NI-B Coatings Electroplated On 4140 Alloy Steel," *International Journal of Electrochemical Science*, vol. 13, no. 4, pp. 3267–3278, 2018.

[12] S. Mosayebi, M. Rezaei, and Z. Mahidashti, "Comparing Corrosion Behavior Of Ni And Ni-Mo Electroplated Coatings In Chloride Mediums," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 594, p. 124654, 2020.

[13] E. Arifi and D. Setyowulan, Perancangan Struktur Baja, Malang: UB Press, 2020.

[14] N. H. Sari, Material Teknik, Yogyakarta: Deepublish, 2018.

[15] M. G. Fontana, Corrosion Engineering, Singapore, 1987.