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The Effect of Electric Current in Hard Chrome Plating Process on the Corrosion Rate of SS400 Low Carbon Steel Plate for Warships

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Abstract

Hard chrome plating is a technique used to protect metal from the effects of corrosion caused by the surrounding environment. The basic principle of the hard chrome plating process on metal is the reduction of chrome ions, resulting in chrome deposition on the cathode, following the principle of electrolysis. Electric current is one factor determining the quality of electroplating results. The immersion test is a correction factor for electroplating results to obtain corrosion rate values. This research used an experimental method involving one independent variable: electric current with current variations of 1 A, 2 A, 3 A, 4 A, 5 A, and 1 sample without chrome coating. In contrast, the dependent variable observed was the corrosion rate resulting from hard chrome plating. And without hard chrome plating. The controlled variable in this study was the length of soaking time for 7 days. The corrosive solution used is sodium chloride (NaCl), with a concentration of 3.5%. The research results show that the electric current resulting from hard chrome plating on SS400 steel significantly affects the results of the immersion test or corrosion rate test.

Keywords: *Corrosion Rate; Electric Current; Hard Chrome Plating; Immersion Test*

Introduction

Indonesia is a country that has marine diversity and richness because of its geographical location, which is flanked by two oceans and two large continents [1]. To maintain and protect Indonesia's marine natural wealth, warships that are part of the TNI's role and duties in the maritime domain are needed. Warships can be used to carry out patrols and surveillance in national waters, especially in areas that are strategic or vulnerable to security threats, such as border waters [2]. Warships used to protect national waters will continue to operate for a long time and, at a high rate, can experience rust on the ship's body and hull. One part of a ship that is prone to rust is the hull or bottom of the ship. To prevent this, warships will generally apply protective paint or anti-rust coating to the ship's hull to prevent the rusting process [3].

Rusting is a corrosion or oxidation process that occurs in metal when the metal is exposed to oxygen and water or experiences humidity for a long time. This results in the formation of metal oxide compounds, commonly known as rust [4]. Protective coatings such as anti-rust paint are often used to protect iron or steel surfaces from exposure to oxygen and water and prevent corrosion or rust formation on ships [3]. Hard chrome plating is a technique used to protect metal from the impact of corrosion caused by the surrounding environment [5]. The basic principle of the hard chrome plating process on metal is the reduction of chrome ions, resulting in chrome deposition on the cathode, following the principle of electrolysis [6].

Steel plate is one of the most common materials used for ship hull construction on warships. The type of steel commonly used in making warship plates is low-carbon steel, such as SS400 steel. It is a relatively cheap steel with good mechanical properties [7]. SS400 steel has a minimum tensile strength of 400 MPa, sufficient for many structural applications on ships [8]. SS400 steel can be easily formed, forged, pressed, and machined. It can also be shaped according to ship design requirements, making it suitable for various warship manufacturing and construction processes.

Materials and Methods

Materials

The materials used are pure SS400 steel and SS400 steel resulting from hard chrome plating with varying electric currents of 1 A, 2 A, 3 A, 4 A, and 5 A, 3.5% solid sodium chloride (NaCl) and distilled water. The equipment used is a 500 mL beaker and a digital analytical balance with an accuracy of up to 0.0001 grams.

Methods

Samples that have undergone hard chrome plating are cleaned with distilled water until they are clean of contaminants. After that, each sample was weighed before being tested for corrosion resistance, then placed in a 500 mL beaker containing 3.5% salt (NaCl) solution, after which it was soaked for 7 days in the solution. Every day at a certain time, the sample is taken and cleaned again with a brush and distilled water until the rust and contaminants are removed from the sample's surface, then dried, and the weight of the sample is weighed again. The difference in weight before and after the immersion test process results in a reduction in sample weight so that the corrosion rate can be calculated and the corrosion resistance value of the sample can be determined [9].

Result and Discussion

SS400 Low Carbon Steel (Structural Steel)

Based on its chemical composition, steel plates can be classified into two main types: carbon steel and alloy steel. Steel is an alloy of iron and carbon with low levels of other elements, for example, Mn, P, S, and Si. Carbon steel can be divided into three: low-carbon steel, medium-carbon steel, and high-carbon steel [10]. The mechanical properties of carbon steel depend on the C content it contains. The higher the carbon content, the higher the hardness and strength, but the ductility decreases or becomes more brittle [11].

SS400 steel is widely used in general structural applications, such as in the construction of ship hulls, ship plates, and oil tanks [10]. In SS400 steel, the main element is iron (Fe). According to Yerikho et al. (2013) [6] , steel whose main element is iron, is superior in terms of its mechanical properties but requires special protection in an open environment to prevent corrosion.

Table 1. Chemical composition of SS400 steel [10]

Element		Content (% weight)
Fe	Ferrum	98.98
C	Carbon	0.200
Si	Silicon	0.09
Mn	Manganese	0.53
P	Phosphorus	0.100
S	Sulfur	0.040
Cr	Chromium	0.030
Ni	Nickel	0.030

Corrosion Process in Iron Metal

Corrosion is the process of a metal surface experiencing permanent damage due to chemical reactions that change pure metal into more stable chemical forms such as sulfides, oxides, and hydroxides in a corrosive environment. Rust on iron is the most common example of corrosion. Rust is hydrated iron oxide [$Fe_2O_3.xH_2O$] [12]. The corrosion process in a metal cannot be stopped, but its rate can be controlled or slowed down to reduce the damage caused. One method to slow down this process is to coat the surface with another metal, for example, chrome metal [13]. Oxidation reactions taking place at the anode [14]:

$$2Fe_{(s)} \rightarrow 2Fe^{2+}_{(aq)} + 2e^{-}$$

The reduction reaction takes place at the cathode:

$$O_{2(g)} + 4H^{+}_{(aq)} + 4e^{-} \rightarrow 2H_2O_{(l)}$$

So, the overall cell reaction:

$$2Fe_{(s)} + O_{2(g)} + 4H^{+}_{(aq)} \rightarrow 2Fe^{2+}_{(aq)} + 2H_2O_{(l)}$$

$$4Fe^{2+}_{(aq)} + O_{2(g)} \rightarrow 4Fe^{3+}_{(aq)} + 2O^{2-}_{(aq)}$$

$$Fe^{3+}_{(aq)} + 3H_2O_{(l)} \rightarrow Fe(OH)_{3(l)} + 3H^{+}_{(aq)}$$

$$2Fe(OH)_{3(l)} \rightarrow Fe_2O_3.3H_2O_{(s)}$$

Corrosion Rate

The corrosion rate is the speed at which corrosion spreads on a metal surface or the decline in metal quality over time caused by the surrounding environment [15]. An immersion test must be carried out to determine the quality of the metal in terms of corrosion resistance. Immersion test is a technique for determining the corrosion rate of a material using the weight loss method, with the formula:

$$CR = \frac{K \times \Delta W}{A \times t \times D}$$

Information:

CR = corrosion rate

K = corrosion rate constant (see Table 2)

ΔW = weight loss (g)

A = specimen surface area (cm2)
t = soaking time (hours)
D = specimen density (g/cm3)

Table 2. Constant value per unit corrosion rate

Corrosion Rate Units Desired	**Constant (K) in Corrosion Rate Equation**
Mils per year (mpy)	3.45 x 10^6
Inches per year (ipy)	3.45 x 10^3
Millimetres per year (mm/y)	8.76 x 10^4
Micrometres per year (µm/y)	8.76 x 10^7
Picometres per second (pm/s)	2.78 x 10^6
Grams per square meter per hour (g/m^2.h)	1.00 x 10^4 x D[A]
Milligrams per square decimetre per day (mdd)	2.40 x 10^6 x D[A]
Micrograms per square meter per second (µg/m^2.s)	2.78 x 10^6 x D[A]

Note: [A] Density is not needed to calculate the corrosion rate for this unit or units. The density value in the constant will eliminate the density value in the corrosion rate equation.
Source: (American Standard Testing and Material, 1999)

Table 3. The relationship between corrosion rate and corrosion resistance [16]

Relative Corrosion Resistance	**Corrosion Rate**				
	mpy	**mm/yr**	**µm/yr**	**nm/hr**	**pm/s**
Very very good	< 1	< 0,02	< 25	< 2	< 1
Very good	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
Enough	20 - 50	0,5 - 1	500 - 1000	50 - 150	20 - 50
Bad	50 - 200	1 - 5	1000 - 5000	150 - 500	50 - 200
Very bad	> 200	> 5	> 5000	> 500	> 200

Hard Chrome Plating

Tables 4 and 5 show that the weight of the chrome deposits on the SS400 steel plate samples resulting from hard chrome plating experienced an increase in weight following the increase in the amount of current flowing during the electroplating process. The greater the electric current that passes through the electrolysis cell, the faster the movement of chrome ions towards the cathode so that the mass of chrome ions deposited on the cathode increases. As a result, there was an increase in sample weight before and after hard chrome plating. From the hard chrome plating process, the following results were obtained (Table 4). From data in Tables 4 and 5, the metal deposition efficiency for hard chrome plating results can be calculated as follows (Table 6). Table 6 shows a graph of the relationship between metal deposition efficiency and the electric current used during the hard chrome plating process (Figure 1).

Table 4. Sediment weight measured through research

Sample	Voltage (V)	Electric current (A)	Initial Weight (g)	Final Weight (g)	Measured Sediment Weight (g)
1	2.6 - 2.7	1.00	20.9828	20.9892	0.0064
2	3.0 - 3.1	2.00	20.3229	20.3362	0.0133
3	3.3 - 3.4	3.00	20.2010	20.2245	0.0235
4	3.5 - 3.6	4.00	19.9419	19.9766	0.0347
5	3.8 - 3.9	5.00	20.2920	20.3307	0.0387

Table 5. Theoretical sediment weight

Sample	Equivalent Weight	Electric Current (A)	Time (s)	Theoretical Sediment Weight (g)
1	8.6660	1.00	3600	0.3233
2	8.6660	2.00	3600	0.6466
3	8.6660	3.00	3600	0.9699
4	8.6660	4.00	3600	1.2932
5	8.6660	5.00	3600	1.6165

Table 6. Metal deposition efficiency resulting from hard chrome plating

Sample	Measured Sediment Weight (g)	Theoretical Sediment Weight (g)	Metal Deposition Efficiency (%)
1	0.0064	0.3233	1.9796
2	0.0133	0.6466	2.0570
3	0.0235	0.9699	2.4264
4	0.0347	1.2932	2.6808

The higher of the electric current flowing through the electrolysis cell, the greater the metal deposition efficiency (Figure 1). This means that the better the deposition occurs relative to the energy used the greater the measured weight of the precipitate that settles, approaching the theoretical deposition weight. However, at an electric current of 5 A, there was a decrease in metal deposition efficiency. According to Alphanoda (2016) [17], in the hard chrome plating process, 80% to 90% of the energy supplied to the system is used to form hydrogen gas (H2) and the remainder for chrome deposition. When excess gas (H2) is formed in the hard chrome plating process, it can be interpreted as a waste of energy used to deposit chrome on the sample.

Immersion Test

From the research results, the SS400 steel plate sample experienced a decrease in sample weight after an immersion test was carried out for 7 days in a corrosive medium with a 3.5% NaCl solution. From the sample weight loss data, the corrosion rate of the sample can be calculated with the following results in (Table 7, 8).

Table 7. Immersion test results on SS400 steel without hard chrome plating

Days to	Weight Loss (g)	Soaking Time (hours)	Corrosion Rate (mpy)
1	0.0040	24	3.8495
2	0.0081	48	3.8976
3	0.0122	72	3.9137
4	0.0169	96	4.0660
5	0.0214	120	4.1254
6	0.0258	144	4.1382
7	0.0306	168	4.2070

Table 8. Immersion test results on SS400 steel with hard chrome plating, electric current 1 A

Days to	Weight Loss (g)	Soaking Time (hours)	Corrosion Rate (mpy)
1	0.0004	24	0.3646
2	0.0041	48	2.0550
3	0.0080	72	2.6627
4	0.0109	96	2.7179
5	0.0144	120	2.8704
6	0.0181	144	3.0052
7	0.0218	168	3.1015

Table 9. Immersion test results on SS400 steel with hard chrome plating, electric current 2 A

Days to	Weight Loss (g)	Soaking Time (hours)	Corrosion Rate (mpy)
1	0.0000	24	0.0000
2	0.0021	48	1.0856
3	0.0057	72	1.9338
4	0.0087	96	2.2222
5	0.0118	120	2.4020
6	0.0148	144	2.5105
7	0.0176	168	2.5542

Table 10. Immersion test results on SS400 steel with hard chrome plating, electric current 3A

Days to	Weight Loss (g)	Soaking Time (hours)	Corrosion Rate (mpy)
1	0.0000	24	0.0000
2	0.0000	48	0.0000
3	0.0000	72	0.0000
4	0.0000	96	0.0000
5	0.0000	120	0.0000
6	0.0000	144	0.0000
7	0.0000	168	0.0000

Table 11. Immersion test results on SS400 steel with hard chrome plating, electric current 4 A

Days to	Weight Loss (g)	Soaking Time (hours)	Corrosion Rate (mpy)
1	0.0000	24	0.0000
2	0.0000	48	0.0000
3	0.0000	72	0.0000
4	0.0000	96	0.0000
5	0.0000	120	0.0000
6	0.0000	144	0.0000
7	0.0000	168	0.0000

Table 12. Immersion test results on SS400 steel with hard chrome plating, electric current 5 A

Days to	Weight Loss (g)	Soaking Time (hours)	Corrosion Rate (mpy)
1	0.0000	24	0.0000
2	0.0000	48	0.0000
3	0.0000	72	0.0000
4	0.0000	96	0.0000
5	0.0000	120	0.0000
6	0.0000	144	0.0000
7	0.0000	168	0.0000

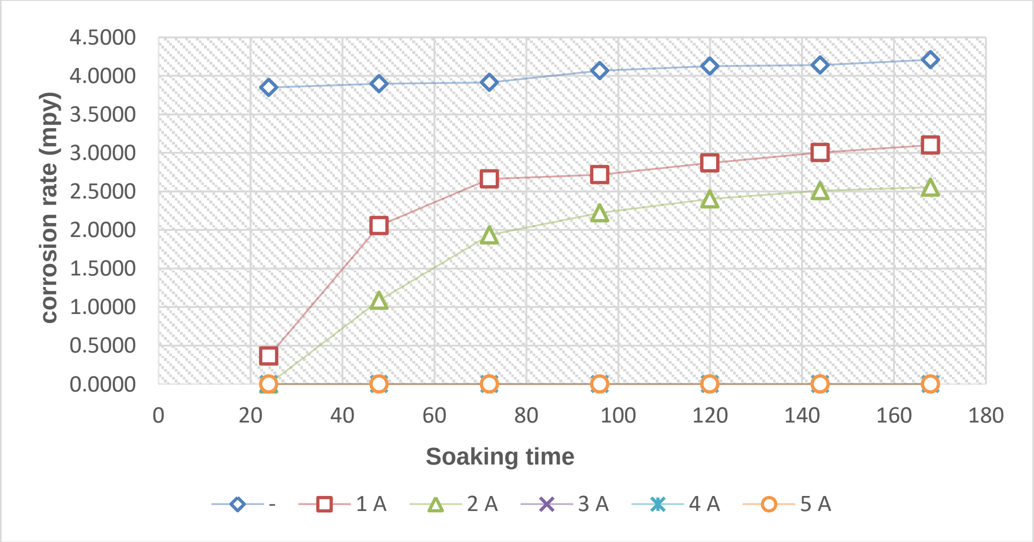

Figure 1. Graph of the relationship between corrosion rate and soaking time

From Tables 7, 8, 9, 10, 11, and 12, a graph of the relationship between corrosion rate and immersion time during the immersion test process can be obtained (Figure 2). The immersion test results table and Figure 2 show the corrosion rate (may) value of each SS400 steel sample without or with hard chrome plating. The corrosion rate value for samples that were not hard chrome plating had a fairly high corrosion rate compared to samples that were coated with chrome. It caused the interaction or reaction of the core metal (SS400 steel) with the corrosive medium in NaCl solution. As a result, there is a decrease in the weight of the sample due to rust or corrosion, where this reaction converts Fe metal into Fe^{2+} ions by releasing 2 electrons into the environment. Through this reaction, holes will form in the Fe area, which releases electrons, decreasing sample weight. Then, by reducing the weight of the sample, the corrosion rate value can be calculated.

In samples coated with chrome metal, the core metal is isolated from the environment, which can oxidize the metal so that corrosion does not occur on the metal surface. However, in the 1 and 2-amp samples, it can be seen that there is a decrease in sample weight due to the corrosion reaction that occurs in the sample. This may occur due to gaps or layers of chrome that are not coated evenly, thus opening up opportunities for interaction between the NaCl solution and the core metal. This gap is the starting point for the corrosion reaction, which causes Fe metal to change into Fe2+ ions in one area and then propagate to other areas, decreasing weight in the 1 and 2 amperes samples. The gap in the 1 amper sample is larger than the gap in the 2 amper sample, so it has a greater corrosion rate value per unit time. In the 3, 4, and 5 amperes samples, it can be seen that the corrosion rate value for these samples is 0, meaning that there is no decrease in sample weight due to corrosion or rust in these three samples. This happens because the sample is coated with chrome metal evenly over the entire metal surface, which protects the core metal from the corrosive NaCl solution and prevents rust on the surface of the core metal.

Based on Figure 2, there is a tendency for the corrosion rate value to increase with each unit of time. This is because the longer the soaking time, the more interactions or reactions occur between the surface of the core metal and the NaCl solution, thereby oxidizing the Fe metal into Fe2+ ions on the surface of the steel. The higher the contact time, the higher the corrosion rate of the steel. The corrosion resistance of the SS400 steel samples without chrome metal coating and the 1 and 2 amper samples have very good indicators. In contrast, the 3, 4, and 5 amper samples have very good indicators because the corrosion rate values are below 1 mph.

Conclusion

The calculation results show that the highest corrosion rate value was obtained on day 7 at 4.2070 mpy for samples without hard chrome plating. From the research results, it was found that SS400 steel samples with hard chrome plating had a better level of corrosion resistance than those without hard chrome plating. In this research, the higher the electric current used in the hard chrome plating process, the lower the corrosion rate on the SS400 steel surface. An increase in the corrosion rate will be followed by the soaking time for the SS400 steel sample during the immersion test process. The longer the soaking time, the higher the corrosion rate value. The increase in the corrosion rate is also influenced by the large surface area of contact between the NaCl solution and the core metal.

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