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IMPACTS OF TEMPERATURE AND COATING PIGMENT RATIOS ON THE CORROSION RATE OF SS400 STEEL

DAMPAK SUHU DAN RASIO PIGMEN COATING TERHADAP LAJU KOROSI PADA BAJA SS400

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ABSTRAK

Baja adalah bahan utama dalam konstruksi kapal, tetapi sangat rentan terhadap korosi. Perlindungan yang efektif memerlukan coating dengan sifat kekerasan, ketahanan, dan daya rekat yang kuat. Penelitian ini bertujuan menganalisis pengaruh pigmen aluminium-graphite dan perlakuan panas terhadap laju korosi, kekuatan adhesi, dan ketahanan coating pada plat baja SS400 yang dilapisi dengan epoxy. Penelitian ini melibatkan variasi perbandingan pigmen 1:1 dan 3:1 serta perlakuan panas pada suhu 100°C dan 150°C. Ketebalan lapisan coating adalah 250 µm dengan campuran epoxy 80% dan aluminium-graphite 20%. Hasil uji menunjukkan bahwa kekuatan adhesi tertinggi, yaitu 19.62 MPa, tercapai pada rasio pigmen aluminium-graphite 1:1 pada suhu perlakuan panas 100°C. Ketahanan coating tertinggi, sebesar 6.86 Joule, dicapai pada kondisi yang sama. Sedangkan laju korosi terendah, 0.047 mmpy, tercatat pada rasio aluminium-graphite 3:1 dengan perlakuan panas 150°C. Temuan ini memiliki implikasi penting dalam meningkatkan ketahanan material baja terhadap korosi dalam konteks pembangunan kapal.

Keywords: *Alumunium; Graphite; korosi; Adhesi; Coating; Impact; Perlakuan panas.*

ABSTRACT

Steel is the primary shipbuilding material; however, it erodes quickly. Adequate protection requires hard, durable, and adhesive coatings. This study examines how aluminium-graphite pigment and heat treatment affect epoxy-coated SS400 steel plate corrosion, adhesion, and coating resilience. This study used a 1:1 and 3:1 pigment ratio with 100°C and 150°C heat treatment. The coating layer was 250 µm thick and comprised 80% epoxy and 20% aluminum-graphite. The maximum adhesion strength, 19.62 MPa, was achieved with an aluminium-graphite pigment ratio of 1:1 and 100°C heat treatment. The top coating resistance was 6.86 Joules under identical conditions. The lowest corrosion rate, 0.047 mmpy, was at a 3:1 aluminum-graphite ratio and 150°C heat treatment. This discovery has significant consequences for shipbuilding steel corrosion resistance.

Keywords: *Aluminum; Graphite; Corrosion; Adhesion; Coatings; Impact; Heat treatment.*

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INTRODUCTION

Steel is the primary material that has long been used to build a ship. However, steel material is very susceptible to corrosion [1], [2]. Corrosion can cause destruction or material damage due to a reaction to the environment, reducing the strength and life of the construction [3]. Corrosion cannot be avoided or stopped but can only be controlled by slowing it down. One way is by coating.

The coating is a surface method that aims to protect the material. Coating is the most widely used method because it is easy to do, and the service life of the coating layer is also quite long, so the costs required are less than other methods [4], [5].

In addition to protecting against corrosion and to survive in the environment, coating applications on ships must also have high hardness, resistance, and strong adhesive properties [6], [7]. The coating layer on the boat will experience friction, which will cause wear and impact. It can cause the coating layer on the ship to be damaged so that the coating function becomes weak [8], [9].

Pigments are often added to organic coatings to improve the general characteristics of the coating, such as corrosion resistance, increased surface coverage, increased paint adhesion, etc. [10], [11]. Another way to improve the quality of the coating layer is by providing heat treatment. Heat treatment can reduce defects in the coating layer (e.g., micro-cracks and pores) and improve the hardness, strength, and mechanical properties of the coating layer [12], [13].

Previous research regarding providing heat treatment to the coating on the corrosion rate can increase corrosion resistance value [14]. Earlier studies regarding mixing aluminum pigment in coatings on adhesion strength and corrosion rate can increase the value of corrosion resistance and adhesion strength (mm per year) [15]. Previous research regarding providing heat treatment on the coating layer's strength can increase the coating layer's resistance [16].

Based on the problems above and from previous studies, this study wanted to analyze the prediction of corrosion rate, adhesion strength, and coating resistance of epoxy coating layers treated with aluminum-graphite pigment and heat treatment.

METHOD

Research Objects and Variations

The research object used was the SS400 steel plate. The dimensions of the adhesion and impact test specimens were 150 x 50 x 5 mm with a total of 6 pieces, while for the corrosion rate test, the dimensions were 50 x 50 x 5 mm with a total of 6 pieces. The total test specimens in this study amounted to 18 pieces.

Table 1.
Test Specimen Design

No	Aluminum-Graphite Variation	Temperature Variation	Corrosion Test	Adhesion Test	Impact Test
1	1:1	TPP	✓	✓	✓
2	1:1	100°C	✓	✓	✓
3	1:1	150°C	✓	✓	✓
4	3:1	TPP	✓	✓	✓
5	3:1	100°C	✓	✓	✓
6	3:1	150°C	✓	✓	✓

TPP: No Heat Treatment
Source: Researcher's Primary Data

Test Specimen Manufacturing

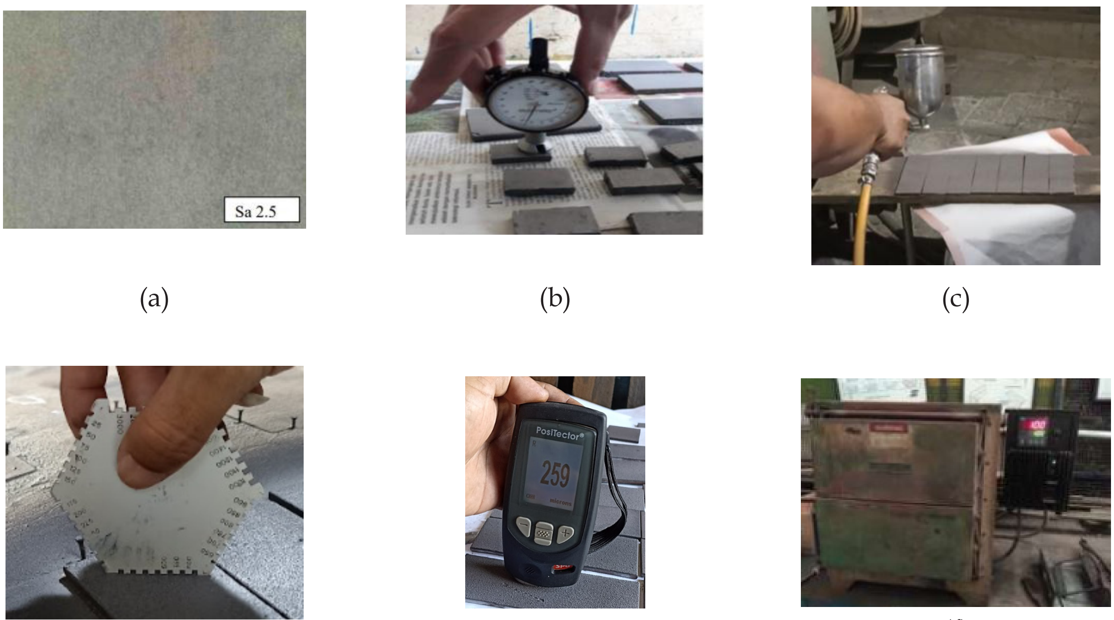
In this study, surface preparation of the specimens before applying the coating was carried out using sandblasting, as seen in Figure 1(a). It involved spraying abrasive material, specifically aluminum oxide, onto the steel surface to eliminate rust, old paint, and impurities, creating surface roughness. The cleanliness of the surface was visually checked by comparing the blasted specimens with a standard image of cleanliness (Sa 2.5) [17].

Afterward, the roughness of the surface was measured using a surface roughness meter, as seen in Figure 1 (b), within the standard range of 30-85 microns [18]. The environmental conditions, including relative humidity below 85% and specimen temperature at least 3^0C above the dew point, were measured as they can impact the coating results.

Once the conditions were counted, the specimens underwent the coating process immediately to prevent rapid corrosion formation, as shown in Figure 1 (c). The spray coating method was employed using epoxy mixed with aluminum-graphite pigment (in a ratio of 80% epoxy to 20% pigment), as can be seen in Figure 1(d), with a coating thickness of approximately 250 µm [19]. During the wet stage of the paint, Wet Film Thickness (WFT) was measured using a wet film comb to determine the thickness of the wet paint [20].

After the paint dries, Dry Film Thickness (DFT) was measured using a DFT measuring instrument, taking three measurements on each specimen and averaging the values to obtain the approximate DFT [21]. The DFT measurement used a surface profile gauge depicted in Figure 1 (e). Lastly, the specimens were subjected to heat treatment in a furnace at either 100°C or 150°C for 1 hour, as shown in Figure 1(f).

From surface preparation through adhesion and impact testing to CV. Cipta Agung in Surabaya hosted the study, while the ITS Corrosion and Material Failure Laboratory hosted the corrosion rate prediction test.



(a) (b) (c)

(d) (e) (f)

Figure 1.
The process of preparing test specimens
(a) Visual inspection of specimen cleanliness at Sa 2.5; (b) surface roughness measurement; (c) specimen coating by spray; (d) Wet paint surface Wet Film Thickness (WFT) measuring; (e) Paint surface Dry Film Thickness (DFT) measurement; (f) Samples are heated in a furnace between 100°C and 150°C.
Source: Research documentation

Adhesion Testing

The purpose of the adhesion test is to determine the strength of the paint layer. The adhesion testing method used is the pull-off test [22]. In Figure 2, the adhesion testing process has been illustrated, where the tools used in this test were a portable adhesive tester, glue, and dolly. Before the adhesion test process, the surface of the specimen was cleaned of dirt and other contaminants. Next, the dollies were attached at three points on each model, left for 24 hours, and removed with a portable adhesive tester. The value of the adhesion test results was calculated for the efficiency not given aluminum-graphite and heat treatment. The formula for calculating efficiency is as equation (1) below:

$$Efisiensi_n = \frac{Average_n - Average_{n-1}}{Average_{n-1}} x\ 100 \quad (1)$$

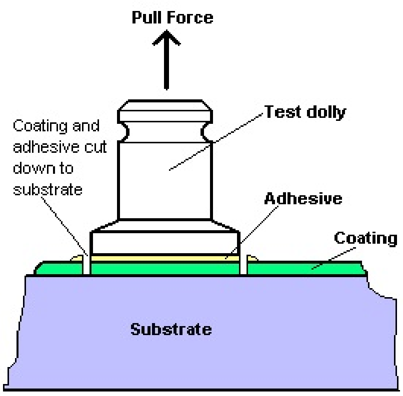


Figure 2.
Illustration of the process of adhesion testing [23]

Corrosion Rate Testing

The purpose of testing the corrosion rate is to determine the prediction of the corrosion rate. The seawater replacement solution used in this test was 3.5% NaCl. The specimen was clamped and dipped into a beaker containing 3.5% NaCl solution. The corrosion rate testing method was a three-electrode cell [24], which used the Autolab PGSTAT1238N potentiostat equipment and NOVA software, as shown in Figure 3.

Figure 3.
Corrosion Rate Testing Process
Source: Research documentation

Impact Coating Testing

The purpose of impact testing is to determine the resistance of the paint layer to impact. Figure 4 is an illustration of an impact coating test where Coated specimens are dropped loads from a certain height, which height can cause failure or damage to the coating layer. The test method used the falling weight method [25]. The test height started at 0.8 m with an interval of 0.1 m height increase. The height limit on the tool used was 1.4 m.

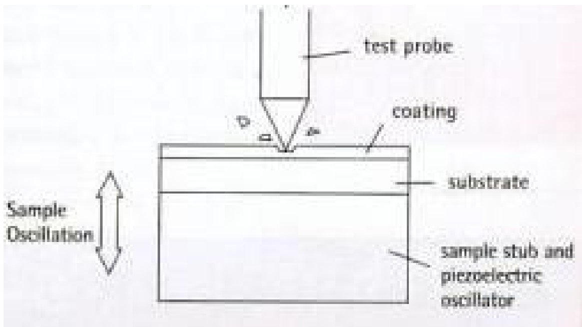


Figure 4.
Illustration of Impact Coating Test [26]

RESULTS AND DISCUSSION

Model Specimen

From the results of visual checking in Figure 5, the blasted specimens had reached the level of cleanliness used, namely Sa 2.5, so it can be stated that all models passed the cleanliness level SA 2.5. After visually checking the cleanliness level, the specimen's surface roughness was measured.

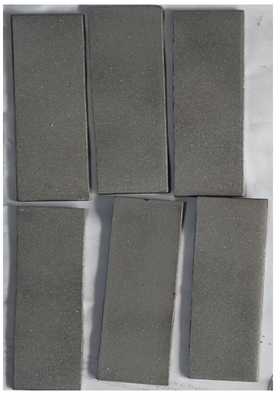


Figure 5.
Sandblasting results on test specimens
Source: Research documentation

Table 2.
Surface Roughness Measurement Results

No	Specimen Dimension	Surface Roughness Value (µm)			
		1	2	3	Average
1	150x50x5mm	80	90	65	78.33
2	50x50x5mm	88	80	80	82.67

Source: Research documentation

Table 2. shows that all specimens had met the surface roughness criteria of 30-85 µm, so it can be stated that all specimens blasted with aluminum oxide had passed the surface roughness. After measuring the surface roughness, the next step was estimating the environmental conditions.

Table 3.
Results of Measurement of Environmental Conditions

No	Parameter	Results
1	Wet Temperature	25°C
2	Dry Temperature	30C
3	Relative Humidity	67%
4	Dew Point	23°C
5	Steel Temperature	32°C

Source: Research documentation

Table 4.
WFT Calculation Results

DFT (µm)	Volume Solid (%)	WFT (µm)
±250	73%	±342

Source: Research documentation

Figure 6
WFT Measurement Results
Source: Research documentation

The WFT calculation in Table 4 shows that the wet paint thickness must be achieved was ± 342 µm. From the WFT measurement results in Figure 6, all specimens had reached the desired wet thickness, so it can be stated that all samples could wait to dry. After measuring the WFT and ensuring the paint was dry, the next step was to estimate the DFT.

Table 5.
DFT Measurement Results

No	Label Specimen	Hasil DFT (µm)			Average (µm)
		I	II	III	
1	1:1-TPP-AD	266	252	256	258.00
2	1:1-100°C-AD	268	258	262	262.67
3	1:1-100°C-AD	260	264	294	272.67
4	3:1-TPP-AD	270	258	276	268.00
5	3:1-100°C-AD	278	276	258	270.67
6	3:1-100°C-AD	280	272	274	275.33
7	1:1-TPP-IM	258	248	260	255.33
8	1:1-100°C-IM	270	254	266	263.33
9	1:1-100°C-IM	262	282	262	268.67
10	3:1-TPP-IM	264	260	254	259.33
11	3:1-100°C-IM	270	278	256	268.00
12	3:1-100°C-IM	264	262	284	270.00
13	1:1-TPP-K	240	260	246	248.67
14	1:1-100°C-K	252	244	260	252.00
15	1:1-100°C-K	256	258	276	263.33
16	3:1-TPP-K	256	260	248	254.67
17	3:1-100°C-K	266	260	274	266.67
18	3:1-100°C-K	246	252	258	252.00

Information:
TPP: No Heat Treatment
AD: Adhesion Test
IM: Impact Test
K: Corrosion Test
Source: Research documentation

Table 5 shows that all specimens had met the desired dry paint thickness criteria of ±250 µm. So, it can be stated that all specimens coated with a mixture of epoxy and aluminum graphite had passed the thickness of the dry paint.

Adhesion Test Results

The adhesion test results provided crucial information regarding the bonding strength and durability of the tested materials. Table 6 shows that the highest adhesive strength value was 19.62 MPa at the ratio of aluminium-graphite with a ratio of 1:1, which was given heat treatment at a temperature of 100°C. Meanwhile, the highest power value was 10.92 MPa at a ratio of aluminium-graphite with a ratio of 3:1, which was given a heat treatment of 100°C.

In Figure 7, it was observed that in all specimens not given heat treatment, adding aluminum-graphite pigment could increase the adhesion value compared to without dye. There was an increase in the adhesion values of all specimens due to heat treatment at 100°C, where the best adhesion values were obtained in specimens added with aluminum-graphite pigment in a ratio of 1:1.

After being given heat treatment with a temperature of 150°C, there was a decrease in the adhesive power values of all specimens compared to those given heat treatment with a temperature of 100°C. However, it can still increase the adhesion value compared to those not given heat treatment.

Elevating the ratio of coating pigment in high-temperature resistant adhesives has proven to be instrumental in enhancing the bonding performance of SS400 Steel. The deliberate augmentation of the pigment content in the adhesive formulation contributes to heightened thermal resistance, thereby fortifying the adhesive's ability to withstand elevated temperatures. Adding pigments and providing treatment increases the physical and chemical bond, thus increasing adhesive and cohesive strength [27], [28].

Table 6.
Adhesion Test Results

Label Specimen	Pull-Off Strength (MPa)			Average (MPa)	Efficiency (%)	STDEV
	Spot I	Spot II	Spot III			
0:0-TPP*	-	-	-	4.97	-	-
1:1-TPP	6.08	5.84	5.4	5.77	16.16	0.28
1:1-100°C	19.25	20.03	19.58	19.62	294.77	0.32
1:1-150°C	18.7	16.85	18.07	17.87	259.62	0.77
3:1-TPP	7.45	12.25	9.21	9.64	93.90	1.98
3:1-100°C	11.56	10.47	10.74	10.92	119.79	0.46
3:1-150°C	10.36	10.24	12.12	10.91	119.45	0.86

Information:
TPP: No Heat Treatment
*: Previous Research [27]

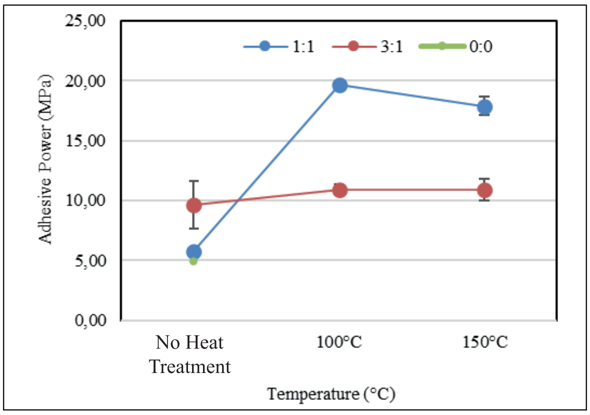


Figure 7.
Graph of Adhesion Test Results
Source: Research documentation

Impact Test Results

The impact test results provided critical insights into the material's resilience and resistance to impact forces, shedding light on its overall strength and durability. Table 7 shows that the highest potential energy value was 6.87 Joule in aluminium-graphite with a ratio of 1:1, which was given heat treatment with temperatures of 100°C and 150°C. Meanwhile, the highest power value was 5.39 Joules at the ratio of aluminium-graphite with a ratio of 3:1, which was given a heat treatment of 150°C.

In Figure 8, it is inferred that in all specimens that were not given heat treatment, the addition of aluminum-graphite pigment did not affect the value of the resistance of the coating layer to impact. There was an increase in the value of the resistance of the coating layer to impact on all specimens due to heat treatment at 100°C, where the best adhesion value was obtained on specimens added with aluminum-graphite pigment in a ratio of 1:1. After being given heat treatment with a temperature of 150°C, there was an increase in the value of the resistance of the coating layer to impact on the specimens added with an aluminum-graphite pigment of 3:1. Meanwhile, in specimens with the addition of aluminum-graphite dye in a ratio of 1:1, the value of the resistance of the coating layer to impact was the same as that given heat treatment at a temperature of 100°C.

This heat treatment imparts a remarkable ability to withstand the vibrational stresses induced by loads, preventing the occurrence of cracks. By subjecting SS400 Steel to controlled heating processes, the coating molecules achieve a state of flexibility that proves crucial in maintaining structural integrity under various mechanical stresses. The dynamic response of the coated surface to external loads is thereby significantly improved, as the heat-treated interface resists the initiation and propagation of cracks, ensuring a more durable and reliable performance [28].

Table 7.
Impact Testing Results

No	Specimen Labels	Load Weight (kg)	High Res. (m)	Potential energy (J)	Notes.
1*	0:0-TPP	0.5	0.8	3.92	Cracked
2	1:1-TPP	0.5	0.8	3.92	Cracked
3	1:1-100°C	0.5	1.4	6.87	Cracked
4	1:1-150°C	0.5	1.4	6.87	Cracked
5	3:1-TPP	0.5	0.8	3.92	Cracked
6	3:1-100°C	0.5	0.9	4.41	Cracked
7	3:1-150°C	0.5	1.1	5.40	Cracked

Information:
TPP: No Heat Treatment
*: Previous Research [29]

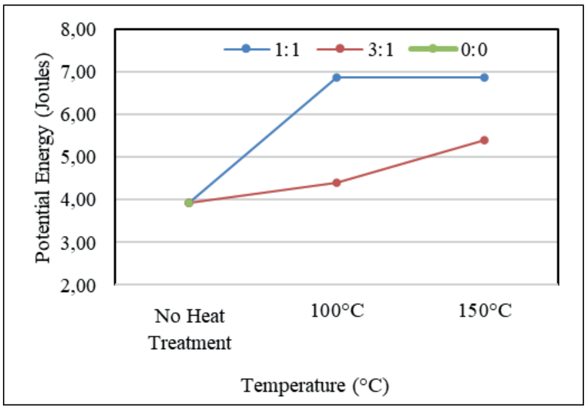


Figure 8.
Graph of Impact Test Results
Source: Research documentation

Corrosion Test Results

The corrosion test results revealed essential findings regarding the material's susceptibility to corrosion and its overall corrosion resistance properties. Table 8 shows that the lowest corrosion rate value was 0.05 mmpy on aluminum-graphite with a ratio of 1:1, which was given heat treatment at a temperature of 150°C. In comparison, the lowest corrosion rate value was 0.04 mmpy at the aluminium-graphite ratio with a ratio of 3:1, which was given heat treatment at a temperature of 150°C.

Figure 9 reveals that in all specimens not given heat treatment, adding aluminum-graphite pigments could reduce the corrosion rate value compared to those not coated. A decrease in the corrosion rate also occurred in all specimens that were given heat treatment at a temperature of 100°C, where the lowest corrosion rate value was obtained in the specimens added with aluminum-graphite pigment with a ratio of 3:1. After being given heat treatment with a temperature of 150°C, there was a decrease in the value of the corrosion rate in all specimens added with aluminum-graphite pigment, where the lowest corrosion rate value was found in specimens added with aluminum-graphite pigment with a ratio of 3:1.

Incorporating pigments and applying treatment processes to SS400 Steel offer a synergistic solution to reduce the corrosion current density, denoted as Icorr, within the coating layer. This dual approach not only mitigates the corrosion rate on SS400 Steel but also plays a crucial role in augmenting the density of the coating layer itself. The intensified density is a robust deterrent, impeding the penetration of aggressive media into the substrate. By effectively lowering the Icorr and fortifying the coating's thickness, this comprehensive strategy acts as a protective shield, bolstering the resistance of SS400 Steel against corrosive elements. It is particularly advantageous in scenarios where the substrate is exposed to harsh environmental conditions, ensuring the prolonged structural integrity of SS400 Steel by minimizing the impact of corrosive agents [30], [31].

Table 8.
Corrosion Rate Test Results

No	Label Specimen	Eccor (Volts)	Iccor (μA/Cm2)	Corr. Rate (mmpy)	Notes
1	TC-TPP	-0.60	$4.64x10e^{-5}$	0.54	Fair
2	1:1-TPP	-0.48	$3.99x10e^{-5}$	0.46	Good
3	1:1-100°C	-0.48	$2.60\ x10e^{-5}$	0.30	Good
4	1:1-150°C	-0.39	$4.57\ x10e^{-5}$	0.05	Very Good
5	3:1-TPP	-0.46	$1.15\ x10e^{-5}$	0.13	Good
6	3:1-100°C	-0.48	$5.81\ x10e^{-6}$	0.06	Very Good
7	3:1-150°C	-0.39	$4.02\ x10e^{-6}$	0.04	Very Good

Information:
TC: Without Coating
TPP: No Heat Treatment
Source: Research documentation

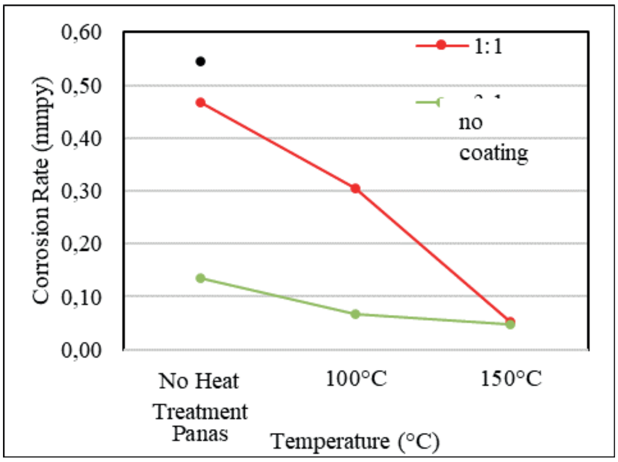


Figure 9.
Graph of Corrosion Test Results
Source: Research documentation

CONCLUSION

Experiments involving the addition of epoxy coating pigment to SS400 steel at temperatures and aluminum-graphite ratios that vary during heat treatment have been conducted successfully. Following the completion of adhesion, corrosion, and impact tests, it was determined that incorporating aluminum-graphite and thermal treatment could increase the coating layer's adhesion resistance and decrease its corrosion rate. The coating resistance remains unaffected by adding aluminum graphite; however, it can be enhanced by applying thermal treatment to the coating layer.

Investigating the microstructural alterations induced by the epoxy pigment ratio and heat treatment temperature conditions is particularly interesting for future research about the material's microstructure. Such research may contribute to a more comprehensive comprehension of how microstructural changes impact the SS400 steel's mechanical characteristics and long-term functionality.

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