Analysis of the Effect of Powder Coating Methods on Corrosion and Abrasion Resistance in Aluminum and Light Steel

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Abstract

Powder coating is a widely used method to protect metals from corrosion and enhance their resistance to environmental conditions. This study aimed to evaluate the effects of epoxy-based powder coatings on aluminum and light steel in terms of corrosion resistance, weather resistance, and maintenance efficiency. Aluminum samples with thicknesses of 15, 18, and 22 mm and light steel samples with thicknesses of 0,4, 0,7, and 2,2 mm were coated using an electrostatic spray gun. Variations were also applied based on the coating thickness, namely aluminum 0,26, 0,28, and 0,31 mm, and light steel 0,1, 0,3, and 0,5 mm. Corrosion rate testing was conducted by immersing the samples in a saltwater solution for 216 h, and surface degradation was evaluated using a scale from 1 to 5, where 1 indicates the lowest corrosion. The results showed that aluminum with a thickness of 22 mm and a coating of 0,31 mm exhibited the best corrosion resistance at level 1 owing to its naturally higher oxidation resistance and good coating adhesion. Light steel also exhibits improved resistance; however,its corrosion level is high. This study confirms that powder coating is an effective and economical method for enhancing the durability of aluminum and light steel, particularly at optimal material and coating thicknesses.
Keywords: aluminum, durability, corrosion resistance, lightweight steel, powder coating

Abstrak

Pelapisan bubuk merupakan metode yang umum digunakan untuk melindungi logam dari korosi dan meningkatkan ketahanan terhadap kondisi lingkungan. Penelitian ini bertujuan mengevaluasi pengaruh powder coating berbasis epoxy pada aluminium dan baja ringan terhadap ketahanan korosi, ketahanan cuaca, dan efisiensi perawatan. Sampel aluminium dengan ketebalan 15, 18, dan 22 mm serta baja ringan dengan ketebalan 0,4, 0,7, dan 2,2 mm dilapisi menggunakan pistol semprot elektrostatik. Variasi juga dilakukan berdasarkan ketebalan lapisan yaitu aluminium 0,26, 0,28, dan 0,31 mm serta baja ringan 0,1, 0,3, dan 0,5 mm. Pengujian laju korosi dilakukan dengan merendam sampel dalam larutan air garam selama 216 jam, dan tingkat kerusakan permukaan dinilai menggunakan skala 1 sampai 5, di mana 1 menunjukkan korosi paling rendah. Hasil menunjukkan bahwa aluminium dengan ketebalan 22 mm dan lapisan 0,31 mm memiliki ketahanan korosi terbaik tingkat 1 karena sifat alaminya yang tahan oksidasi dan adhesi lapisan yang baik. Baja ringan juga menunjukkan peningkatan ketahanan, tetapi tingkat korosinya lebih tinggi. Penelitian ini menegaskan bahwa powder coating efektif dan ekonomis untuk meningkatkan durabilitas aluminium dan baja ringan, terutama pada ketebalan material dan lapisan yang optimal.
Kata kunci: aluminium, ketahanan, ketahanan korosi, baja ringan, pelapisan serbuk

1. Introduction

Corrosion is one of the main problems faced by various industrial sectors worldwide because it can reduce the strength of materials and shorten the service life of metal components. The impact of corrosion is not only technical but also causes significant economic losses. Globally, losses due to corrosion are estimated to reach around USD 2.5 trillion per year, equivalent to 3.4% of the total world Gross Domestic Product (GDP).[1] [2] [3] In addition to economic losses, the corrosion process also has an impact on the environment because it contributes to increased carbon dioxide emissions from the production of replacement steel that has corroded, accounting for approximately 4–9% of total global steel industry emissions [4]. Corrosion occurs not only on steel but can also affect light metals such as aluminum, copper, and magnesium, especially when these metals are in environments with high humidity or high salt content [5] [6] [7].

The use of metallic materials, such as lightweight steel and aluminum, in Indonesia is increasing, particularly in the construction and automotive sectors, which require materials that are both high-strength and lightweight. However, Indonesia's tropical climate, which tends to be hot, humid, and frequently exposed to sea air, poses its own challenges as it can accelerate the corrosion process on metal surfaces [8] [9] [10]. Research has shown that rising temperatures and salt levels in coastal air directly increase the corrosion rate of carbon steel. [11]. Next, research was conducted by N. Li et al., (2023) [12] found that the 7B04-T74 aluminum alloy exposed to tropical marine environments experiences pitting corrosion due to exposure to chloride ions and high humidity, which accelerates the formation of corrosion compounds such as $Al(OH)_3$ and Al_2O_3. Cut et al. (2024) [13] observed that structural steel in the eastern coastal region of Aceh experiences significant atmospheric corrosion caused by a combination of high temperatures and high salt content in the air, which accelerates the deterioration of metal material quality. Al is a lightweight metal with good mechanical properties, corrosion resistance, and high electrical conductivity. However, its weakness lies in its relatively low mechanical strength compared to other metals. To address this, alloying elements, such as copper (Cu), magnesium (Mg), silicon (Si), and manganese (Mn), or other methods, such as adding zirconia, can be used to improve the mechanical properties [14][15] [16] [17]. Aluminum has a face-centred cubic (FCC) crystal structure with an atomic radius of 0.1431 mm, which provides unique characteristics and supports its mechanical and physical properties [18]. In contrast, light steel (cold-formed steel) is a construction material formed at room temperature using thin plates with a high width-to-thickness ratio, making it lightweight, yet strong [19] [20] [21]. G550 grade steel, with a yield strength of 550 MPa, is often used because of its high load resistance. However, the thinness of the plate makes light steel prone to local buckling in the web and flange; therefore, modifications to the cross-sectional geometry, such as the addition of longitudinal stiffeners, are necessary to improve its compressive capacity and performance under loads [22]. This also has the added benefit of providing other advantages such as corrosion resistance, fatigue (wear) resistance, and a low coefficient of expansion. This material is used in a wide range of applications, including household appliances, aircraft materials, automobiles, ships, and building construction [23] [24] [25]. To address this issue, an effective and environmentally friendly protection method is required to extend the durability and lifespan of the material [26]. One efficient method is to apply an aluminum layer or use coating materials that can resist oxidation [27].

One method of protecting against corrosion is coating, with powder coating being a commonly used technique [28]. This technique is becoming increasingly popular for coating metal surfaces, such as iron and aluminum. To achieve optimal painting results, the surface must be cleaned and prepared before application. The electrostatically charged powder layer is then applied and heated in an oven at 180-220°C to ensure that the coating adheres perfectly [29] [30]. Powder coating has several advantages, such as low volatile organic compound content, efficient material usage, energy savings, and no hazardous waste production. Therefore, this method is more environment-friendly and economical than conventional paintings [31] [32] [29].

Various studies have shown that coating methods, such as anodising and powder coating, play an important role in improving the corrosion resistance of metals, particularly aluminum. Cabral-Miramontes et al. [33] reported that the use of a citric–sulfuric solution can produce an oxide layer that is stronger and chemically more stable. This finding is supported by Fedyaev et al. [34], who indicated that environmental factors, such as temperature, radiation, and humidity, greatly affect the durability of the protective coating. Recent research by Fan et al. [35] showed that both coating methods can increase the corrosion resistance by up to 40% compared to conventional methods. This aligns with the increased effectiveness of these coatings. In addition, other studies have shown that the quality and density of the protective layer are crucial for determining the effectiveness of corrosion protection. Oh et al. [36] showed that PEO on aluminum 6061 forms a compact alumina (Al_2O_3) layer with few defects, significantly improving the corrosion resistance compared with uncoated surfaces. Baxevani et al. [37] found that the application of pre-anodizing before powder coating provides more optimal protection, especially in environments with high humidity.

Most previous studies have focused on only one type of material, whereas research comparing the corrosion resistance of aluminum and lightweight steel using the powder coating method under tropical climate conditions is limited. Based on this, the researcher will analyse the effect of applying the powder coating method on the corrosion resistance and the effectiveness of protection for both materials, considering the differences in the thickness dimensions of each aluminum and lightweight steel material.

2. Materials And Methods

In this study, two types of materials were used as the main specimens for the coating process and corrosion testing of aluminum 1100 and SPPC-HD Light Steel, as shown in Fig. 1. Aluminum 1100 is a type of commercial aluminum with high purity, approximately 99% Al content. This material is known for its excellent formability, good corrosion resistance, and ability to form a spontaneous Al_2O_3 oxide layer when exposed to air. This natural oxide layer provides basic protection against corrosion. Therefore, Al 1100 is widely used in various industrial applications that require a high surface stability and good conductivity. In this study, aluminum 1100 was chosen as the specimen material because of its sensitivity to corrosive media, making it easier to observe surface changes resulting from the coating process [38].

The second material used in this study was SPCC-HD, which is a low-carbon steel produced by a cold-rolling process that results in a smooth surface and stable mechanical characteristics. SPCC-HD has good formability and a high degree of ductility, making it suitable for deep-drawing and deep-curling processes. Its low carbon content also facilitates welding and maintains consistent material properties during formation. This material is also suitable for powder coating applications because its surface texture enhances layer adhesion, while its relatively low corrosion resistance makes coating necessary to improve protection and extend the lifespan of components [39].

As the basis for specimen characterisation, Table 1 lists the thickness variations of the two main materials studied, namely, light steel and aluminum, with each material having three thickness categories. Table 2 presents the differences in the coating layer thicknesses of both materials; both light steel and aluminum were tested at three coating thickness levels. The thicknesses of the two materials were measured using a micrometer.

Table 1. Types of material thickness with the same coating

No.	Material	Material thickness	Coating thickness	Dimensions of the coated material
1.	Light steel	0,4	0,1	0,6
2.	Light steel	0,7	0,1	0,9
3.	Light steel	2,2	0,1	2,4
4.	Aluminum	15	0,1	15,2
5.	Aluminum	18	0,1	18,2
6.	Aluminum	22	0,1	22,2

Table 2. Types of layer thicknesses with the same material

No.	Material	Material thickness	Coating thickness	Dimensions of the coated material
1.	Light steel	0,4	0,1	0,6
2.	Light steel	0,4	0,3	1
3.	Light steel	0,4	0,5	1,4
4.	Aluminum	15	0,26	15,52
5.	Aluminum	15	0,28	15,58
6.	Aluminum	15	0,31	15,62

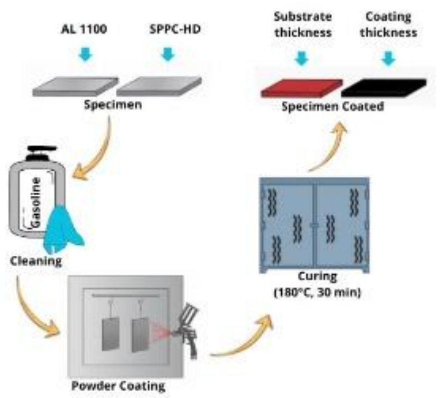
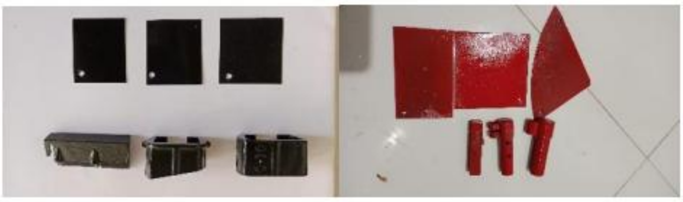


Fig. 1. Graphic illustration of the preparation process of coating

The specimens were coated using a powder-coating method. Previously prepared aluminum and light steel specimens were coated with an epoxy-based powder coating. shows the physical characteristics of the powder coating before it was applied to the specimen surface. Epoxy is a thermoset resin with excellent mechanical properties, heat resistance, moisture resistance, chemical resistance, and high adhesive strength. As a coating material, epoxy can be applied in liquid or powder form, is surface-tolerant, and is flexible for use as a primer, intermediate, or topcoat [40].

If the epoxy particles adhere evenly to the surface of the specimen, an electrostatic spray gun is used as an aid, which depicts the spraying device used in the coating process. In the painting process using a spray gun, the distance between the spray gun and the specimen surface must be carefully considered to ensure that the particle distribution remains uniform and does not accumulate in certain areas, depending on the object being painted. If the distance is too small, the paint will run, and if the distance is too large, the surface will become rough. If the spraying distance is inconsistent, the paint is streaky and slack shine. The general distance for a spray gun is 15-20 cm [41].

In the initial stage, before soaking in the saltwater solution, the coated specimen was visually inspected using a mobile phone camera to ensure that the coating was evenly applied, there were no surface defects, and the coating colour was uniform across all parts of the specimen. This process is illustrated in Fig. 2.



(a) **(b)**

Fig. 2. a). Coating thickness of specimen b). Iron thickness specimen before immersion in the salt solution

After ensuring that the quality of the layer on each specimen was good, the next step was to prepare the corrosion-testing medium. In this stage, a saltwater solution with a specific concentration was used as the immersion environment to test the resistance of the coating to corrosion; the concentration of the solution significantly determined how the corrosion reaction occurred on the metal surface.

Salt is an ionic compound consisting of positive (cations) and negative (anions) ions that forms a neutral compound (without a charge). The salt used was Sodium Chloride (NaCl). The salt consisted of 40 percent sodium and 60 percent chloride. When dissolved in water, chloride ions transform into hydrochloric acid, which lowers the pH value. The effect of chloride ions on the corrosion rate is also influenced by the salt concentration [42].

As a theoretical basis for understanding the corrosion process caused by the salt content in the immersion medium, a reference that can generally illustrate the extent of material damage is needed. The corrosion rate can be calculated using weight loss or electrochemical methods [43]. The corrosion rate was determined by measuring the mass loss of the specimens during immersion. Weight loss was calculated using Equation (1). Once the weight loss value was obtained, the corrosion rate of the specimen was calculated. The conversion of the corrosion rate into units of milli-per-year (mpy) is expressed by Equation (2).

$$W = W_2 - W_1 \quad (1)$$

A corrosion rate (mpy) of $534.W/D.A.T$ (2)

where: W weight reduction (mg), W_2 final weight, W_1 initial weight, A cross-sectional area (in), T time (hours), D specimen density (g/cm), Mpy Mils per year Constant when corrosion rate is expressed mpy, 1 mil 0,0254 mm. In addition to the weight-loss method, the corrosion rate can be determined using an electrochemical approach based on the principles of Faraday's law. The formula for calculating the electrochemical corrosion rate is presented in Equation (3) as follows:

CR(mpy) = $K.a.i.n.D$ (3)

where:

CR Corrosion rate, D Density (g/cm^3), K constant, mpy 0,129 μm/yr 3,27 mm/yr, a atomic weight of metal,n Number of electron lost, i current density (μA/cm^2).

Fig. 3. Soaking of Test Specimens

Based on the explanation of saltwater immersion, this study was conducted by soaking the specimens in a salt solution for 9 d or 216 h. During the soaking process, observations were made of any changes on the surface of the specimens were observed. The stages of this study included sample preparation, soaking process, and observation of the soaking results. To clarify the condition of the specimens during soaking, the visual observation results are presented in Fig. 3.

3. Results And Discussion

Visual observation is the first step in analysing corrosion occurrence. Visual observation was performed after soaking tests on mild steel and aluminum using a saltwater solution as the immersion medium. Its appearance after immersion is shown in Fig. 4.

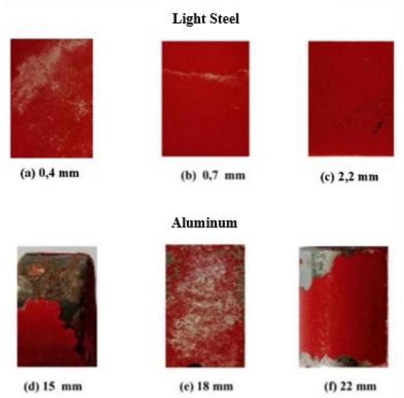


Fig. 4. Specimen results from immersion tests with different material thicknesses
Light steel a). 2.2 mm b). 0.7 mm c). 0.4 mm
Aluminum d). 15 mm e). 18 mm f). 22 mm

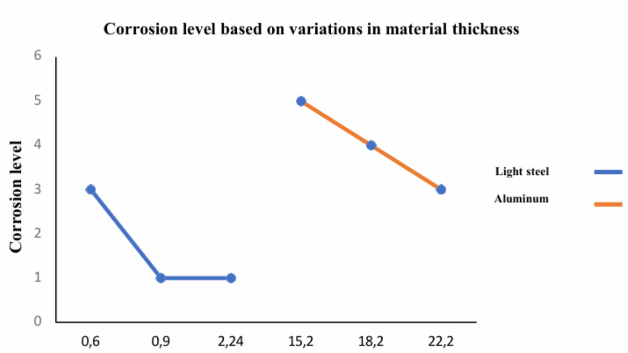


Fig. 5. Graph of corrosion rate versus material thickness

Visual observations of the specimens with varying material thicknesses were conducted, as shown in Fig. 4. It was found that the degree of surface damage was significantly influenced by the thickness of both light steel and aluminum. This damage pattern is further clarified by the graph in Fig. 5. This shows that the corrosion values tended to increase as the material thickness decreased.

The surface of the light steel exhibited varying levels of corrosion depending on the thickness of the material. In the 2.2 mm specimen, the paint layer still appeared to be in fairly good condition, with only a few small spots of corrosion visible, indicating that the protective coating was still functioning. In contrast, the 0.7 mm specimen shows more pronounced corrosion in the form of elongated lines, suggesting that the solution has penetrated through cracks in the coating, thereby affecting the strength of the steel. The most severe condition was observed for the 0.4 mm light steel. At this thickness, the damage was more extensive, and much of the coating surface peeled off, indicating that thinner materials are much more susceptible to thinning due to corrosion. The damage patterns in aluminum materials also vary. The 15 mm aluminum exhibited significant peeling of the layer and the formation of a thick oxide layer, but its thickness was still able to maintain the overall strength of the material. In the 18 mm aluminum, corrosion appeared to spread evenly with the characteristic greyish-white color of aluminum oxidation, indicating that the protective coating was no longer effective. Meanwhile, the 22 mm aluminum exhibited damage mainly along the edges, where liquid could more easily enter and trigger early oxidation, although the central part of the material remained relatively safe owing to its greater thickness.

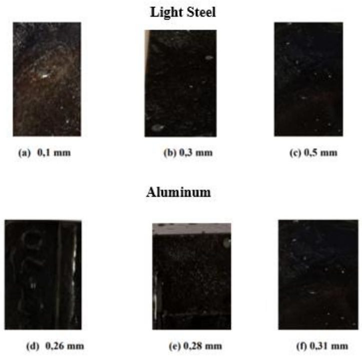


Fig. 6. Results of immersion tests on specimens with different coating thicknesses Lightweight steela). 0,1 mm b). 0,3 mm c). 0,5 mm. Alumunium d). 0,26 mm e). 0,28 mm d). 0,31 mm

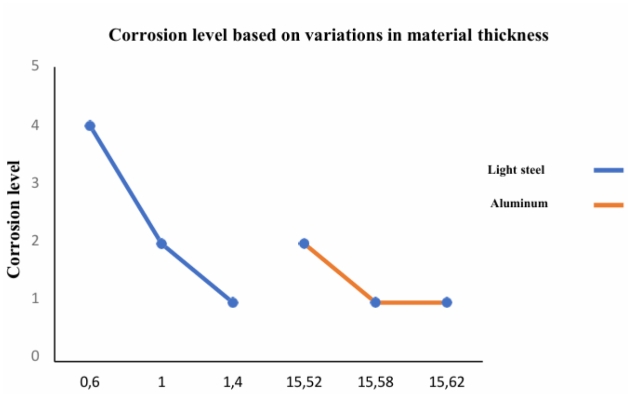


Fig. 7. Graph of corrosion values on layer thickness

Fig. 6, this shows that variations in the layer thickness result in clear differences in the surface conditions, where thinner layers are more prone to damage than thicker layers. This is consistent with the graph shown in Fig. 7, this demonstrates that the corrosion values consistently decreased as the coating thickness increased, thus reinforcing the idea that thicker layers provided more effective protection.

Variations in the thickness of the light steel layer showed a clear difference in its ability to resist corrosion. On the 0.1 mm specimen, corrosion spots are quite evident, and part of the surface has even exposed the base metal, indicating that this thickness is not yet able to provide adequate protection during immersion. The 0.3 mm specimen showed slightly better performance, although signs of corrosion still appeared; their intensity was lower, and most of the surface remained fairly well covered. The highest resistance in light steel was found at a thickness of 0.5 mm, where almost no damage was detected, and the layer remained firmly adhered across the entire area. In aluminum materials, the response to corrosion is also affected by the layer thickness. The 0.26 mm layer began to show subtle visual changes as an early indication of interaction with the solution, although no significant damage occurred. Aluminum with a 0.28 mm layer appeared more stable, with only a few minor surface oxidation spots. The best protection was observed for the 0.31 mm specimen, which kept the aluminum surface smooth and almost free of corrosion marks, indicating that increasing the layer thickness provides a much more effective protective effect.

The difference in the degree of damage between the two images is influenced by the manner in which the chloride ions penetrate the epoxy-based coating. Thin coatings tend to lose adhesion more quickly because the accumulation of corrosion products beneath the surface creates pressure that pushes the coating to lift off. In aluminum, this mechanism is even more pronounced because the material is highly susceptible to pitting corrosion when it reacts with chloride ions. Consequently, the coating was easily detached from the surface. This phenomenon aligns with the concept of localised corrosion, in which chloride ions can damage the passive layer of aluminum and rapidly trigger damage at specific locations [44].

4. Conclusion

This study demonstrates that epoxy-based powder coatings can enhance the corrosion resistance of aluminum and mild steel. The protection provided is significantly influenced by the thickness of the material and coating layer. Testing was conducted by immersing the samples in a saltwater solution for 216 h and evaluating the degree of surface damage on a scale of 1 to 5. Aluminum with a thickness of 22 mm and a 0.31 mm coating layer exhibited the best protection at level 1 owing to its naturally higher oxidation resistance and good coating adhesion, resulting in the least surface degradation. Mild steel with a thickness of 2.2 mm and a 0.5 mm coating layer also experienced increased resistance, although not as effectively as aluminum. Specimens with thinner coatings or materials sustained damage more quickly. Powder coating has proven to be an effective and economical coating method, and further research is recommended to evaluate the effects of extreme environments and the mechanical properties of the coating to optimise industrial applications.

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