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Comparative Analysis of Epoxy Coating Quality on ASTM AH-36 Steel Plates Using Surface Preparation Methods

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Abstract

The shipping industry, critical to the global economy, faces significant challenges due to corrosion in marine environments, particularly affecting steel structures like ASTM AH36 grade used in ships. This study investigates the effectiveness of two surface preparation methods—Abrasive Blast Cleaning and Power Tool Cleaning—on the adhesion of epoxy coatings, which are essential for enhancing corrosion resistance. Employing ASTM standards, we assessed surface roughness and adhesion strength, revealing that Abrasive Blast Cleaning produced a superior average roughness of 106.34 µm compared to 17.67 µm from Power Tool Cleaning. The Tape X-Cut test further demonstrated that the former achieved a perfect adhesion rating of 5A, while the latter only reached 4A, indicating slight peeling. These findings underscore the critical role of surface preparation in optimizing coating performance, suggesting that adopting Abrasive Blast Cleaning can significantly extend the lifespan and operational efficiency of both commercial and military vessels. This research not only addresses the urgent need for improved protective measures in the shipping sector but also contributes to reducing economic losses attributed to corrosion, estimated at 3-4% of GDP annually.

Keywords: *Shipping Industry; Adhesion Strength; Corrosion; Epoxy Coating; Surface Preparation*

Abstrak

Industri perkapalan, yang krusial bagi ekonomi global, menghadapi tantangan signifikan akibat korosi di lingkungan laut, yang terutama mempengaruhi struktur baja seperti baja ASTM AH36 yang digunakan pada kapal. Penelitian ini mengkaji efektivitas dua metode persiapan permukaan—Abrasive Blast Cleaning dan Power Tool Cleaning—terhadap adhesi pelapis epoksi, yang penting untuk meningkatkan ketahanan terhadap korosi. Menggunakan standar ASTM, kami menilai kekasaran permukaan dan kekuatan adhesi, dan menemukan bahwa Abrasive Blast Cleaning menghasilkan kekasaran rata-rata superior sebesar 106,34 µm dibandingkan dengan 17,67 µm dari Power Tool Cleaning. Uji Tape X-Cut lebih lanjut menunjukkan bahwa metode pertama mencapai peringkat adhesi sempurna 5A, sementara yang kedua hanya mencapai 4A, yang menunjukkan sedikit pengelupasan. Temuan ini menegaskan peran krusial persiapan permukaan dalam mengoptimalkan kinerja pelapisan, yang menyarankan bahwa penerapan Abrasive Blast Cleaning dapat secara signifikan memperpanjang umur dan efisiensi operasional kapal komersial maupun militer. Penelitian ini tidak hanya menjawab kebutuhan mendesak akan langkah perlindungan yang lebih baik di sektor perkapalan, tetapi juga berkontribusi dalam mengurangi kerugian ekonomi yang disebabkan oleh korosi, yang diperkirakan mencapai 3-4% dari PDB tahunan.

Kata kunci: Industri Perkapalan; Kekuatan Adhesi; Korosi; Pelapis Epoksi; Persiapan Permukaan

1. Introduction

The shipping industry is one of the most critical sectors and plays a vital role in supporting the global economy. The integrity of ship structures is highly dependent on the ability of materials to withstand the highly corrosive marine environment. In practice, ASTM AH36 steel is widely used for ship hulls, decks, and primary structural components in both commercial and military vessels due to its exceptional mechanical properties and compliance with maritime construction specifications. However, continuous exposure to seawater, high humidity, chloride ions, and aggressive marine environments greatly accelerates material degradation through corrosion processes [1].

Corrosion in ship structures represents a significant concern as it directly impacts structural integrity and service lifespan. The reduction in structural strength may manifest as uniform corrosion or localized corrosion such as pitting, both of which contribute to material thickness loss and a decline in ultimate strength. Corrosion in ships, particularly in structural elements, can reduce ultimate strength by up to 30% [2]. This degradation may result from uniform corrosion, which can cause material loss of up to 25%, as well as pitting corrosion with a volume loss (ΔV) of 16%. These conditions indicate that surface protection is not merely an additional measure but a fundamental necessity to maintain structural performance throughout the operational lifespan of the vessel [3]. In the chemical and petrochemical industries, the cost of dealing with corrosion issues can reach 70 to 80 percent of the entire maintenance budget [4]. This number highlights the significant impact of corrosion on the operational expenses, making efforts to mitigate its effects through effective surface protection indispensable.

One of the most widely applied protection methods for steel materials is epoxy coating. Epoxy coatings are known for their excellent chemical resistance, strong adhesion, and ability to form an effective barrier against corrosive agents. For this reason, they are extensively used in the shipping, oil, and gas industries to control corrosion rates in steel components [5]. Furthermore, the economic impact of corrosion—reported to reach 3–4% of a country's Gross Domestic Product (GDP) annually—highlights the importance of implementing effective protection systems [6]. A case study on corrosion management for offshore assets shows that 60% of highly critical assets are selected for routine maintenance to ensure optimal performance against corrosion threats [7]. Therefore, the performance of a coating system is not solely determined by the coating material itself but is also strongly influenced by the quality of its application process. Other studies show that differences in surface roughness and cleaning methods can affect adhesion strength of coatings by as much as 51% [8]. This indicates that choosing the right surface preparation method significantly influences the success of the coating, which in turn improves corrosion resistance.

In this context, the surface preparation process plays a crucial role in ensuring coating performance. The purpose of this process is not only to remove contaminants, corrosion products, and previous coatings but also to create a surface profile that enhances coating adhesion. Two commonly used methods in industrial practice are abrasive blast cleaning and power tool cleaning [9]. Abrasive blast cleaning generally produces a more uniform surface cleanliness and roughness profile, whereas power tool cleaning is more practical and cost-efficient in terms of equipment and operation [10]. These differences in characteristics are expected to influence the adhesion performance of the resulting epoxy coating.

Despite the widespread use of these surface preparation methods, studies that directly compare the effects of abrasive blast cleaning and power tool cleaning on the adhesion strength of epoxy coatings applied to AH36 steel remain limited and inconsistent, particularly in the context of ship structural applications. Previous research has largely focused on general coating performance or corrosion resistance, while the specific relationship between surface preparation methods, substrate characteristics, and coating adhesion strength has not been thoroughly investigated. This research gap highlights the need for a more focused experimental approach that will compare the adhesion strength of epoxy coatings based on different surface preparation techniques.

Based on this background, this study aims to analyze and compare the effects of abrasive blast cleaning and power tool cleaning on the adhesion strength of epoxy coatings applied to ASTM AH36 steel. Specifically, this study will evaluate the differences in adhesion performance resulting from each surface preparation method and identify the most effective approach to improving coating adhesion. The results of this study are expected to provide scientific contributions as well as practical recommendations for selecting the optimal surface preparation method to enhance coating durability and extend the service life of ship structures.

2. Material and Method

2.1. Substrate Material

In this study, ASTM AH36 steel is used, with the material composition listed in Table 1, which falls under the category of low-carbon steel. This type of steel is available in various forms, such as plates, profiles, and rods, and is known for its good mechanical properties, including strength, ductility, toughness, high formability, and ease of welding, as outlined in Table 2. Due to these properties, ASTM AH36 is widely used in various structural applications, such as building construction, bridges, and connections utilizing bolts, welding, or rivets. However, the main limitation of this steel lies in its low chromium and nickel content, which results in relatively low corrosion resistance[11].

Table 1. ASTM AH36 Steel Composition

Elements	Plate Thickness (mm)				
	≤20	20 - 40	40 – 65	65 – 100	>100
Copper (Cu)	0,20%	0,20%	0,20%	0,20%	0,20%
Carbon (C)	0,25%	0,25%	0,26%	0,27%	0,29%
Manganese (Mn)	-	0,80-1,2%	0,80-1,2%	0,85-1,2%	0,85-1,2%
Phosphorus (P)	0,04%	0,04%	0,04%	0,04%	0,04%
Sulfur (S)	0,05%	0,05%	0,05%	0,05%	0,05%
Silicon (Si)	0,40%	0,40%	0,15-0,40%	0,15-0,40%	0,15-0,40%

Table 2. Mechanical Properties of ASTM AH3 Steel

Properties	Amount
Tensile Strength, Ultimate (Mpa)	400-550
Tensile Strength, Yield (Mpa)	250
Elongation at Break	23%
Modulus Elasticity (Gpa)	200
Poisson Ratio	0,26
Shear Modulus (Gpa)	79,3

2.2. Surface Preparation

Figure 1. Surface preparation with a power tool

This study uses ASTM AH36 steel with dimensions of 300 x 300 x 7 mm, classified under rust grade A, as the main material. The samples are divided into two groups according to the surface preparation methods used: Power Tool Cleaning and Abrasive Blast Cleaning. In the Power Tool Cleaning method, the steel surface is polished using a grinder with a grinding wheel to reduce the formation of burrs, ridges, or unwanted scratches, as shown in Figure 1. The polishing process is repeated, followed by cleaning the surface with a cloth to remove any residue and dirt. Afterward, the steel surface is ready for the coating application[12]

On the other hand, in the Abrasive Blast Cleaning method, this process is used to remove heavy contaminants such as rust, mill scale, and old paint by blasting high-speed abrasive particles onto the steel surface, as shown in Figure 2. This method follows the SSPC SP-10: Near White Blast Cleaning standard, which requires 95% of the steel surface to be free from contaminants[13]. Before the blasting process begins, the steel surface is manually cleaned to remove dust and light dirt. Abrasive material in the form of steel grit is then blasted using air pressure from a compressor, aiming to achieve optimal surface cleanliness for the application of the organic coating layer.

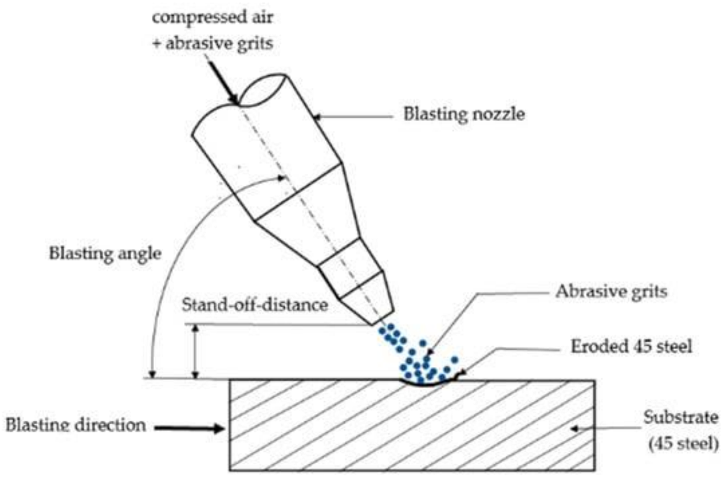


Figure 2. Illustration of abrasive blast cleaning[14]

2.3. Surface Roughness

Surface roughness is an important parameter that affects the adhesion strength between the substrate and the coating layer. The rougher the surface of the substrate, the larger the contact area between the substrate and the coating, allowing for mechanical interlocking to occur[15]. This process happens when the coating material penetrates the pores, holes, crevices, and voids on the substrate surface, forming a stronger bond as the coating layer cures. The greater the surface roughness, the more effective the penetration of the coating material, which, in turn, enhances the adhesion strength. However, excessive roughness can lead to issues such as bubble defects or circular defects, where air bubbles become trapped between the substrate surface and the coating layer, reducing adhesion strength and accelerating coating degradation.

To measure surface roughness, testing is conducted using several methods outlined in ASTM D4417 standards, including visual surface profile comparators, surface profile depth micrometers, and replica tapes[13]. In this study, method B (surface profile depth micrometer) was used, as it is considered more accurate and practical. The testing was carried out using the Elcometer 123 Surface Profile Gauge.

2.4. Coating Material

The coating material used in this study is surface-tolerant epoxy paint, with a mixing ratio of paint to hardener of 4:1, as shown in Figures 3A and 3B. Prior to application, material preparation was carried out by checking the expiration date, availability of materials, and readiness of supporting equipment. Additionally, environmental conditions were checked to ensure compliance with coating application standards. The coating material composition was then measured according to the technical data sheet (TDS), and the paint and hardener mixture was stirred until homogeneous[16]. Afterward, the prepared steel substrate was visually inspected to ensure it was free from rust, dust, and other contaminants. Environmental conditions, including steel temperature, air temperature, dew point, and relative humidity, were also checked to ensure these parameters met TDS standards. Once the inspection was complete and the results met the criteria, the mixed epoxy paint was applied using the rolling method with a roller, as shown in Figure 3C, with the aim of achieving optimal coating quality.

(a) **(b)** **(c)**

Figure 3. Mixing Ratio: (a) volume hardener 250 ml, (b) volume paint 1000 ml, (c) applying coating

2.5. Layer Thickness

The coating thickness testing on the ASTM AH36 steel substrate was conducted in two stages: first, during the wet film thickness (WFT) condition, and second, after the coating had dried (dry film thickness/DFT). For the wet film thickness measurement, the Elcometer 112 Wet Film Thickness Gauge was used in accordance with ASTM D4414 standards[17]. The measurement was performed by placing the gauge perpendicular to the freshly coated substrate surface, and the thickness value was obtained from the side of the gauge exposed to the coating[18]. This method aims to measure the coating thickness before the solvent evaporates. The wet film thickness was also calculated to ensure that it aligns with the target dry film thickness, using the following equation (Equation 1)[9].

$$\textbf{\textit{Wet Film Thickness}}\ (\mu\text{m}) = \frac{\textbf{\textit{Dry Film Thickness}}\ (\mu\text{m})}{\%\ \textbf{\textit{Volume Solid}}} \tag{1}$$

After the coating had dried, the thickness measurement was continued using the Elcometer 456 Coating Thickness Gauge, referring to ASTM B499 standards[19]. Measurements were taken at 7 different points, with two readings at each point. The dry film thickness (DFT) value was obtained by averaging the two measurements at each point, which were then combined to calculate the overall average thickness of all points. This method provided a quantitative value for the dry coating thickness after the coating application process.

2.6. Characterization of Layer Adhesion Strength Test

The Tape X-Cut test is used to evaluate the adhesion strength of the coating layer on the ASTM AH36 steel substrate, following ASTM D3359 standards[20]. The testing process begins by making two “X”-shaped cuts on the coating layer using a cutter, each measuring 1.5 in (40 mm) in length and 1 in (25 mm) in width at a 45° angle. A tape approximately

18 cm long is then applied to the cut area and rubbed to ensure it adheres perfectly. After 90 seconds, the tape is quickly removed at a 180° angle, and the peeling of the coating layer is observed to evaluate the extent of damage. The adhesion strength is then classified using the Rating Number scale based on ASTM D3359 standards, as shown in Table 3. The degree of coating removal is visually compared with the ASTM D3359 illustrations to determine the rating, ranging from no peeling (5A) to lost coating in the entire X area (0A), providing a quantitative measure of the coating's adhesion performance.

Table 3. Rating Description Number ASTM D-3359

Qualitative Adhesion Strength Scale	Description
5A	No peeling at all
4A	Slight peeling or loss of coating at the X intersection area
3A	Peeling or notching up to 1/16 in (1.6 mm) at the X intersection area
2A	Peeling or notching on both sides of the X intersection up to 1/8 in (3.2 mm)
1A	Coating lost in most of the X area
0A	Coating lost in the entire X area

3. Results and Discussion

3.1. Visual After Surface Preparation

Before applying the coating, surface preparation is a crucial step as the cleanliness and roughness of the substrate surface significantly affect the performance of the protective layer in preventing corrosion on steel. Each surface preparation method has different procedures and cleanliness parameters, which are examined through visual inspection by comparing the condition of the prepared surface against the established visual standards, such as SSPC VIS 1 and SSPC VIS 3. The surface preparation using the power tool cleaning method, as shown in Figure 4A, indicates that although some residual contaminants remain, the majority of impurities such as mill scale, rust, and old paint have been successfully removed, resulting in a surface cleanliness and roughness that meets the St 3 ISO 8501-1 and SSPC SP3 standards. Meanwhile, the abrasive blast cleaning method, as shown in Figure 4B, produces a steel ASTM AH36 surface free from contaminants, meeting the ISO 8504-2 and SSPC SP10 standards, and achieving the ideal cleanliness level for further coating applications.

(a)

(b)

Figure 4. Visual After Surface Preparation: (a) power tool cleaning, (b) abrasive blast cleaning

3.2. Surface Roughness

The ability of the coating layer to adhere to the substrate material is significantly influenced by the surface roughness resulting from the preparation process. A rougher surface increases the bond strength between the layer and the substrate. The power tool cleaning method produces a lower roughness value, with an average of 17.67 µm, because this method uses limited mechanical force, resulting in minimal surface degradation. In contrast, the abrasive cleaning method uses high-pressure media, which not only cleans the surface but also generates a higher roughness value, with an average of 106.33 µm. This increased roughness in the abrasive cleaning method creates more surface area for the coating to adhere to, which can enhance the adhesion strength, but also risks greater wear on the substrate if not controlled properly. Therefore, the selection of the surface preparation method must balance the need for roughness with the potential for damaging the material.

Table 4. Surface Roughness Test Data

Surface Preparation Method	Surface Roughness (µm)	Average (µm)
Power Tool Cleaning	22	17,6666667
	13	
	18	
Abrasive Blast Cleaning	96	106,333333
	121	
	102	

3.3. Environmental condition inspection

After the substrate surface has been cleaned through visual inspection and the roughness level has been determined according to standards, the next step is to apply the coating material. This should be done immediately to prevent contamination of the surface with dust or dirt. Before painting, the sample and environmental conditions are tested using the Elcometer 319 Dew Point to ensure that the field parameters meet the coating application standards. The parameters checked include steel temperature, dry temperature, wet temperature, dew point (DP), and relative humidity (RH). The test results showed a steel temperature of 31.5°C, dry temperature of 30.8°C, wet temperature of 24.7°C, dew point of 22.2°C, and a relative humidity (RH) of 60.3%. According to ASTM D3276, the recommended surface temperature range is between 10°C and 50°C, with an ideal RH range of 10% to 85%[21]. The results indicate that the environmental parameters are safe, meaning the rolling method can be used to apply the coating material with a target dry film thickness (DFT) of 250 µm.

3.4. Wet Film Thickness

The wet film thickness (WFT) refers to the coating thickness measured while the paint is still in its wet state, with the measurement taken using the Elcometer 112 wet film thickness gauge. Before application, the wet film thickness must be adjusted to the standards outlined in the product's technical data sheet (TDS). In this study, referring to the TDS of the surface-tolerant epoxy paint, the desired dry film thickness (DFT) is 250 µm, which is then converted to a wet film thickness of 337 µm through calculations based on Equation 4.1. According to the TDS, the surface-tolerant epoxy paint has a volume solid content of 74 ± 2%, and the calculated wet film thickness falls within the recommended range of 150–305 µm, as per the TDS, thus confirming that it is suitable for application in this study[16].

Table 5. Calculation of Wet Film Thickness

Coating Type	Wet Film Thickness	Volume Solid	Dry Film Thickness
Cat Surface Tolerant Epoxy	337 µm	74%	250 µm

3.5. Dry Film Thickness

After the paint is applied and undergoes the curing process on the substrate surface, the dry film thickness is measured using the Elcometer 456 Coating Thickness Gauge at seven different points on each sample, with two measurements taken at each point. The data is then averaged to obtain the final dry film thickness value. Based on Table 4.6, the measurement results show variations in the dry film thickness between points and samples, which are due to the application method used, namely the rolling method with a roller. While the spray method is more commonly chosen for its ability to produce more uniform layers, the rolling method was selected for this study because the surface-tolerant epoxy paint has high viscosity. The measurement results show that the dry film thickness with the power tool cleaning method averages 394.29 µm, while with the abrasive blast cleaning method, it averages 317.14 µm. Both methods show variations caused by the limitations of the rolling method.

Table 6. Dry Film Thickness measurement results

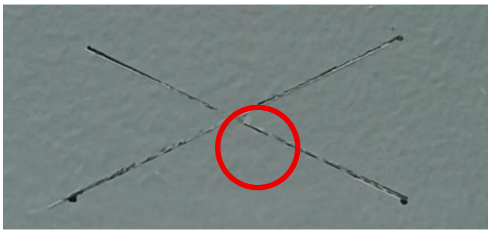
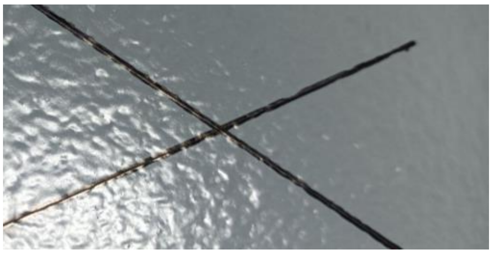
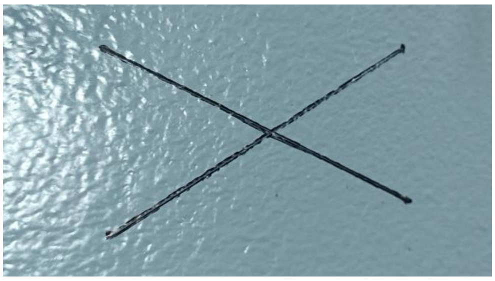
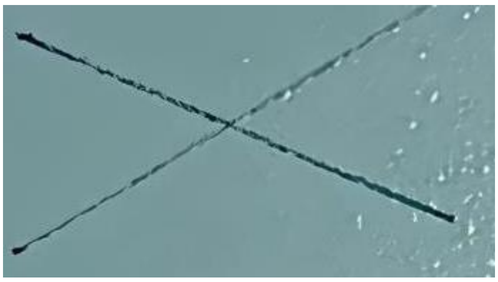
Surface Preparation Method	Sample Measurement Locations							Average DFT
	A	B	C	D	E	F	G	
Power Tool	319	406	433	329	339	533	401	394,2857143
Abrasive Blast	293	326	324	349	324	295	309	317,1428571

3.6. Tape X-Cut Test

The Tape X-Cut test is used to assess the adhesion strength of the coating layer on the substrate by applying tape to an X-cut pattern and quickly pulling it off at a 180° angle. This test follows ASTM D3359 standards, and the visual observations are compared with the illustrations and Rating Number table from ASTM D3359 to evaluate the extent of coating adhesion to the substrate. Each surface preparation method is tested at three different points to ensure consistency in adhesion results. The test measures the level of coating removal and is classified into different adhesion categories based on the amount of damage observed, ranging from a perfect adhesion to total detachment of the coating. This process provides a reliable indication of the coating’s durability and its ability to withstand mechanical stress and environmental exposure.

The Tape X-Cut test results presented in Table 7 show that the Abrasive Blast Cleaning method delivers the best adhesion performance with a consistent rating of 5A, indicating that the coating layer adheres perfectly without any peeling. In contrast, the Power Tool Cleaning method only achieved a rating of 4A, which indicates slight peeling at the intersection of the cuts due to roughness and surface cleanliness that were not optimal. This suggests that the higher cleanliness and roughness achieved by the Abrasive Blast Cleaning method significantly enhance the adhesion strength of the coating layer to the substrate.

Table 7. X-Cut Tape test results

Surface Preparation Method	Visual Results Tape X-Cut	Qualitative Adhesion Strength Scale
		4A
Power Tool		4A
		4A
		5A
Abrasive Blast		5A
		5A

4. Conclusion

Based on the results of the research and observations conducted, it can be concluded that the Abrasive Blast Cleaning method is the most effective surface preparation method for removing contaminants from the substrate. Surface roughness testing using the Elcometer 123 Surface Profile Gauge, in accordance with ASTM D4417 Method B, shows that this method produces the highest roughness level with an average of 106.34 µm, significantly higher than the Power Tool Cleaning method, which only reached 17.67 µm. Furthermore, the adhesion strength test using the Tape X-Cut method also demonstrates that Abrasive Blast Cleaning provides the best adhesion, with a Rating Number of 5A, indicating that there is no peeling of the coating layer on the steel substrate.

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