

Article

Effectiveness of Bonding Steel Elements with Polyester-Coated Paint

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Abstract: The aim of the paper is to assess the impact of the effectiveness of bonding steel elements with paint coating. The adhesive joints were made using two types of the adhesives: two-component epoxy resin adhesive based on Bisphenol A and polyurethane. Three types of adhesive joints were made: (i) reference samples, (ii) samples with a paint polyester coating, and (iii) samples with a zinc primer and paint polyester coating. These coatings were applied using the electrokinetic method. A shear strength test of the adhesive joints (EN DIN 1465 standard), a coating adhesion test (ASTM D3359-B standard), and surface wettability tests (based on contact angle) were used. Through analyzing the test results, it can be seen that the strength of the adhesive joints of the reference samples made with epoxy adhesive is 46% lower than that of the specimens with primer and paint coating applied. However, in the case of the adhesive joints made with the polyurethane adhesive, the aforementioned difference in the strength value of the adhesive joints of the reference samples and paint-coated samples with an applied primer is 76%. Adherends with a paint coating and a previously applied primer obtained the lowest value of the contact angle (38.72°) and are characterized by good wettability.

Keywords: adhesive joint; paint coating; surface treatment; wettability; steel; shear strength



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1. Introduction

Joining materials has long played a significant role in many industries, and one of the methods of joining materials is bonding [1,2]. The bonding process is inherent in the phenomenon of adhesion, which also occurs in the area of surface engineering, including the application of paint, enamel or varnish coatings, and coatings with special properties [3–9].

The variety of application with respect to adhesives is very large [1,10–12]. The bonding process itself has a number of advantages and applications in the automotive, wind turbine blade, aircraft, and marine industries, as mentioned in some recent research studies [13–18]. Due to the existence of adhesives, it is possible to produce parts and assemblies with a smoother surface. The bonding process also allows for the use of lightweight construction materials. By using bonding technology, it is possible to join very small elements, as well as those with unusual shapes. In many cases of joining elements with other techniques, there is a risk of electrochemical corrosion, and in the case of the bonding process, the adhesive layer insulates both joined elements, which almost completely eliminates the problem [3,12]. An important step in preparing the adhesive joints is the proper selection of the method of the surface treatment of the adherends, which is reflected in numerous works [19–26]. The choice of the method of surface treatment of the adherends depends on many factors, including the type of material and its properties. The surface treatment enables the appropriate surface structure and its proper energy activation, which

contributes to the adhesion phenomenon that is a prerequisite for obtaining a bond (e.g., adhesive–surface, coating–surface) with a specific adhesion force [27–30]. The surface treatment process can be assessed by wettability or surface free energy based on contact angle measurements [30–38]. Prakash and Prasanth [39] underlined the importance of evaluating the properties of the surface by determining, e.g., the wettability of various processes. They also emphasized that the wettability of a liquid on a surface varies depending on surface properties such as roughness, surface energy, and structure. Janssen et al. [40] found that contact angle values can be a direct indicator of solvent wettability and enable the selection of a suitable solvent or surface treatment to ensure good solvent wetting.

Another important feature of bonding is also the ability to join different types of materials. Among the types of materials joined by adhesive bonding, both steels [10,21,25,26,32] and metal alloys, including aluminum alloys [11,25,31], are worth mentioning. One of the possibilities is also the bonding of materials on the surfaces of which various types of coatings are applied (e.g., for anti-corrosion protection), including, e.g., elements with different types of coatings [5,41–44].

Considering the above, during bonding, coated materials can be considered as hybrid materials (substrate and coating), but from a surface treatment point of view, coating can also be considered as one of the surface treatment methods.

This paper presents various problems related to metal bonding technology and powder coating technology. The factors such as the proper treatment of the surface before bonding, the right choice of adhesive, or the method of its application are very important when making adhesive joints with the required strength. Applying paint coatings to metal elements also has a significant impact on the strength of the adhesive joint and its functionality.

The aim of this work was to assess the impact of the effectiveness of bonding steel elements with paint coatings, based on the results of strength tests. In addition, attention was paid to the type of paint coating used and the use of a primer compared to uncoated elements (reference samples), evaluating these factors in terms of the strength (EN DIN 1465 standard) results obtained, the coating adhesion test (ASTM D3359-B standard), and surface wettability tests (based on contact angle). The adhesive joints were made using two types of adhesives: two-component epoxy resin adhesive based on Bisphenol A and polyurethane. Three types of adhesive joints were made: reference samples, samples with a paint coating in the form of polyester (powder) paint, and samples with a zinc primer and paint coating in the form of polyester paint. The paint coating was applied using the electrokinetic method.

As part of our research, attention was paid to the behavior of materials containing coatings (single—paint and combined—primer layer and paint coating) in the adhesive connection. Attention was paid to the issue of whether the presence of the above-mentioned coatings affects the strength of adhesive bonds between materials and coatings. Of course, the literature presents issues related to the bonding of materials containing various coatings, but in this case, a complex system involving basic material (substrate), a primer, and paint coating was also compared, and the primer used in this study is not a typical primer offered by industrial chemistry manufacturers, but a primer applied as a paint coating according to the technology used in a construction industry plant.

2. Materials and Methods

2.1. Paint Coatings

Powder paint and primer were used to make the paint coatings for the steel samples. Selected properties of the created paint coatings are presented in Table 1.

The method of producing the coatings and the technological parameters of this process are listed in Section 2.3. The polyester paint, zinc primer, and samples with a paint coating and samples with a primer and paint coating were prepared in an industrial plant. No commercial paints were used, and the developed process of applying such coatings was used to make the paint coatings.

Table 1. Variants of paint coatings.

Properties	Description	
Type of paint coating	Paint coating	Primer and paint coating
Paint color	9001 (creamy white)	7024 (grey graphite)
Paint surface	smooth mat	smooth mat
Resin	polyester	polyester
Paint curing temperature [°C]	200	200
Degree of paint gloss [%]	18–30	28–40
Additionally applied primer layer	-	zinc primer layer

2.2. Adherends

The adherend samples were prepared from an unalloyed carbon steel sheet with the designation 1.0503 (PN-EN 10027-2). The selected mechanical properties of this steel sheet are shown in Table 2.

Table 2. Mechanical properties of steel adherends (PN-EN 10027-2).

Properties	1.0503 Steel
Tensile strength R _m , MPa	560–850
Yield point R _e , MPa	275–490
Elastic modulus E, GPa	198–207
Elongation A ₅ , %	14–17
Percentage reduction of area, %	35–45
Hardness in a softened state, HB	≤229

2.3. Process of Preparing and Applying Paint Coatings

Three types of adherends were joined:

- Reference samples;
- Samples with a paint coating in the form of polyester (powder) paint;
- Samples with a zinc primer and paint coating in the form of polyester paint.

Polyester powder paint was used to make the painting surfaces. Coatings of this kind can be obtained via electrokinetic spraying followed by curing the powder. They are characterized by significant corrosion resistance and impact and abrasion resistance. Polyester paints can be used outdoors. They do not change their color under the influence of weather conditions or UV radiation. An advantage of using these powder coatings was that they provided coatings of desirable thicknesses (for a single application).

Zinc primer is a protective layer that also protects against corrosion. It includes modified high-density epoxy resins as well as moisture resistance. In combination with metal, it also becomes a corrosion-resistant electrochemical. The structure of the zinc primer coating facilitates the adhesion of subsequent layers, including paint layers. The thickness of the zinc primer layer was 60–80 µm, and its curing was carried out at 180 °C. After applying the zinc primer, it is possible to apply subsequent layers of paint coatings (i.e., in this case, polyester paint). A scheme of the process for preparing samples with a coating of polyester paint and with a primer and polyester paint is shown in Figure 1, and a description of the stages is given below.

The first stage of the process of preparing paint coating samples with the applied primer and the paint coating was surface treatment. Two baths were carried out: a chemical bath and iron phosphating. The samples were then rinsed with demineralized water for 1 min. The samples were then dried in a warm drying oven at 120 °C for 10 min. Then, a zinc primer (thickness 60–80 µm) was applied. The samples were cured in an oven at

180 °C for 15 min. Such ovens are equipped with blowing devices at the entrance so that water does not enter the furnace while moving the elements from the wash tubs.

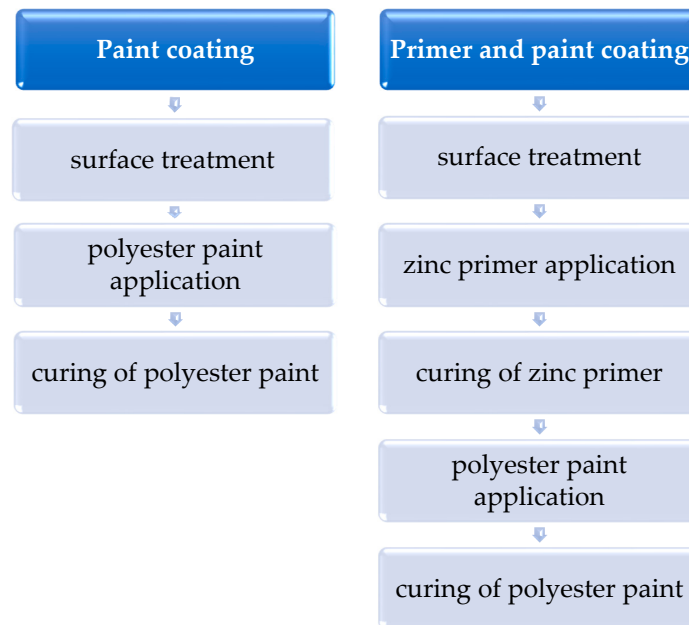


Figure 1. Scheme of the process of preparing samples with a coating of polyester paint and with a primer and polyester paint.

The next step was the application of polyester paint using the Tribo method with a gun (Adal, Czosnów, Poland). In such a device, powder particles are charged by the electrokinetic method due to friction. After coating, the samples were cured at 160 °C for 15 min.

The preparation process for the samples with the applied paint coating was carried out in a similar way. First, a chemical bath was prepared to degrease the surface, followed by iron phosphating. The samples were rinsed with demineralized water and then dried at 120 °C. The next stage was the application of a paint coating (polyester paint) with a gun. At the end, the sample was cured at 180 °C for 15 min.

2.4. Shape and Dimensions of Adhesive Joints

The adhesive joints during the tests were in the form of a single-lap joint. The adherend material was steel sheet (1.0503) with dimensions ($L_s \times w_s \times t_s$) of $100 \pm 0.02 \text{ mm} \times 25 \pm 0.12 \text{ mm} \times 2 \pm 0.01 \text{ mm}$. Adhesive layer length (l_{ad}) was $14 \pm 0.41 \text{ mm}$, and the thickness of the adhesive layer (t_{ad}) was $0.20 \pm 0.03 \text{ mm}$. A scheme of the adhesive joints used during the tests is shown in Figure 2.

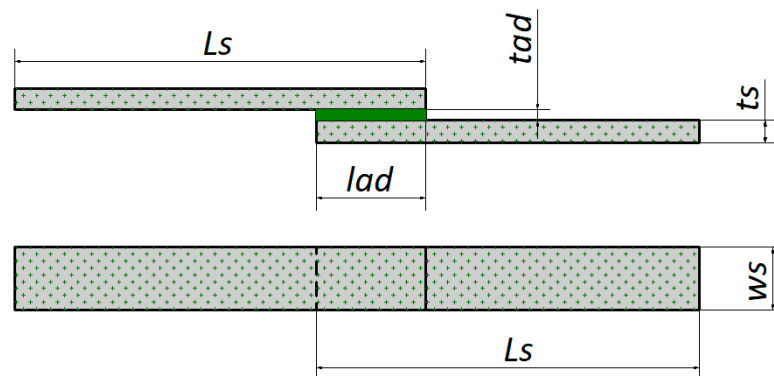


Figure 2. Scheme of a single-lap adhesive joint: L_s —length of the sample, t_s —sample thickness, w_s —sample width, l_{ad} —length of the adhesive layer, t_{ad} —adhesive layer thickness.

The thickness of the adhesive layer was controlled by pressure, and a special holder was used to fix the joined samples and apply pressure.

2.5. Adhesives

Two types of adhesives were used to prepare the adhesive joints: a two-component epoxy resin adhesive based on Bisphenol A and a polyurethane adhesive. This study involved the use of two adhesives that differ in both chemical base and properties. Both are used as construction adhesives, with the polyurethane adhesive being more flexible and also combining sealing properties to a great extent. It is widely used in the automotive industry. As a structural adhesive with good adhesion to many materials, the epoxy adhesive prepared on the basis of epoxy resin on bisphenol A (together with a specific curing agent) was chosen due to its ability to achieve high-strength bonds. However, in relation to other epoxy adhesives, the use of a polyamide curing agent contributes to an increase in the flexibility of the epoxy adhesive.

The two-component epoxy adhesive contained a modified epoxy resin based on bisphenol A with an epoxy number of 0.41 mol/100 g and viscosity at 25 °C ranging from 900 to 1500 mPa·s (Epidian 53—trade name, Sarzyna Resins, Nowa Sarzyna, Poland) and a polyamide curing agent with an amine number between 290 and 360 mg KOH/g and viscosity at 25 °C ranging from 10,000 to 27,000 mPa·s, (PAC—trade name, Sarzyna Resins, Nowa Sarzyna, Poland). The epoxy resin and the amide curing agent were mixed in a stoichiometric resin/curing agent ratio of 100:80 (part by weight). The properties of the individual components of the adhesive and the method of the epoxy adhesive preparation are described in [45]. The designation of the epoxy adhesive used in the tests is E53/PAC/100:800.

The polyurethane adhesive (Soudal Flex PU40—trade name, SOUDAL, Czosnów, Poland) was a one-component, solvent-free elastomeric sealing adhesive. The base of this adhesive is polyurethane.

2.6. Adhesive Joints Technology

The process of preparing the adhesive joints included the following stages: (i) the preparation of the adherends' surface, (ii) the preparation of the adhesive (in the case of the epoxy adhesive), (iii) the application of the adhesive, (iv) the creation of one-lap adhesive joints, and (v) curing.

- (i) In the case of the reference samples, prior to applying the paint coating, the surfaces of the samples were degreased with technical acetone (Aned, Nowa Sucha, Poland) to remove any impurities.
- (ii) In the case of the two-component epoxy adhesive, it was necessary to carry out the adhesive preparation step. For this purpose, the appropriate amounts of adhesive components (epoxy resin and polyamide curing agent) were measured using a TP-2/1 balance (Fawag, Lublin, Poland), and then the epoxy resin and the amide curing agent were mixed in a stoichiometric resin/curing agent ratio of 100:80 (part by weight). In order to mix the ingredients, a plate mixer and a polymer cup were used using the special adhesive mixing station. The mixing speed was 460 rpm, and the mixing time was 2 min. After mixing the adhesive components, the adhesive was degassed at a special station equipped with a container and a vacuum pump for 2 min. Regarding the polyurethane adhesive, there was no need to carry out the adhesive preparation step.
- (iii) After preparing the epoxy adhesive, a layer of the adhesive was applied using a polymeric spatula. The same operation was carried out for the polyurethane adhesive.
- (iv) After the surface and epoxy adhesive were prepared and the individual adhesives were applied, one-lap adhesive joints were created.
- (v) The curing process was carried out in one step at ambient temperature under a load of 0.02 MPa, and the curing time was 7 days. The thickness of the adhesive layer was controlled by pressing and using a special holder for fixing and pressing the joined samples. According to the information presented in [44], one-part polyurethane

adhesives can react with moisture to polymerize and cure. Since the curing of a one-component adhesive and moisture-curing polyurethanes depends on the diffusion of moisture through the polymer, the maximum depth of cure that can be achieved in a reasonable amount of time is limited to nearly 9.5 mm. Taking this fact into account, they assumed the same thickness of the adhesive joint as in the case of the epoxy adhesive in order to ensure that the curing process took place over the entire thickness of the adhesive joint.

The treatment of the surfaces, the epoxy adhesive preparation process, and the curing of the adhesive joints (using two types of adhesive) were conducted at ambient temperatures and a air humidity of 33–35%.

A summary of the number of adhesive joints made with various types of steel samples with paint coating and adhesives is presented in Table 3, and a few examples of the adhesive joints are shown in Figure 3. Comparative samples in the tests were reference samples that did not contain the paint coating; they were only degreased with acetone (as mentioned at the beginning of Section 2.5).

Table 3. Summary of the number of adhesive joints created.

Type of Adhesive	Type of Adherend			Sum
	Reference	Paint Coating	Primer and Paint Coating	
Epoxy	6	6	6	18
Polyurethane	6	6	6	18
Sum	12	12	12	36



(a)



(b)



(c)

Figure 3. Examples of adhesive joints made using samples. (a) Reference, (b) with paint coating, (c) with primer and paint coating.

2.7. Tests

To assess the impact of bonding effectiveness, the shear strength of the adhesive joints was tested (EN DIN 1465 standard), and the steel elements with paint coatings were subjected to the coating adhesion test (ASTM D3359-B standard) and surface wettability tests (based on the contact angle).

2.7.1. Strength Test, Failure Analysis, and Statistical Analysis

The shear strength tests of the adhesive joint samples were carried out on a Zwick/Roell Z150 testing machine in accordance with the DIN EN 1465 standard. The parameters for the strength test of the adhesive joint samples were as follows: initial force—5 N and crosshead speed—20 mm/min. The shear test of the adhesive joints was conducted at an ambient temperature and an air humidity of 33–35%. The conditioning time of the adhesive joint samples from the end of the curing process was 24 h (in the same conditions in which the strength tests were carried out).

A visual assessment of the adhesive joint failures after the strength test was conducted in accordance with EN ISO 10365. According to the aforementioned standard, failure types

can be divided into six groups, three of which relate to substrate failure and the other three pertain to damage to the adhesive layer.

After receiving the measurement results, extreme results were discarded in order to calculate the numerical mean of a given measurement. The Pearson correlation coefficient $r(X,Y)$ was also used to compare the selected values. This is a coefficient that determines the level of linear dependence between random variables. The linear correlation coefficient of two variables is the quotient of the covariance and the product of the standard deviations of these variables [46]:

$$r_{X,Y} = \frac{\text{cov}(X,Y)}{\sigma_X \sigma_Y} \quad (1)$$

where cov is the covariance, σ_X is the standard deviation of X , and σ_Y is the standard deviation of Y .

2.7.2. Coating Adhesion Test

Coating adhesion tests (cross-section) to the steel substrate were executed using the cross-cut method. Adhesion tests were carried out based on the ASTM D3359-B standard using the Elcometer 107 F10713348-6 set (Ako, Gdynia, Poland). For this test, the samples with paint coatings with dimensions of $100 \times 25 \times 2$ mm (i.e., the samples intended for bonding) were used. Incisions were made in the center of the sample to remove all doubt from the results obtained; successive cuts were made on the remaining surface of the coated steel sample. The results of the cut lines were used to interpret the obtained results, based on the data contained in Table 4 (according to the ASTM D3359-B standard).

Table 4. Evaluation criteria of coating adhesion test results (according to the ASTM D3359-B standard)—Method B adhesion rating scale [21].

Rating Scale	Evaluation Criteria of Coating Adhesion Test Results
5B	The edges of the cuts are completely smooth; no squares of the mesh skin have been torn off.
4B	Only small flakes of the coating at the edges of the cut grid have been torn off. No square of the rectangular slit grid has been torn off. The total area of the damaged coating is not more than 5%.
3B	Coating peels off with small flakes along the cut line of the net and visible cracks and small pieces of coating peeling between the lines of the net. Total area of damage greater than 5% but not more than 15%.
2B	The coating flakes off along the cuts partially or fully as long ribbons and/or flakes off partially or completely from the squares of the cut grid. Damage area greater than 15% and less than 35%.
1B	The coating flakes off along the cuts in the form of long ribbons and/or flakes off partially or completely from the squares of the score grid. Damage area greater than 35% and less than 65%.
0B	Any degree of detachment of the coating that cannot be classified as 1B.

2.7.3. Surface Wettability Test and Contact angle Measurement

Determination of wettability by the degree of wetting of the analyzed surfaces of coated steel samples was made on the basis of measuring the value of the contact angle using distilled water (selected as a polar liquid). The criteria presented in Table 5, which were developed on the basis of information contained in [47], were used for this assessment. Our focus was on the solid–liquid interaction (i.e., steel substrates with a paint coating—distilled water).

Table 5. Criteria for assessing surface wettability.

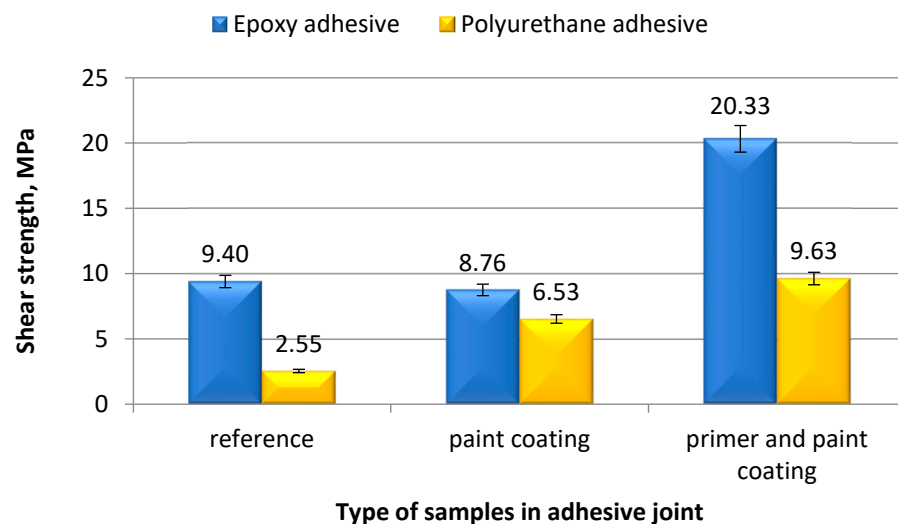
Range of Contact Angle Values	Degree of Wetting	Interaction Strength
		Solid–liquid
$\theta = 0^\circ$	Perfect wetting	Strong
$0^\circ < \theta < 90^\circ$	High wettability	Strong (values closer to 0°)
		Weak (values closer to 90°)
$90^\circ \leq \theta < 180^\circ$	Low wettability	Weak
$\theta = 180^\circ$	Non-wetting	Weak

Contact angle measurements were carried out using the Phoenix 300 goniometer (SEO, Saneop-ro, Republic of Korea) and Surfaceware 7 software. Direct contact angle measurements were used. The volume of the distilled water drops was $2 \pm 0.12 \mu\text{L}$, and the height of application with a liquid drop dispenser was 20 mm from the surface of the tested sample. The measurement of the contact angle of 5 drops was carried out automatically immediately after depositing a drop of distilled water into a particular type of surface of the steel samples. The measurement of the contact angle was carried out on three types of samples: (i) reference samples, (ii) samples with a paint polyester coating, and (iii) samples with a zinc primer and paint polyester coating (listed in Table 3).

3. Results

3.1. Strength Test

The shear strength test results for the adhesive joints of the three types of samples (reference, with a paint coating applied, and with a primer and paint coating applied, all of which were made via using an epoxy adhesive and polyurethane adhesive) are shown in Figure 4.

**Figure 4.** Shear strength of adhesive joints made with epoxy and polyurethane adhesive.

Based on the results presented in Figure 4, it is possible to assess the effect of the applied paint coating on the strength of the adhesive joints. Through analyzing the adhesive bond strength results of the three types of specimens related to the epoxy adhesive, it can be seen that they have the highest adhesive bond strength of the specimens with a primer and paint coating applied, which is 20.33 MPa. The lowest strength is shown by the adhesive joints of the samples with the applied paint coating (8.76 MPa). The strength of the adhesive joints with a zinc primer and paint coating applied is 57% greater than the strength of the joints of the samples with only a paint coating applied. Through analyzing the test results,

it can be seen that the strength of the adhesive joints of the reference samples is 7% higher than the strength of the adhesive joints of the samples with the paint coating. The strength of the adhesive joints of the reference samples is 46% of the strength of the adhesive joints of the samples with the applied primer and paint coating.

Through analyzing the graph of the shear strength test results for the adhesive joints of the three types of samples related to the polyurethane adhesive, it can be concluded that the highest strength value is shown by the samples with a zinc primer and coating applied. Their strength is equal to 9.63 MPa and is 74% higher than the shear strength of the reference samples, which is 2.55 MPa. Considering the results of the strength tests, it can be also stated that the strength of the adhesive joints of the reference samples is 39% of the strength of the adhesive joints of the samples with paint coating applied. Additionally, the shear strength of the adhesive joints of the samples with a paint coating applied is 32% higher than the strength of the adhesive joints of the samples with the primer and coating.

3.2. Failure Analysis

The types of failure patterns among the adhesive joints containing the three types of adherends are presented in Table 6 and Figure 5.

Table 6. Adhesive layer failure patterns of adhesive joints (according to EN ISO 10365).

Type of Adherend and Adhesive	Failure Patterns of Adhesive Layer *			
	CF	SCF	AF	ACF (p)
Epoxy adhesive				
Reference			•	
Paint coating		•		
Primer and paint coating	•			
Polyurethane adhesive				
Reference			•	
Paint coating		•		
Primer and paint coating		•		

* CF—cohesion failure, SCF—special cohesion failure, AF—adhesion failure, ACF (p)—adhesion and cohesion failure with peel.

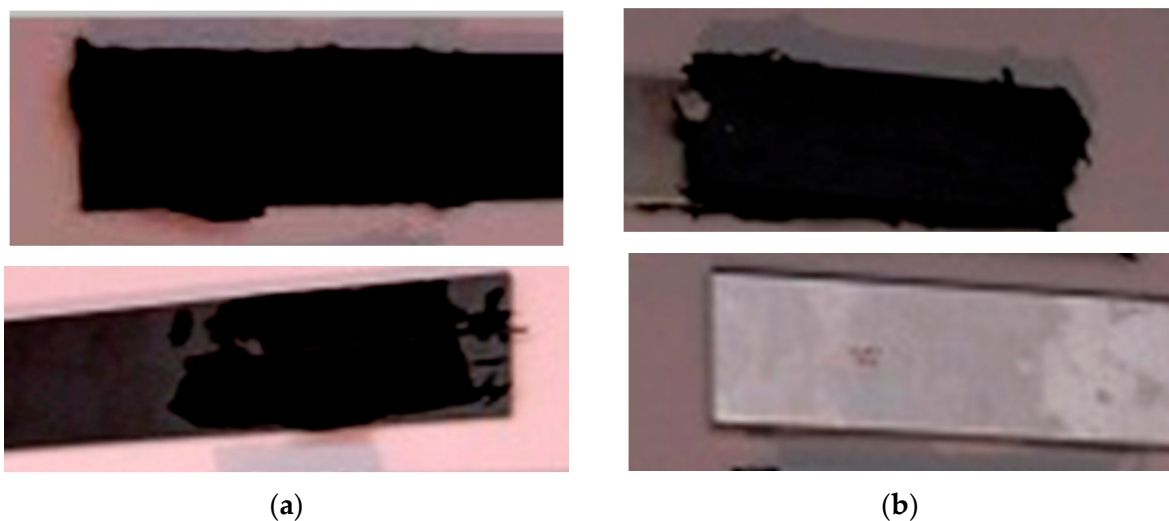


Figure 5. Examples of the failure of the adhesive joint of the polyurethane adhesive. (a) SCF—special cohesion failure, primer and paint coating samples; (b) AF—adhesion failure, reference sample.

Table 6 shows the dominant type of failure in a given adhesive joint depending on the type of joined steel sample, i.e., reference, with a paint coating applied, and with a primer

and paint coating applied (Figure 5). Since there was no damage to the binder, results pertaining to the type of damage to the adhesive layer are presented. Figure 5a shows an example of a polyurethane adhesive joint failure (specimens with primer and coating) that corresponds to the special cohesion failure (SCF) that was most common during the strength tests.

By visually assessing the failures of the adhesive joint samples (according to EN ISO 10365) after the strength test, the following types of failure were noted: cohesion failure (CF), special cohesion failure (SCF), and adhesion failure (AF). However, adhesion and cohesion failure with peel failure (ACF (p)) was not observed. According to the EN ISO 10365 standard, cohesion failure (CF) is defined as a failure along the middle part of the adhesive layer, while special cohesion failure (SCF) also applies to the failure of the adhesive layer, but the course of this failure is heterogeneous in the area of the adhesive layer. In the case of the adhesive joints to which reference samples were joined, adhesion failure was observed (partial separation of the adhesive layer from the substrate), which may indicate less favorable surface characteristics compared to the samples with a paint coating.

In the case of the adhesive joints made with the epoxy adhesive, the following results were observed in relation to the size of the failure area:

- For reference samples, the estimated area of adhesive failure (AF) was approximately 75%;
- For samples containing the paint coating, the estimated area of special cohesion failure (SCF) was approximately 65%;
- For samples containing the primer and paint coating, the estimated cohesion failure area (CF) was approximately 60%.

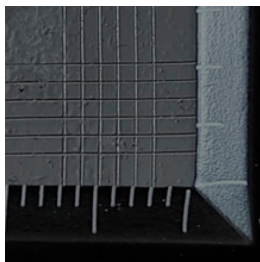
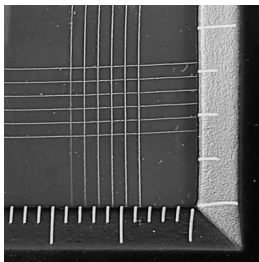
In the case of the adhesive joints made with the polyurethane adhesive, the following results were observed in relation to the size of the failure area:

- For reference samples, the estimated area of adhesive failure (AF) was approximately 95%;
- For samples containing the paint coating, the estimated area of special cohesion failure (SCF) was approximately 15%;
- For samples containing the primer and paint coating, the estimated area of special cohesion failure (SCF) was approximately 15%.

3.3. Coating Adhesion Test

The coating adhesion test results are presented in Table 7.

Table 7. Coating adhesion test results of adhering paint coatings to a steel sheet.

Type of Adherend Samples	Paint Coating	Primer and Paint Coating
Coating adhesion test (according to ASTM D3359-B standard)		
	5B	5B

Based on the interpretation of the cutting line results (based on the information in Table 5), it can be stated that the surfaces of both of the samples with paint coatings are characterized by good adhesion (rated as B5), as the edges of the cuts are completely smooth, and no squares of the mesh skin have been torn off. The edges of the cut line are slightly less smoothed for the paint coating itself, but according to the definition (Table 5), the results for this coating are also included in category 5B. This may indicate the selection of the correct process for making such paint coatings on a steel sheet. The applied coating

adhesion test (cross-section) is one of the available methods for determining the adhesion of coatings, which is why it was chosen for comparative purposes. This is a visual method, so objectivity in assessing the cross-cut method should be maintained.

3.4. Wettability Test

The surface wettability of the three types of samples subjected to the bonding process was determined on the basis of contact angle measurements using distilled water as a polar liquid. Images of a drop of measuring liquid being applied to the surface of the tested samples are shown in Figure 6. The results of the contact angle measurements with distilled water and the evaluation of the surface wettability of the samples, taking into account the criteria given in Table 5, are summarized in Table 8.

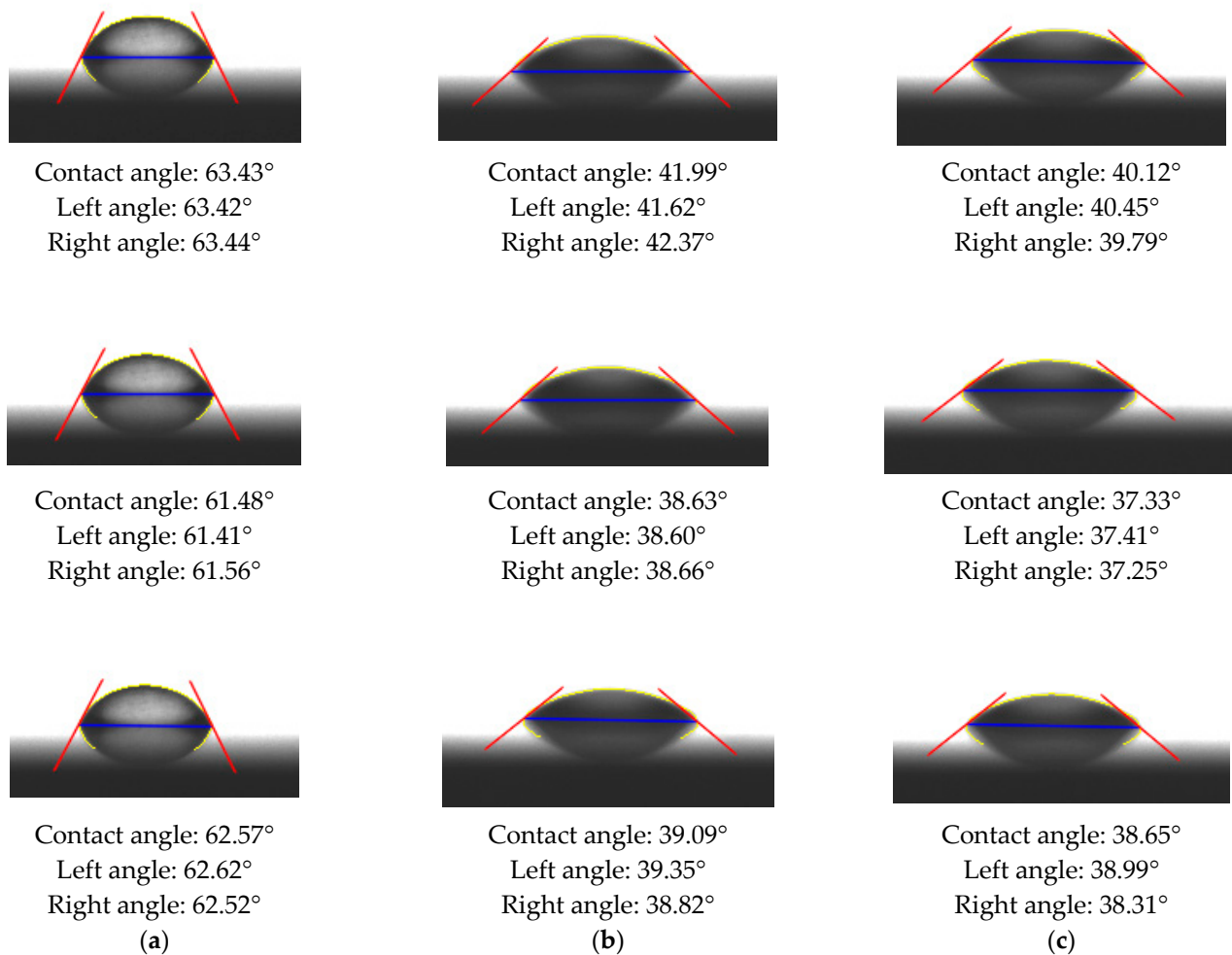


Figure 6. Images of measuring liquid being dropped onto the surfaces of the following samples: (a) reference; (b) paint coating; (c) primer and paint coating.

Table 8. Contact angle and wettability assessment.

Property	Type of Adherend Samples		
	Reference	Paint Coating	Primer and Paint Coating
Contact angle (average value)	62.37° ($\pm 1.02^\circ$)	39.24° ($\pm 1.91^\circ$)	38.72° ($\pm 1.45^\circ$)
Degree of wetting	High wettability	High wettability	High wettability

From the results, it can be seen that the contact angle with distilled water on the surface of the reference samples is the largest among the surface samples tested (62.37°). However, the contact angle of the surface of the sample with the paint coating applied (in both cases of these samples) is smaller and amounts to 39.24° for samples with paint coating, and 38.72° is the contact angle value for the samples with a primer and paint coating. It can be assumed that samples with a smaller contact angle are characterized by better surface wettability. Paint coatings formed from the majority of coating systems used on a large scale have low hydrophobicity, which is associated with the ease of dirt settling on them. Hydrophobicity is often expressed by contact angle values. On this basis, it can be assumed that the smaller the value of the contact angle, the greater the adhesion of the adhesive to such a coating, although, of course, this also depends on the chemical base of the adhesive.

4. Discussion

A comparison of strength results for all types of adhesive joints is also shown in Figure 7.

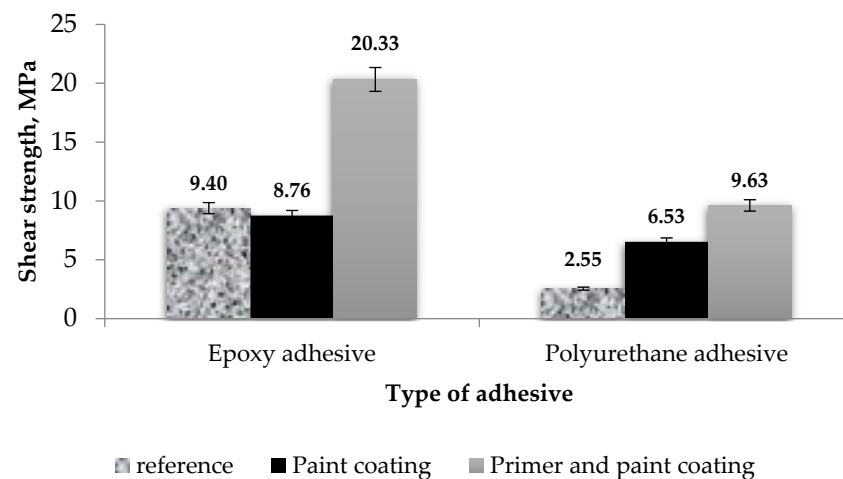


Figure 7. Comparison of shear strength of adhesive joints.

Through analyzing the above figure and all of the shear strength results for the adhesive joints of the steel elements made using two types of adhesive, it can be concluded that the adhesive joints made with the polyurethane adhesive show lower strength shear strength values for any type of adhesive joint. The highest strength value belonged to an adhesive joint made with the epoxy adhesive. A zinc primer was applied to the surface of these elements, as was a paint coating in the form of powder paint. The average strength of these adhesives joints is equal to 20.33 MPa. This value significantly exceeds the research results of other adhesive joints. The lowest shear strength is shown by the adhesive joints of the reference sheet samples made using polyurethane adhesive. The strength of this type of adhesive joints is 12% of the strength of the adhesive joints of the specimens with a primer and coating (made with epoxy adhesive). In the case of the adhesive joints made with the polyurethane adhesive, the importance of using a paint coating on the surface of steel elements is noted. A significant impact of the presence of a paint coating on the strength of steel sheet joints was observed. In addition, the zinc primer increases this strength compared to the paint coating by about 32%. However, in the case of the adhesive joints made with epoxy adhesive, the presence of a paint coating slightly reduces the strength of the adhesive joints (by about 6%), and the use of a zinc primer and paint coating causes a more than two-fold reduction in the strength of the considered adhesive joints. In both cases, the highest adhesive joint strength value was achieved by the joints in which the parts to be joined had a paint coating with a pre-applied primer. Through comparing these results to the measured contact angle values, it was noted that, in this case (joining elements with a paint coating with a primer applied earlier), the lowest contact angle value

(38.72°) was obtained (among the tested surfaces of the samples), and these samples are characterized by having the best wettability.

Based on the obtained results, it was noted that the presence of a paint coating increases the strength of adhesive joints, although it depends on the type of adhesive used. The adhesive bonds formed between the particles of the surface layer of the coating and the particles of the adhesive are probably different because adhesives with different chemical bases were used. This affects the subsequent adhesive strength of the adhesive joint.

The Pearson correlation coefficient $r(X,Y)$ was calculated using the value of the contact angle of the surfaces of the three types of adherends (Table 8) and the shear strength of the adhesive joints (Figure 6). Through analyzing the Pearson's correlation coefficient r values (X,Y), it could be seen that the correlation coefficient (r) between the contact angle and the strength of the adhesive joints made with the epoxy adhesive was -0.47 , indicating a negative correlation between the compared values. In the case of comparing the value of the contact angle and the strength of adhesive joints made with the polyurethane adhesive, the correlation coefficient is -0.91 , which also provides a negative but strong correlation between the compared values, and the greater the absolute value of the correlation coefficient, the stronger the linear relationship between the variables. These values mean that, as the value of the contact angle decreases (increasing the wettability), the strength of the adhesive joints increases.

By relating the obtained contact angle values (Table 8) of the three types of adherend surface to the assessment of wettability, determined on the basis of Table 5 and [47], it was decided that all three types of samples can be considered to have surfaces with high wettability. Moreover, based on the ASTM D5946 standard, it can also be assumed that the joined materials (in three variants of the samples) show high wetting properties because the wetting angle is less than 71°. However, it should be noted that, according to the referenced standard, the contact angle itself is not a completely acceptable measure of paint, coating, or adhesive adhesion, but the contact angle values can be used to determine the level of surface treatment. It should also be emphasized that, in many works (e.g., see Baldan [2], Zhang et al. [34], Prakash and Prasanth [37], Sommers and Jacobi [48]), the contact angle value has been used to determine the wettability of a surface.

The authors of [21] presented the influence of the surface treatment on the adhesive properties of the steel sheet surfaces and the strength of adhesive joints, in which paint coatings were also analyzed. It has been shown that the surfaces of steel samples show a similar contact angle value (60.47°), and slightly different contact angle values were obtained after various surface treatments with paint coatings, which means that special attention should be paid to the development of technology for preparing the surface of elements for adhesion processes.

On the basis of the information obtained, it was noted that the presence of a paint coating increases strength, although it depends on the type of adhesive used. It is possible that the coating may increase the strength of the adhesive bond, depending on the materials of the coating, the method of its application, and the type of substrate material to which it is applied. Furthermore, it is likely that a different difference can be observed between the adhesive strength of uncoated and coated materials. Coatings can perform various functions and enhance joint performance in various ways. In [5], the effect of cathodic and powder coatings and also the method used to apply the primer on the adherend's surface on the strength and the types of failure of the aluminum alloy adhesive joints was presented. Based on the test results, it was found that both the method of applying the adhesion promoter and the presence of the cathodic coating had an impact on the strength of the adhesive joints. The use of an adhesion promoter significantly affects the strength of both uncoated aluminum alloy adhesive joints and powder-coated joints. In this article, the adhesion promoter was applied before applying the paint coat, and for this case, we obtained the highest strength values of the adhesive joints of the steel samples with paint coatings with a previously applied primer in individual groups of joints made with the epoxy and polyurethane adhesives. Therefore, it can be assumed that the presence

of a primer in the system of joined materials is conducive to obtaining strong adhesive joints. The surface treatment of the sheet metal surface before applying paint coatings may also affect the final strength of adhesive joints, and it is worth paying attention to this consideration when applying paint coatings.

The research presented by Sonmez et al. [41] and also that of the authors of [49] propose that both the type of coating and the type of adherend have a great impact on adhesion. Gao et al. [19] also pointed out that the type of coating, as well as the type of substrate, affects the strength of the adhesive joints.

Taking into account the aspect of preparing the surface of steel sheets before bonding, attention should be paid to the technology used to apply the paint coatings (with and/or without a primer), the availability of devices and whether their use is time-consuming, their protective and functional properties, the strength required for the adhesive joints, and the value of the transferred loads. If strength is required at the level of the assembly joints and the tightness of the joints is highly important, a specific type of adhesive can be selected. However, if corrosion protection of the joined elements is also required, the process for making such a coating (with or without primer) should be decided on after taking into account the strength of the adhesive joints.

5. Conclusions

Based on our results, the following conclusions can be drawn:

- (i) The presence of the paint coating increased the wettability of the surface of the adherends.
- (ii) The method of applying the paint coating on the surface of the steel sheet ensured its good adhesion to the steel substrate.
- (iii) The measured shear strength results differed for each type of adhesive joint.
- (iv) The greatest shear strength was shown for the adhesive joints of steel elements with a primer and paint coating applied using the epoxy adhesive. The adhesive joints made via the use of the polyurethane adhesive were characterized by the smallest shear strength values.
- (v) In both cases where adhesive joints had a zinc primer applied along with a paint coating in the form of powder paint, an increase in the shear strength of the adhesive joints was observed.
- (vi) The appropriate application of paint coatings has a significant impact on adhesive joint strength. Due to the application of a paint coating that aims to ensure, e.g., corrosion protection, the shear strength of the adhesive joint increases.

In summary, it can be seen that the effectiveness of joining steel elements with paint coatings not only depends on the type of surface treatment method used before applying the coating (here, the use of a primer) but also on the type of the adhesive used.

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