

The coating application for enhanced adhesion between GFRP composites and cathaphoresis-coated (KTL) steel – part 2: surface properties

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Abstract

Purpose – This study examines the effect of increased surface energy on adhesion strength. Surface modifications were made using chemical coating methods such as primer paint (primer) and cathaphoresis (KTL, Kathodische Tauchlackierung). The wetting behaviour of adhesive on these surfaces and the resulting contact angles were analysed to evaluate bonding effectiveness.

Design/methodology/approach – Primer paint was applied to glass fibre reinforced plastic (GFRP) materials and cathaphoresis coating was applied to steel. Contact angles of the coated surfaces were measured and compared to those of the uncoated (natural) surfaces.

Findings – Results showed that applying primer to GFRP and KTL to steel increased their surface energy compared to untreated surfaces. A decrease in contact angle correlated with improved wetting, suggesting enhanced adhesion potential.

Originality/value – While the effects of surface coatings on adhesion have been studied, there is limited research specifically on the adhesion-enhancing potential of KTL coatings. Typically used for corrosion resistance, KTL is shown here to also improve adhesion. The novelty lies in experimentally demonstrating KTL's dual role as both a protective and adhesion-enhancing layer.

Keywords Surface tension, Surface energy, Contact angle, Wettability, Adhesive bonding

Paper type Research article

1. Introduction

Reducing vehicle weight is a primary goal for manufacturers responding to regulations, environmental concerns, market competition and performance demands. Glass fibre reinforced plastic (GFRP) composites, due to their high strength-to-weight ratio, are widely used in transportation. In railway vehicles, components like front caps (Figure 1a) and interior trims (Figure 1b) are commonly made of GFRP.

Since GFRP and steel have different structures, they are typically joined using adhesives. The success of such bonding depends heavily on the surface properties of both materials. Surface energy, wettability and contact angle are critical parameters in this context.

In the previous study, Part 1, the effects of two fundamental applications–surface roughness and surface coating methods–aimed at increasing adhesion strength before the bonding

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Declaration of competing interest: The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



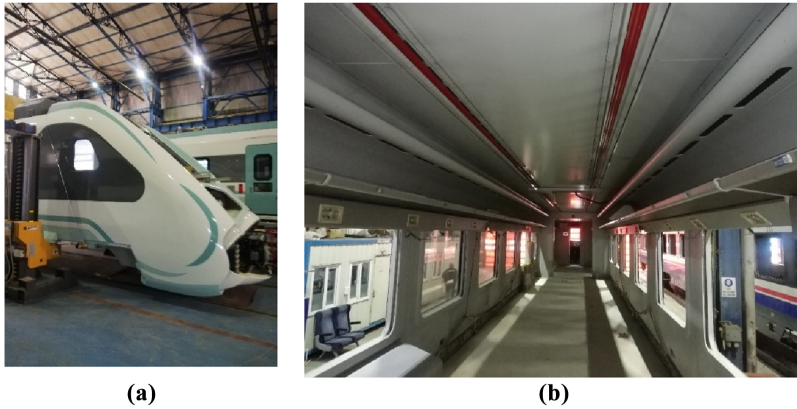


Figure 1. GFRP components of railway vehicles. Source: Authors' own work

process were investigated and compared with each other. While methods like plasma treatment, corona discharge and silanization exist, this study focused on primer coating and KTL as the surface modification techniques. In adhesive bonding applications, surface treatment methods such as plasma treatment, corona discharge and silanization are commonly employed with the primary objective of increasing surface energy and thereby enhancing adhesion performance. Plasma and corona treatments typically activate the surface by generating temporary polar functional groups, which increase surface tension. However, this effect is often short-lived and requires immediate bonding after treatment. Silanization, on the other hand, can establish chemical bonds that improve adhesion, but it is highly sensitive to application conditions and environmental parameters. As an alternative to these methods, the cataphoretic (KTL) coating process not only offers corrosion resistance but also creates a permanent, uniform and high-energy thin film on the metal surface, significantly improving adhesive performance. The findings of this study demonstrated that despite its low surface roughness, the KTL coating achieved a surface energy level (~ 25 mN/m) comparable to that of primer coatings and substantially reduced the contact angle, thereby enhancing the wettability of the adhesive on the substrate. Furthermore, KTL applications are particularly advantageous in industries such as automotive and railway manufacturing, where long-term durability and high environmental resistance are critical. In this context, KTL emerges as an integrated surface modification solution, offering both enhanced adhesion strength and environmental protection in a single step.

In the adhesive process, excessive surface roughness – as seen in the natural GFRP sample – can prevent the adhesive from fully penetrating the surface. Instead, the adhesive remains suspended, forming air gaps that reduce bonding strength. This behaviour aligns with the Cassie–Baxter model. Despite low surface roughness, primer-coated GFRP and KTL-coated steel surfaces formed strong chemical bonds with the adhesive. This improvement in adhesion strength is explained by Wenzel's model. In particular, it was pointed out that KTL coating on metal parts creates an effective film layer on the metal surface for the bonding process in addition to protecting the metal against corrosion (Baykara & Bilgin, 2025). The natural surface energy in materials is one of the basic properties that distinguish them from other materials such as electrical-heat conductivity, Poisson's ratio, yield and tensile stress. In this research, the adhesion effect of primer paint and KTL coating on the surface of the adhesive agent as a result of increasing the surface energy of the natural surfaces of GFRP and steel materials will be investigated.

The surface energy (for solids) and surface tension (for liquids) of materials are two terms that play a role in the bonding process. Surface tension is the force required to expand the unit length of the surface of a liquid, whose unit is usually given as mN/m. Surface energy is the energy required to create a unit area of a solid surface and is expressed in mN/m. In simple terms, the lower the surface tension of liquid paint, the more easily it wets a surface; the higher the surface energy of solidified paint, the better it wets subsequent layers on top of it (Behera, Kumar, Dogra, Nosonovsky, & Rohatgi, 2019).

1.1 Surface energy of steel

Steel's surface energy varies with type, surface condition as clean, oxidised, contaminated, etc. temperature and environment. Cleaned by acetone, low-carbon steel has a surface energy of about 68.8 mN/m. Of this energy, approximately 64.6 mN/m is the dispersive component and approximately 4.2 mN/m is the polar component (Behera *et al.*, 2019). Coatings like galvanization, primers or KTL can significantly increase this value. This value determines how well other substances (e.g. liquids or adhesives) that come into contact with the surface of the material can adhere to the surface. The surface energy of steel materials varies depending on the type of steel used, the way the surface is treated and environmental factors. Higher surface energy generally leads to better adhesion, wetting and colouring properties. However, the fact that steel surfaces are generally prone to oxidation can affect surface energy values over time (Vitos, Ruban, Skriver, & Kollár, 1998; Jones, 2013). Lee *et al.* (2018) analysed the surface properties of metals by first-principles calculations and created a comprehensive database containing surface energy (γ), surface stress (τ) and surface relaxation data. The atomic number dependent variations of γ and τ values for simple and transition metals were analysed and it was observed that these values have a minimum in the middle for transition metals. Magnetic effects and oscillations in surface charge density explain these behaviours.

1.2 Surface energy of GFRP

It is the result of interactions between molecules on the surface under the influence of external forces applied to the surface of the material. This energy often determines the shape and spreading behaviour of liquid droplets that contact the surface of the material. Surface energy plays an important role in the adhesion, painting, coating and general handling properties of GFRP. Higher surface energy generally results in better adhesion and coating properties. In GFRP materials, the surface energy usually depends on the interactions between the glass fibre of the components and the resin such as epoxy or polyester. The glass fibre surface usually has a low surface energy, while the resin surface can have a higher surface energy. This difference affects the adhesion properties of GFRP, especially its interaction with adhesives or coatings. The surface energy of GFRP materials depends on the glass fibre, resin type and surface modifications. The values for GFRP are the surface energy measured on the surface of the cured polyester resin that forms the matrix of the glass fibre reinforced polyester composite. The surface energy of the GFRP material is approximately 36.4 mN/m. Of this energy, approximately 34.2 mN/m is the dispersive component and approximately 2.2 mN/m is the polar component (Baley, Busnel, Grohens, & Sire, 2006). GFRP's surface energy depends on its fibre-resin interaction. Glass fibre has low surface energy; resin can be higher. Polyester-based GFRP has a typical surface energy of 30–40 mN/m. Epoxy-based GFRP may reach 40–50 mN/m. (Tang *et al.*, 2017). Dillingham and Oakley (2006) investigated the use of surface energy as an indicator to assess the suitability of fibre-reinforced composite surfaces for bonding. Since processes such as sandblasting roughen the surface, surface energy measurement by conventional contact angle methods becomes difficult. To overcome this problem, it has been shown that the adhesion performance (in particular the fracture energy) can be predicted using the diameter of a small drop of a low viscosity liquid with surface tension properties similar to the adhesive. This method is reported to be a sensitive technique that can be used as a quality control tool in manufacturing processes (Dillingham & Oakley,

2006). Ryntz, Scarlet, Henchel, and Arthur (1993) analysed the effect of the increasing use of plastics in the automotive industry, especially on plastics with low surface free energy. Thermoplastic olefins (TPO) are prominent, accounting for 20% of plastics used in the transport industry and various surface pretreatments used to provide adhesion to these materials were evaluated. New coating methods that enable direct adhesion to TPO surfaces are also briefly discussed (Ryntz *et al.*, 1993).

As a result, the surface energy of the steel surface is high and consists mainly of the dispersive component as London forces, while the polar component is low. In contrast, the surface energy of the polyester-based GFRP composite is lower overall and is almost entirely dispersive. The polar component makes up a very small part. This difference is due to the fact that the oxidized surface of steel allows polar interactions through hydroxyl groups, albeit limited, whereas the polyester resin surface is chemically less polar.

1.3 Epoxy and polyurethane primer paints

Chemical coating processes increase the surface energy of a material. This thin film layer on the material plays an important role in determining how well adhesives, coatings or paints will wet and adhere to the surface. The surface energy of epoxy primers is approximately 40–47 mN/m, while the surface energy of polyurethane primers is approximately 35–42 mN/m. These values may vary depending on the formulation, curing, pigments and additives contained in the paint. The surface energies of epoxy and polyurethane based paints in liquid and cured solid states are close to each other (Table 1).

The surface tension of epoxy primers in liquid mixtures is usually about 25–30 mN/m. For example, the surface tension of a water-based epoxy primer formulation has been measured to be approximately 28.9 mN/m. Two-component solvent epoxy primers are formulated in a similar range for proper wetting; even lower values of about 23–25 mN/m can be achieved with silicone/acrylic surface additives in some products. Similar wetting criteria apply to polyurethane based primers and typical surface tension values are around 25–35 mN/m. The cured surface has a surface energy of approximately 36–46 mN/m. Manufacturers may add silicone-based additives to reduce surface tension during application. Cured films maintain higher energy, ensuring better topcoat adhesion.

After curing into a solid film, the surface energy of primers generally stabilizes at a higher value. Epoxy primers, which contains polar groups such as hydroxyl and ether bonds, create highly adhesive surfaces. Their surface energy typically ranges between 40–50 mN/m, with literature values around 45–46 mN/m for amine-cured films. The surface energy of polyurethane primers can be slightly more variable depending on the resin structure and formulation; it is usually in the order of approximately 30–40 mN/m, with values as low as approximately 33 mN/m observed in some hard/wet polyurethane films and reported to be as

Table 1. Surface tensions of epoxy and polyurethane based primers in liquid state and surface energies of fully cured

Primer type	Surface tension (liquid, mN/m)	Surface energy (cured film, mN/m)
Epoxy-based primer (liquid state)	~25–30 mN/m (typical; e.g. ~28.9 mN/m @ 20 °C)	– (not applicable for liquid)
Epoxy-based primer (cured film)	– (not applicable for solid)	~40–50 mN/m (typical; e.g. ~45 mN/m)
Polyurethane-based primer (liquid state)	~25–35 mN/m (typical formulation)	– (not applicable for liquid)
Polyurethane-based primer (cured film)	– (not applicable for solid)	~30–46 mN/m (varies depending on formulation)

Source(s): Authors' own work

high as approximately 45–46 mN/m in different formulations (Chudinov, Shardakov, Kondyurina, & Kondyurin, 2024). These values are sufficient for the basecoat or topcoat paint to be applied on the primer to wet the surface easily and adhere well. The surface energy of many plastic/metal surfaces is generally >40 mN/m.

Cruz, Rocha, and Viana (2016) developed a new environmentally friendly and low-cost surface treatment method to increase the surface energy of thermoplastic polymer surfaces. Nanoparticles were dispersed and thermally fixed on the thermoplastic polyurethane (TPU) surface and their interaction with the surface was increased and the surface roughness increased significantly (621%). By scanning electron microscopy (SEM) and atomic force microscopy (AFM) analyses, the distribution of nanoparticles and the degree of embedding in the surface were examined; by contact angle measurements, it was determined that the surface tension increased by 45% and thus the wettability of TPU improved (Cruz *et al.*, 2016). Brostow, Dutta, and Rusek (2010) modified a commercial epoxy resin diglycidyl ether of bisphenol A (DGEBA) with fluorinated poly (aryl ether ketone) and metal microparticles (Ni, Al, Zn, Ag) and coated on mild steel surface. Two different curing agents, triethylenetetramine cured at low temperature and hexamethylenediamine cured at high temperature, were used to investigate the effect of different curing temperatures. The effects of different amounts of metal powder and curing agent on tribological properties (dynamic friction and wear) and surface energy were evaluated. In samples cured at 30 °C, friction and wear were significantly reduced due to phase separation between fluoropolymer and epoxy. On the other hand, friction and wear increased in the samples cured at 80 °C as the cross-linking reaction became dominant. Also, a significant decrease in surface energy was observed with the addition of additives (Brostow *et al.*, 2010).

1.4 KTL coating

Anodic KTL is a method of electropheretically coating a primer paint on metal surfaces. In this system, the paint resin has an anionic (negatively charged) structure and the workpiece is connected as an anode (positive electrode). E-coat paint in the liquid phase is typically a bath containing 80–90% water, 10–20% paint solids (resin, pigment, additive). The surface tension of pure water is quite high, approximately 72 mN/m, which can make it difficult for the paint to wet the surface and can lead to various surface defects in the coating film. Therefore, in industrial e-coat baths, surfactants (wetting agents) are added to the formulation to reduce the surface tension. Once cured and forming a thin solid film on the metal surface, the total surface energy values of the cured anodic e-coat film are in the range of about 40–50 mN/m. These data are summarized in the Table 2.

As a result, it generally has a surface tension in the range of 30 to 50 mN/m. This value can vary depending on the amount of surfactants and resins in the bath, bath temperature, age and the presence of possible contaminants (e.g. oil or silicone). Surface tension is critical to coating quality because low surface tension allows better wetting of metal surfaces, resulting in uniform coating, better paint adhesion and higher corrosion resistance. High surface tension, on the other hand, can lead to surface defects such as crater formation or coating deficiencies in

Table 2. Typical surface tension/energy values for anodic KTL systems

Property (state)	Value (magnitude)	Polar component	Dispersive component
Surface Tension (KTL bath, 25–30 °C, liquid)	~25–30 mN/m (target: <30)	– (total)	– (total)
Surface Energy (Cured KTL film, solid)	~40–50 mN/m (e.g. ~46 mN/m)	~10–15 mN/m	~30–40 mN/m

Source(s): Authors' own work

edge areas. Regular monitoring of this parameter is very important for the efficiency of the KTL process and coating quality. Skotnicki and Jędrzejczyk (2021) investigated the effect of surface preparation on the quality of paint coating applied by KTL on steel parts. Chemically cleaned and mechanically (sandblasting) prepared surfaces were compared and tested for corrosion resistance, surface roughness, coating thickness, hardness and friction behaviour. As a result, the surface preparation method significantly affected the coating properties. Coatings applied to chemically cleaned surfaces showed higher quality than sandblasted surfaces. Dobránsky, Gombár, Fejko, and Bali (2023) aimed to optimize and evaluate the thickness of the organic coating layer formed by cataphoresis varnishing on AW 1050-H24 aluminium substrate. In the analyses performed on 30 samples created by the experimental design method, it was determined that the applied voltage was responsible for 33.82% of the change in coating thickness and the coating time was responsible for 28.67%. The interaction of voltage and time also showed an effect of 20.25%. The developed regression model was able to predict with an accuracy of 85.88% and it was confirmed that the most favourable conditions were 240 V and 6, 0 minutes, giving a maximum coating thickness of 26.114 μm (Dobránsky *et al.*, 2023). Korczeniewski *et al.* (2020) investigated the effects of multi-walled carbon nanotubes (MWCNT) oxidation and simultaneous peeling process on electropretic resolution (EPD). The results show that the water contact angle can vary over a wide range (125–163°) and this value is determined by the diameter of the deposits in the solvent. By determining the parameters influencing the morphology, the study enables the preparation of surfaces with orientable roughness and wetness properties (Korczeniewski *et al.*, 2020).

In the research conducted in Part 1, the importance of the effective adhesion strength caused by the surface coating rather than surface roughness in bonding GFRP parts was determined as a result of tensile tests. In this study, the parameters that will affect the basic adhesion strength of these chemical coatings such as contact angle, wettability, surface energy and tension on the surface were analysed (Figure 2).

It is the mathematical expression of the surface energy of a material by surface contact angle measurements. Thus, wettability and adhesion properties of a material can be determined.

The total surface energy (γ_s), of a solid is the sum of two components: dispersive (γ_s^d) (Van der Waals) and polar (γ_s^p) (hydrogen bonding, dipole-dipole) (Equation 1).

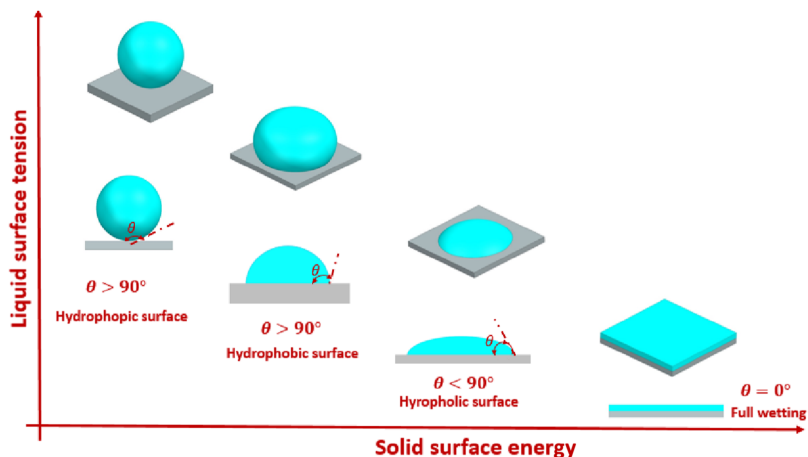


Figure 2. Surface energy and surface tension relationship of solid and liquid. Source: Authors' own work

$$\gamma_s = \gamma_s^d + \gamma_s^p \tag{1}$$

In the Owens–Wendt equation (Equation 2), the surface energy of a solid can be calculated according to the contact angles obtained by using at least two different liquids such as polar (pure water) and apolar (diiodomethane). In this study, a single liquid was used as pure water to determine the general surface energy trend (Table 3).

$$\gamma_l(1 + \cos \theta) = 2 \left(\sqrt{\gamma_s^d \cdot \gamma_l^d} + \sqrt{\gamma_s^p \cdot \gamma_l^p} \right) \tag{2}$$

- γ_l : Surface tension of the liquid
- γ_l^d : Dispersive component of the liquid
- γ_l^p : Polar component of the liquid
- θ : Contact angle

Whereas the contact angle is determined using pure water, the surface energy of a solid can be estimated using a different equation for the dispersive component of the solid surface tension, derived from the Young–Dupre relation and the equation for the dispersive interaction relation used in the Fowkes model (Equation 3).

$$\gamma_s = \gamma_L \left(\frac{1 + \cos \theta}{2} \right)^2 \tag{3}$$

- γ_s : Surface energy of a solid
- γ_L : Pure water surface energy

2. Materials and methods

Primer paint is widely used in industrial applications, particularly to minimize surface defects of GFRP parts, enhance adhesion performance and protect against UV rays, humidity and chemical substances to ensure long service life. The KTL coating process is commonly applied in the metal industry to protect metal parts from corrosion and to extend their service life. The originality of this research lies in the fact that the thin KTL film coating applied to the steel surface will be penetrated by the adhesive agent, contributing to the chemical interaction and adhesion strength between GFRP and DC01A. In this study, two different materials were used: GFRP and DC01A cold-rolled steel. The dimensions and specifications of these materials are provided in Part 1. Three of the GFRP specimens had untreated natural surfaces with no chemical coating. The application procedures, curing conditions and coating thicknesses of both primer and KTL coatings are detailed in Part 1.

Table 3. Pure water and diiodomethane surface energy component values

Liquids type	Surface energy γ_l (nM/m)	Dispersive component of liquids γ_l^d (nM/m)	Polar component of liquids γ_l^p (nM/m)
Pure water	72.8	21.8	51.0

Source(s): Authors’ own work

Surface energy is a key factor influencing adhesion strength in bonding applications, particularly through its impact on wettability. The ability of an adhesive to spread on a surface is directly governed by the polar and dispersive components of the surface energy. The Owens–Wendt model is widely adopted in academic studies due to its capability to resolve both components using a single test liquid, which simplifies the experimental procedure while ensuring reproducibility and reliability. Consequently, it is frequently utilized to evaluate surface modifications prior to bonding and to optimize surface preparation. In contrast, alternative models often require multiple liquids, increasing experimental complexity and cost.

The materials examined for surface properties in Part 2 are the same as those in Part 1, namely GFRP with a natural surface without any chemical coating (Figure 3a), GFRP with a primer coat applied to the surface (Figure 3b) and steel materials with KTL applied to the surface (Figure 3c).

The success of the bonding process largely depends on the effectiveness of surface preparation. As part of the surface preparation procedures, initial cleaning and degreasing were carried out using a Scotch-Brite pad to remove contaminants such as dirt, dust, oil and oxide layers from the substrate. Subsequently, in order to make the surfaces chemically and physically suitable for adhesive bonding, a primer was applied to the GFRP surfaces, while a KTL was applied to the steel surfaces. These treatments enhanced the surface energy of the samples, improved wettability and promoted the formation of strong chemical bonds, thereby ensuring a durable and reliable adhesive performance.

All contact angle measurements were conducted using the KRÜSS DSA100 contact angle measurement device. A high-resolution CMOS digital camera 1280×1024 pixels was employed to accurately detect the droplet edges. Static contact angle measurements were performed using deionized water, with $2 \mu\text{L}$ droplets dispensed onto the surface via a precision microsyringe. The device software automatically calculated the contact angle values by analysing the droplet profile based on the Young–Laplace equation. The measurement repeatability was within a precision of $\pm 0.1^\circ$ and the system was equipped with a backlit LED illumination unit and a horizontally adjustable sample stage. These features enabled high-

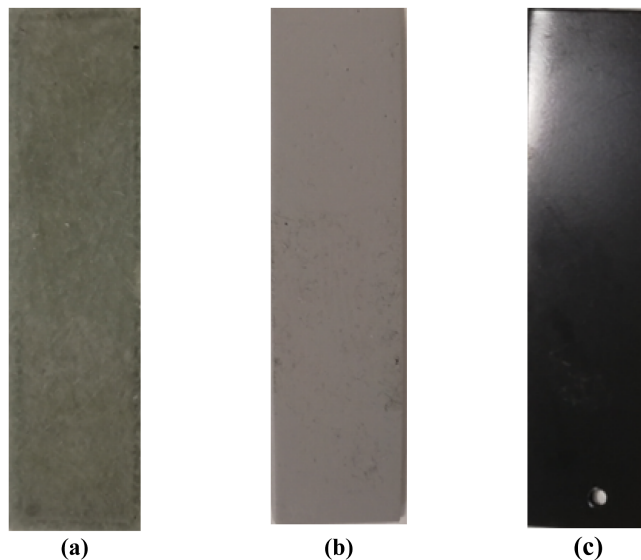


Figure 3. (a) GFRP Natural surface, (b) GFRP painted primer, (c) Steel coated cataphoresis test samples. Source: Authors' own work

accuracy analysis of surface wettability and surface energy. As a result, data on the contact angle, surface characterisation, wettability, surface energy and stress of the natural surface GFRP surface (Figure 4), primer-coated GFRP surface (Figure 5) and KTL-coated steel surface (Figure 6) were obtained. Three measurements were made from each group.

As a result, the contact angles of the different surfaces obtained were determined according to the Sesil method (Table 4). The standard deviation of the measured contact angles was calculated (Figure 7).

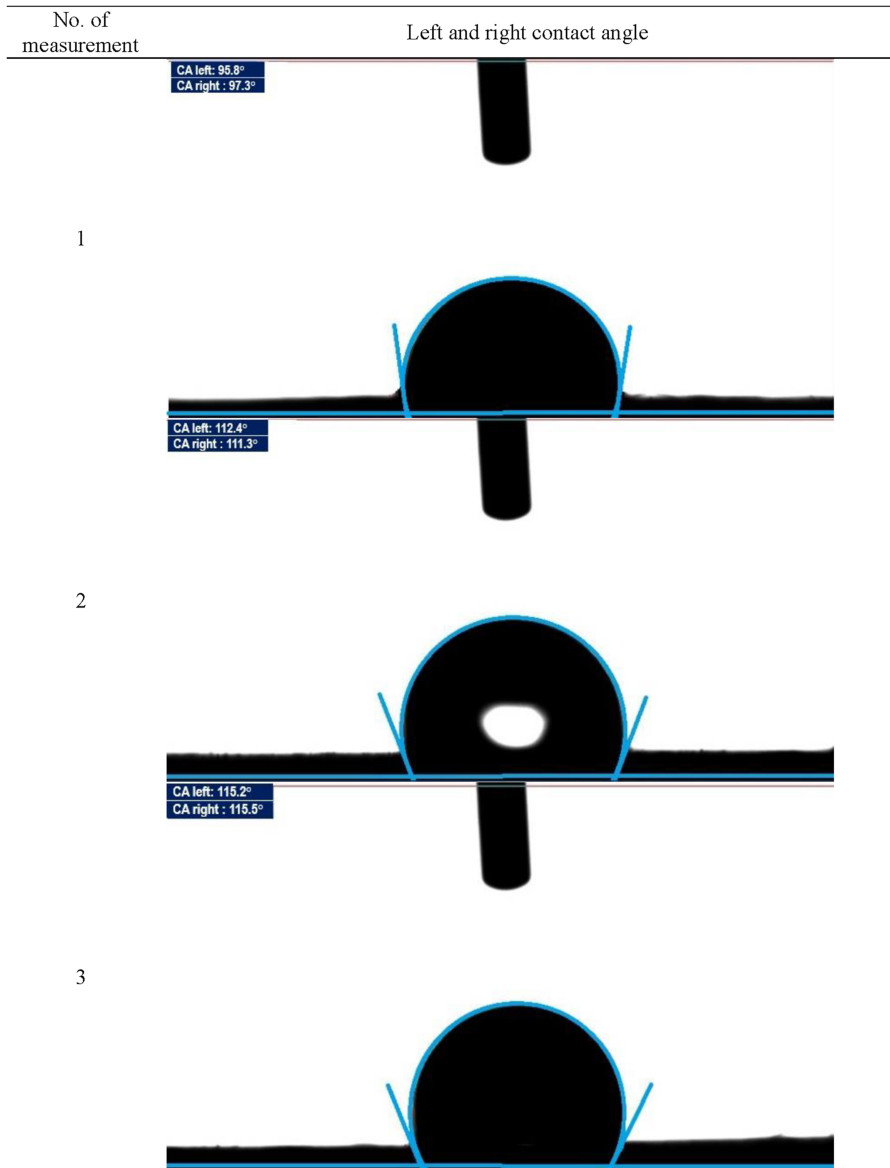


Figure 4. Natural GFRP surface contact angle measurements. Source: Authors' own work

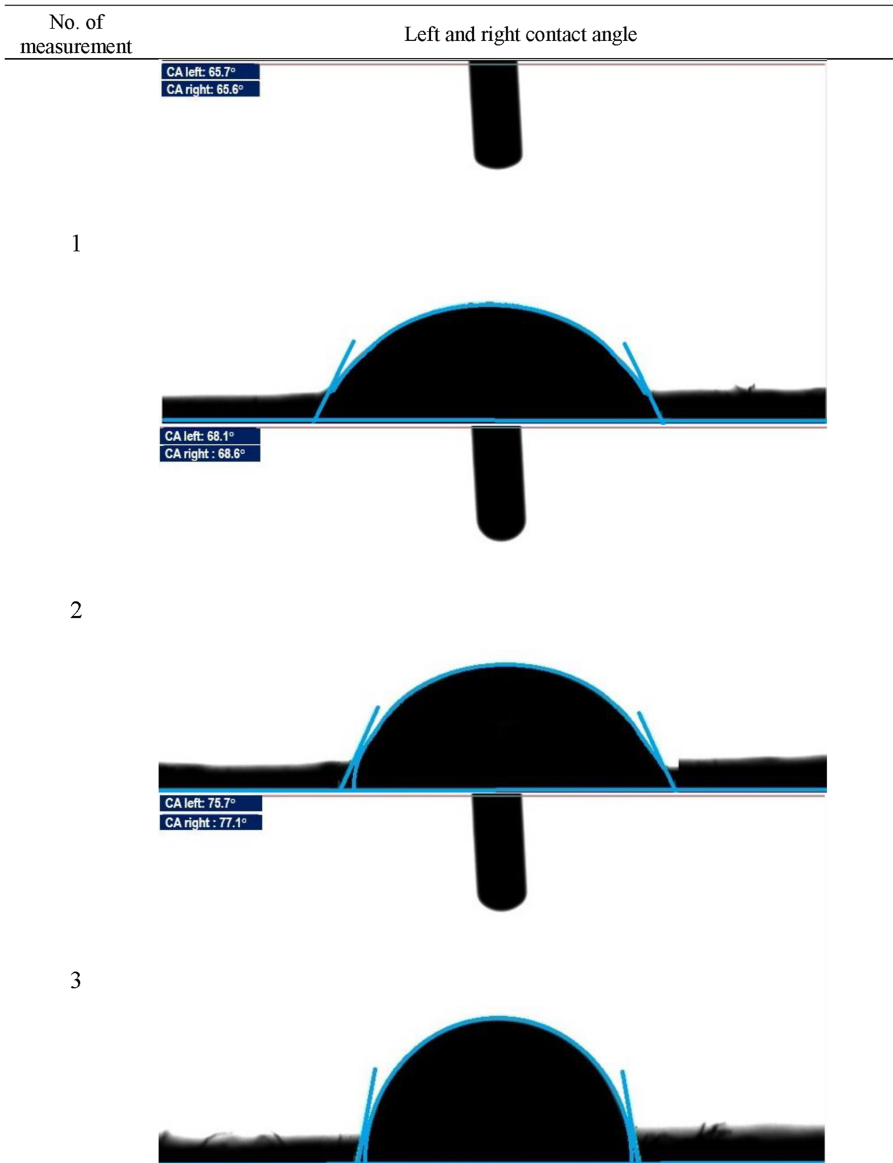


Figure 5. Primer coated GFRP surface contact angle measurements. Source: Authors' own work

Primary coatings provide the most stable surface modification, showing the lowest standard deviation in contact angle measurements. Natural surfaces give the most irregular result, while KTL coatings are in an intermediate position. This confirms the reason why primers are preferred for adhesion applications.

With the data obtained, the surface energy of each sample can be calculated by [Equation 3](#) and [Table 4](#) using the pure water drop surface tension and the contact angle obtained as a result of the profile formed by the water drop on the sample.

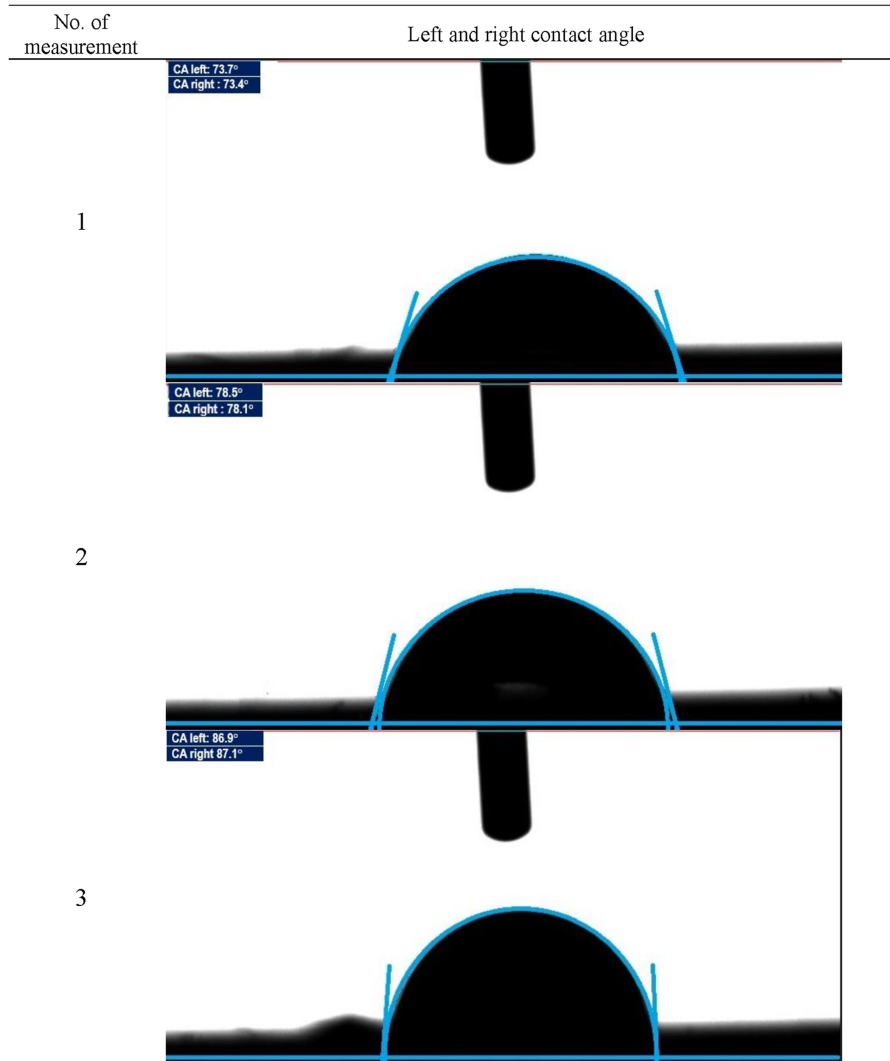


Figure 6. Cataphoresis coated steel surface contact angle measurements. Source: Authors' own work

$$\gamma_{GFRP \text{ with natural surface}} = 72.8x \left(\frac{1 + \cos 107.91}{2} \right)^2 = 8.727 \text{ nM/m}$$

$$\gamma_{GFRP \text{ with primer coated}} = 72.8x \left(\frac{1 + \cos 70.13}{2} \right)^2 = 25.206 \text{ nM/m}$$

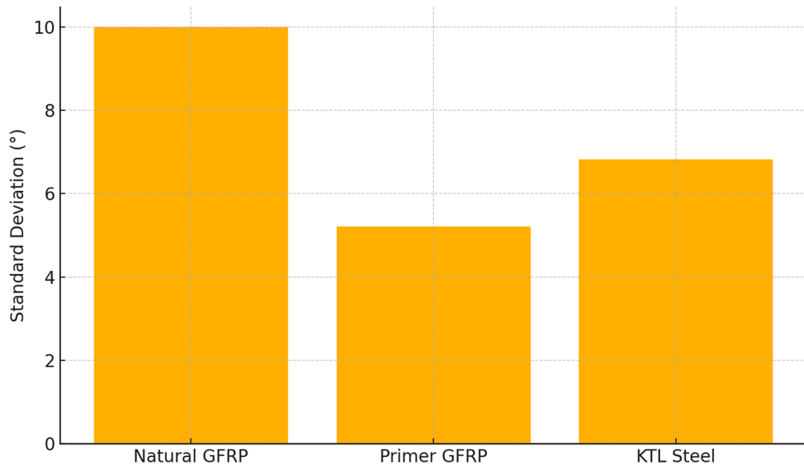
$$\gamma_{Steel \text{ with KTL coated}} = 72.8x \left(\frac{1 + \cos 79.615}{2} \right)^2 = 25.352 \text{ nM/m}$$

In the light of this information, [Table 1](#) was edited and a new table showing both contact angle and surface energy was created ([Table 5](#)).

Table 4. Average contact angle and standard deviation values of surfaces with different coating types on different materials

No. of measurements	Natural GFRP surface Average contact angle	Primer coated GFRP surface Average contact angle	KTL coated steel surface Average contact angle
1	96.55°	66.65°	73.55°
2	115.35°	68.35°	78.30°
3	111.85°	76.40°	87.00°
Standard deviation	9.998166	5.208246	6.820984

Source(s): Authors' own work

**Figure 7.** Average contact angle with standard deviation. Source: Authors' own work

A 3-D graph was obtained from the data in Table 5 using Python (Figure 8)

As a result, according to Figure 2, the 3D scatter plot shows the surface type (categorical positions for Natural GFRP, primer-coated GFRP and KTL-coated steel) on the X-axis, contact angle (θ°) on the Y-axis and surface energy (nM/m) on the Z-axis. Each data point is coloured according to the respective surface type (red for natural GFRP, green for primer-coated GFRP and blue for KTL-coated steel; these colours are indicated in the legend box). As seen in the Figure 8, Natural GFRP (red dot) shows that it is a hydrophobic surface with

Table 5. Avg. contact angle and surface energy classification

	Avg. Contact angle θ°	Surface energy (nM/m)
Natural GFRP surface	107.915	8.727
Primer coated GFRP	70.13	25.206
KTL coated steel	79.615	25.352

Source(s): Authors' own work

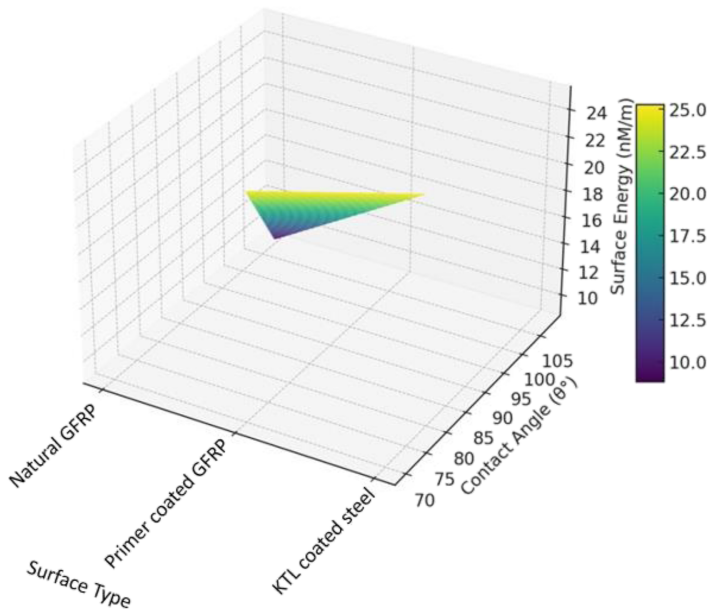


Figure 8. 3D plot of contact angle, surface energy and surface type. Source: Authors' own work

high contact angle and low surface energy. In contrast, primer-coated GFRP (green) and KTL-coated steel (blue) are more hydrophilic surfaces with lower contact angles and higher surface energies. The graph demonstrates an inverse relationship between contact angle and surface energy. High-energy surfaces have better wettability and lower contact angles. In contrast, natural GFRP shows poor wettability due to its low surface energy. It does not allow it to spread over the surface.

3. Discussion and results

In this study, the surface energy of fully cured polyurethane-based primer coatings was determined to be 25.2 mN/m for the primer-coated GFRP surface and 25.4 mN/m for the KTL-coated steel surface. The difference in surface energy between GFRP and steel materials can be attributed to both the inherent structural differences of the substrates and the distinct chemical coating processes applied to each.

The 3D plot generated in the study (Figure 8) clearly illustrates the inverse relationship between contact angle and surface energy. The natural GFRP surface, with a contact angle of approximately 108°, exhibits a hydrophobic character and a relatively low surface energy (~8.7 mN/m). In contrast, the primer-coated GFRP ($\theta \approx 70^\circ$, $\gamma \approx 25.2$ mN/m) and the KTL-coated steel ($\theta \approx 79.6^\circ$, $\gamma \approx 25.4$ mN/m) demonstrate significantly enhanced wettability due to their lower contact angles and higher surface energies. These findings confirm that both chemical coatings are effective in improving the adhesive potential of the surfaces by increasing their surface energy.

Although the contact angles of the KTL-coated and primer-coated surfaces are comparable, the lower standard deviation observed in the primer-coated GFRP indicates a more homogeneous surface modification. This consistency can be attributed to the controlled application process and the chemically stable nature of the primer formulations.

In conclusion, both primer and KTL coatings significantly enhance the surface energy of the substrates to which they are applied, thereby promoting better wettability and creating more favourable conditions for strong adhesive bonding.

4. Conclusion

In Part 1, as a result of the adhesion strength tensile test between primer-coated GFRP and KTL-coated steel, it was determined that the primer-coated GFRP specimen with 1 mm adhesive thickness in single lap joint type with KTL-coated steel was 300% stronger than the GFRP specimen with natural surface. In this study, it was found that the reason for the significant increase in bond strength was due to the fact that the adhesive agent provided low contact angle/high surface energy on the primer and KTL-coated surfaces. Therefore, the lower contact angle indicates that the adhesives will wet the surface better on the primer and KTL-coated surfaces, which explains the higher bond strength measured in Part 1.

The colour 3D scatter plot effectively separates each data point and highlights the expected inverse relationship between contact angle and surface energy. Such visualisation allows materials scientists and engineers to quickly compare different surface treatments and their effects on hydrophobic or hydrophilic behaviour.

In the research, coating the surface of a solid material with a primer or KTL increases the surface energy of the solid material, which decreases the contact angle of the pure water drop, making the surface more easily wettable. This trend is clearly seen in the data obtained. The natural surface GFRP has a surface energy of 8,7 mN/m, while the primer-coated GFRP and KTL-coated steel have much lower contact angles of 70–80° and higher surface energies of 25 mN/m compared to natural GFRP. These values indicate that the coated surfaces are more hydrophilic, while the natural GFRP surface is more hydrophobic, which is consistent with general wettability principles.

5. Limitations and future study

This study evaluated the surface energy and wettability properties of primer-coated GFRP and KTL-coated steel surfaces through contact angle measurements with pure water. This approach contributes to the complete differentiation of the polar and dispersive components of surface energy. Future studies involving ageing tests, surface energy analysis with multiple liquids and mechanical tests under conditions similar to operational conditions in bonding areas will contribute to validating the results obtained under real-world conditions. Additionally, investigating the compatibility of different adhesive chemicals with surface-treated composite and metal surfaces will contribute to the development of more robust bonding strategies for railway and automotive applications.

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