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Comparative Analysis of Graphene and Conventional Coatings for Enhancing Aluminum Busbars' Electrical Conductivity and Corrosion Resistance

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Abstract— This study explores the use of graphene coatings to enhance the electrical conductivity and corrosion resistance of aluminum busbars. Graphene was synthesized via Chemical Vapor Deposition and transferred onto aluminum, with comparisons made against bare and tin-coated samples. A single graphene layer significantly increased surface conductivity, achieving 11 times better performance than tin-coated and 33 times better than uncoated aluminum before corrosion. Characterization using Raman spectroscopy, resistivity measurements, and wettability tests confirmed successful graphene synthesis and transfer. Long-term performance was tested in NaCl solution, where graphene-coated samples exhibited only a 10.71% resistance increase, compared to 21.80% for tin-coated and 197.90% for uncoated aluminum. Initially, graphene improved water repellency, but after corrosion, the samples became hydrophilic. Despite its limitations in maintaining durability under harsh conditions, graphene proves highly effective in improving aluminum's electrical and anti-corrosive properties, with potential for further optimization.

Keywords: Graphene coatings, Aluminum busbars, Electrical conductivity, Corrosion resistance, Chemical vapor deposition, and Hydrophobicity.

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1. Introduction

Aluminum, widely used in industries ranging from aerospace to electronics, is prized for its light weight, strength, and recyclability. However, its susceptibility to corrosion and limitations in electrical conductivity remain challenges for many applications, particularly in harsh environments. Traditional coating methods, such as anodizing and polymer coatings, have been employed to improve aluminum's performance.

Graphene, a two-dimensional allotrope of carbon, has emerged as a revolutionary material with exceptional properties. Discovered in 2004 by Andre Geim and Kostya Novoselov, graphene consists of a single layer of carbon atoms arranged in a honeycomb lattice. Its unique combination of mechanical strength, thermal conductivity, and electrical performance surpasses that of many conventional materials. For instance, graphene exhibits a Young's modulus of 1 TPa, an intrinsic strength of 130 GPa, and thermal conductivity exceeding 3000 W/mK. Given these properties, graphene has attracted attention as a potential coating material to enhance the anti-corrosive and electrical properties of aluminum. Unlike conventional coatings, which may degrade over time or offer suboptimal conductivity, graphene provides a robust, chemically inert barrier that protects against corrosion while significantly enhancing electrical conductivity. There are several methods for producing graphene, including mechanical exfoliation, chemical vapor deposition (CVD), chemical

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exfoliation, liquid-phase exfoliation, and thermal reduction of graphene oxide. Each method affects the scalability and quality of graphene coatings on aluminum in different ways.

A busbar is a metallic strip or bar used for conducting electricity in electrical systems, acting as a central point for distributing power across circuits, components, or devices. Typically made of copper or aluminum, busbars are found in electrical switchboards, substations, and other equipment that handle high-current loads. Copper is favored for its excellent electrical and thermal conductivity, while aluminum is valued for being lightweight and cost-effective, though it has lower conductivity compared to copper. Aluminum busbars, though not as conductive as copper, are lighter, cheaper, and can be extruded into various shapes, enhancing their mechanical strength and resistance to short-circuit forces. However, aluminum's susceptibility to corrosion requires protective coatings like graphene to ensure longevity and performance. Figure 1 shows an industrial busbar system, illustrating copper components that represent busbars typically made from conductive materials like copper or aluminum.



Figure 1. A generated image of busbars

Busbars are often coated to enhance durability and corrosion resistance, with tin, nickel, and silver being common options—each offering trade-offs in cost, conductivity, and environmental impact—while non-metallic coatings can reduce conductivity. Coatings also prevent galvanic corrosion and improve aesthetics, but paint can limit thermal performance. Recent advancements highlight graphene as a promising solution, particularly with aluminum, due to its superior conductivity, anti-corrosive properties, and mechanical strength, addressing many existing limitations in busbar materials.

The skin effect in AC systems concentrates current near the surface of conductors, making thick copper busbars inefficient as frequency increases; applying graphene coatings, with their superior conductivity and anti-corrosive properties, enhances surface current conduction, reduces material usage, and improves busbar performance, especially in high-frequency applications.

Graphene coatings have been extensively studied for their potential to enhance corrosion resistance across various metals. It was found that graphene coatings effectively reduced corrosion on copper but offered limited protection on aluminum due to galvanic corrosion and the quality of graphene deposition [1]. Graphene’s chemical inertness, which makes it effective against corrosive chemicals, contributes to its ability to offer resistance comparable to that of hydrogen fluoride, one of the most potent corrosive agents [2], [3]. Additionally, graphene’s resistance to oxygen diffusion [4] and its hydrophobic properties due to its high surface area and nonpolar nature [5] enhance its effectiveness as a protective layer.

Advances in nanotechnology have led to the development of various nanocoatings made from nanomaterials to improve corrosion resistance on metals like aluminum. Several studies highlight the impact of graphene coatings on corrosion resistance. The use of graphene and graphene/polymer coatings on metals such as steel, aluminum, and copper in corrosive environments was reviewed by [6]. The hydrophobic properties of graphene was studied by fabricating biomimetic hydrophobic

patterned graphene coatings on aluminum alloy, achieving a static water contact angle of 130.8±1° and enhanced anti-corrosive properties [7]. It was reported that multi-layer graphene coatings on copper achieved corrosion resistance of approximately 400 hours in chloride solutions, overcoming the limitations seen with single-layer graphene due to defects [8].

Research on graphene's contribution to corrosion resistance includes a study, which showed that adding graphene oxide to chromium electroplated aluminum improved microhardness and corrosion resistance due to coating compactness and galvanic effects [9]; an investigation of a double-layer PANI-(graphene oxide)/epoxy coating protecting carbon steel in saltwater [10]; and a work demonstrating that dip-coated graphene on aluminum significantly enhanced corrosion resistance, with performance three orders of magnitude better than uncoated substrates [11]. Additional research on graphene coatings includes an examination of graphene-coated aluminum current collectors used in Li-ion batteries [12], and a review of graphene-based materials for anticorrosive coatings [13]. It was found in [14] that the mechanical properties of aluminum could be improved with a graphene coating, resulting in an 88% increase in Young's modulus. While graphene's strength is limited in the elastic region, a 60% increase in ultimate tensile strength was observed in the plastic region. A comprehensive review of the fabrication methods, performance enhancements, and challenges associated with these composites was also provided [15].

Relatively few studies have been conducted on the electrical conductivity of graphene. A nanocomposite film combining graphene and polysiloxane was developed by [16] to enhance both corrosion protection and electrical conductivity, achieving a corrosion rate reduced to 2.5% of the uncoated sample and an electrical conductivity of 1700 S/m. A systematic review of Cu/Al metal matrix composites reinforced with graphene was conducted by [17], highlighting improvements in electrical, thermal, and mechanical properties for smart electronics. The review explores the optimization of electrical and thermal charge transport in these composites through graphene reinforcement and addresses challenges, alternative solutions, and future prospects for graphene-reinforced Cu/Al metal matrix composites in smart electronics. It was shown by [18] that embedding graphene in metals like copper, aluminum, and silver enhances electron mobility and density, achieving electrical conductivity over 3,000 times greater than Cu and surpassing Ag, offering significant improvements for efficiency in electrical and electronic applications.

Other relevant studies include investigations on the thermal and electrical conductivity of copper-graphene heterosystems, focusing on the effects of strain and thickness [19]; the electrophoretic deposition of graphene coatings on copper to enhance thermoelectric performance [20]; the enhancement of electrical and thermal conductivity in polypropylene through graphene nanoplatelets [21]; and the electrical properties of graphene conductive composites [22]. The effect of defects in graphene on its performance as a protective layer on copper, particularly its oxidation behavior, was investigated in [23]. Various techniques, including SEM, OM, XPS, and Raman spectroscopy, were used to analyze graphene films created via chemical vapor deposition. It was found that while graphene initially acts as a passivation layer, its effectiveness diminishes over time due to grain boundaries and point defects, though defects such as copper step bunches had less impact.

Our study distinguishes itself by directly comparing graphene coatings with current market options for electrical power distribution, such as bare and tin-coated aluminum busbars. It simulates real-usage conditions to assess the long-term performance of graphene-coated aluminum under corrosive environments, aiming to showcase its potential to revolutionize protective coatings with superior corrosion resistance and electrical performance. While not addressing the production challenges of high-quality single-layer graphene, the study focuses on its practical applications and long-term benefits compared to conventional methods like anodizing and polymer coatings.

2. Material and Method

2.1 Properties of the Experiment Sample

The experimental samples consist of long, thin, stick-like pieces made from 2 mm thick sheets of 6000 series aluminum. Each sample measures 5 mm in width and 67 mm in length, with a narrow section in the middle measuring 4.2 mm in width. For comparison, we use three types of aluminum samples: bare (uncoated), tin-coated, and graphene-coated.

2.2 Graphene Synthesis

To synthesize high-quality graphene, the CVD method is chosen due to its reliability and suitability for mass production. The CVD furnace (PROTECH-PT-O1200-60IIIC-4C Model) at İzmir Katip Çelebi University is used for the production process (see Figure 2).



Figure 2. CVD furnace used in this study

The synthesis of high-quality graphene involves six steps. First, in the preliminary preparation stage, a 0.1 mm copper sheet is cut, cleaned with a copper etchant, and rinsed with pure water to prepare the substrate. Next, the heating step involves placing the copper in a CVD furnace, where hydrogen and argon gases are introduced, and the furnace is heated to 1070°C over 60 minutes. In the annealing step, the temperature is maintained at 1070°C for an hour to modify the surface of the copper, improving its ability to capture carbon atoms, and reducing surface roughness. During the growing step, methane gas is introduced to initiate graphene formation on the copper, with the duration of the process depending on the desired graphene layer count. In the cooling phase, the furnace temperature gradually decreases to room temperature, and the flow of methane is stopped, while hydrogen gas is increased. Finally, the final step involves backfilling the furnace with inert gases before opening it, completing the graphene synthesis process (see Figure 3).

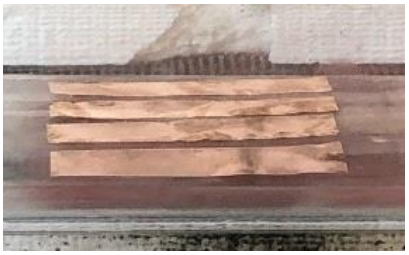


Figure 3. Copper substrates with graphene layer after CVD

2.3 Transferring Graphene onto Aluminum Samples

To transfer graphene onto the aluminum sample, the open (uncoated) side of the graphene is used. First, this surface is coated with polymethylmethacrylate (PMMA) using a spin coating method (see Figure 4).



Figure 4. Copper substrates with graphene layer before PMMA coating (left), PMMA application using spin coating method (center), and PMMA-coated copper substrates with graphene layer (right)

After applying the PMMA coating, the copper substrate is removed from the graphene film using a copper etchant, typically iron chloride (FeCl3), due to its ability to slowly and effectively dissolve copper for precise control. Following the etching process, the graphene is rinsed in pure water to eliminate residual etchant. The PMMA-coated graphene film is then transferred onto a Si/SiO2 wafer and subsequently onto the aluminum sample. The aluminum sample is immersed in the same pure water container as the graphene film and carefully aligned with the uncoated side of the graphene. Finally, the assembly is baked at 80°C to enhance adhesion between the graphene film and the aluminum.

The final step in transferring the graphene film to the aluminum sample involves chemically etching the PMMA using acetone. The sample is immersed in acetone to remove the PMMA from the graphene surface. It is then rinsed in pure water to remove any residual acetone. Finally, the sample is baked at 80°C for 45 minutes to evaporate any remaining water on the surface.

Thus, the graphene is successfully synthesized and coated onto the aluminum sample.

2.4 Tin Coating of Aluminum Samples

To assess the efficiency and reliability of the graphene coating, tin-coated aluminum is used for comparison. Tin coating, commonly applied to aluminum busbars in the electrical distribution industry, helps protect the conductivity of aluminum by shielding it from corrosive environments. A tin coating with a thickness of 9-13 µm is applied to the aluminum sample.

2.5 Characterization of Samples

2.5.1 Raman spectroscopy

Raman spectroscopy is employed to evaluate the quality, efficiency, and characteristics of the graphene film, as well as to determine the number of graphene layers. This analysis is conducted on graphene-coated samples using a Renishaw/In Via device at the İzmir Katip Çelebi University Central Research Labs.

2.5.2 Testing electrical resistance

The electrical resistance test evaluates conductivity to determine how well graphene coatings improve aluminum's conductivity. The four-point probe method was used to measure the electrical resistivity of materials because it provides high-accuracy measurements, minimizes errors caused by probe contact resistance, and can measure both low and high resistivity materials. This method offers more accurate results compared to the traditional two-point method by effectively eliminating contact resistance from the measurement. Each sample undergoes two tests: one before and one after a corrosion test. During the test, currents ranging from -0.01 mA to 0.011 mA are applied in 0.001 mA increments, and voltage is recorded at each step. Resistance values are then calculated after 22 current pulses. The test is performed using the Keithley 2400 Sourcemeter. Uncoated aluminum, tin-coated aluminum, and graphene-coated aluminum samples are tested before and after corrosion resistance

experiments.

2.5.3 Contact angle (wettability)

The contact angle test measures the wettability performance of a sample, which indicates how well a liquid interacts with a solid surface. Wettability is assessed by measuring the contact angle, which is the angle between the liquid-vapor interface and the solid-liquid interface. Materials with a water contact angle smaller than 90° are considered hydrophilic, those with an angle larger than 90° are classified as hydrophobic, and materials with a contact angle over 150° are deemed superhydrophobic. Hydrophobic materials, which repel water, generally exhibit better anti-corrosive properties. The contact angle and surface tension measurement device at İzmir Katip Çelebi University Central Research Labs is used to perform this test. It is applied to all types of samples -uncoated bare aluminum, tin-coated aluminum, and graphene-coated aluminum-twice. Each sample underwent the test once before the corrosion resistance experiment and once afterward.

2.5.4 Exposing to corrosion

The corrosion resistance experiment compares the anti-corrosive properties of samples with different coating methods. A corrosive solution, consisting of pure water and 3.5% by weight NaCl, is applied to the surfaces of the samples for 220 hours. NaCl, is applied to the surfaces of the samples for 220 hours (see Figure 5). After this period, the samples are rinsed repeatedly in pure water to remove the corrosive solution and then heated to 80°C to evaporate any residual water molecules. Following the experiment, wettability and electrical resistance tests are repeated to assess the effects of exposure to the corrosive environment.

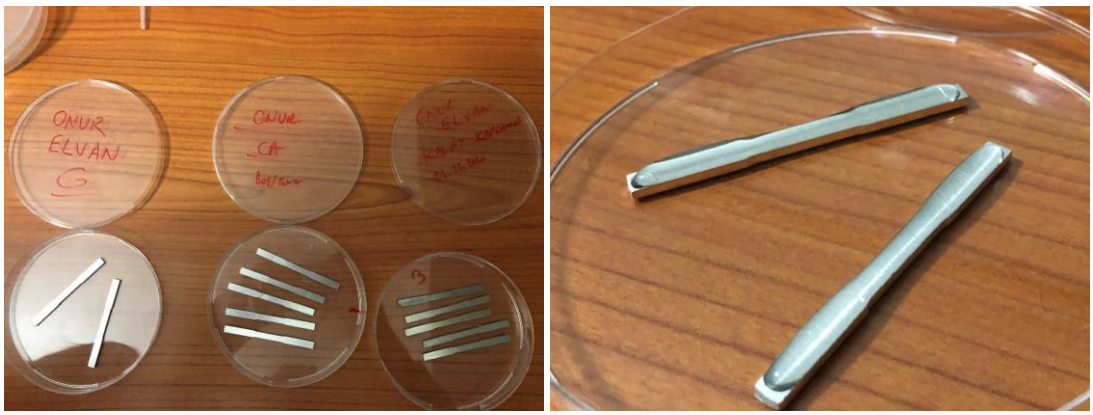


Figure 5. Samples exposed to corrosive conditions

3. Results and Discussion

Up to now, a graphene film has been successfully synthesized and applied to aluminum samples. The graphene-coated aluminum busbars were then compared to conventional tin-coated and uncoated bare aluminum bars. Electrical resistance and anti-corrosive properties were evaluated both before and after exposure to a corrosive environment.

3.1 Synthesized and Coated Graphene Film Results

The Raman spectroscopy results for the graphene film on the aluminum sample are consistent with literature studies [24], [25]. Background noise is present due to the underlying aluminum. In this experiment, the G band is observed at 1587 cm^{-1} and the 2D band at 2679 cm^{-1} (see Figure 6).

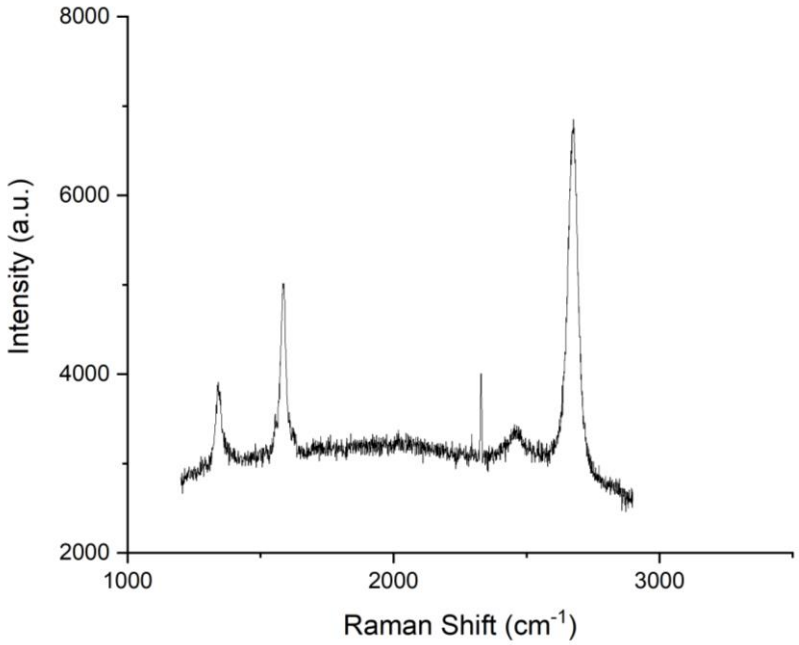


Figure 6. Raman spectroscopy result of graphene-coated aluminum sample

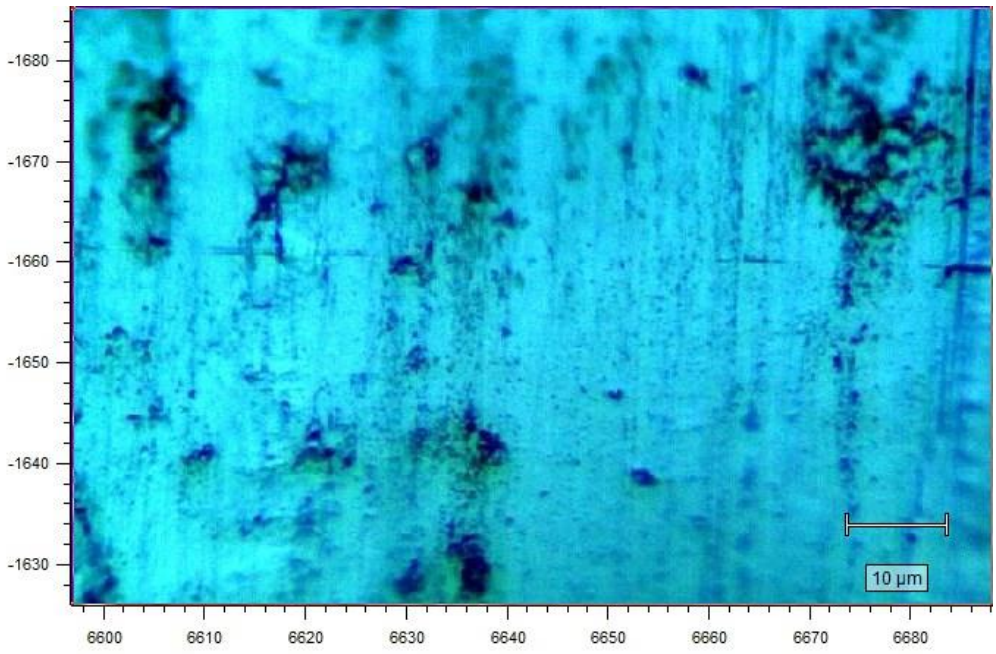


Figure 7. Raman image of the graphene-coated aluminum sample, with a magnification of 100x

Figure 7 shows an image from Raman spectroscopy of the graphene-coated aluminum sample, magnified 100 times. The thickness of the graphene layer can be determined by the ratio of the G band to the 2D band's intensity [25]. The analysis indicates that a single layer of graphene has been successfully synthesized and coated onto the aluminum samples.

3.2 Electrical Resistance Test Results

Four point probe method was used to measure electrical resistance characteristics of graphene-

coated aluminum, bare aluminum, and tin-coated aluminum.

Figure 8 shows a comparison of the electrical resistance test results for uncoated aluminum samples before and after the corrosion test. As evident from the graphs, a significant increase in resistance is observed after the corrosion test.

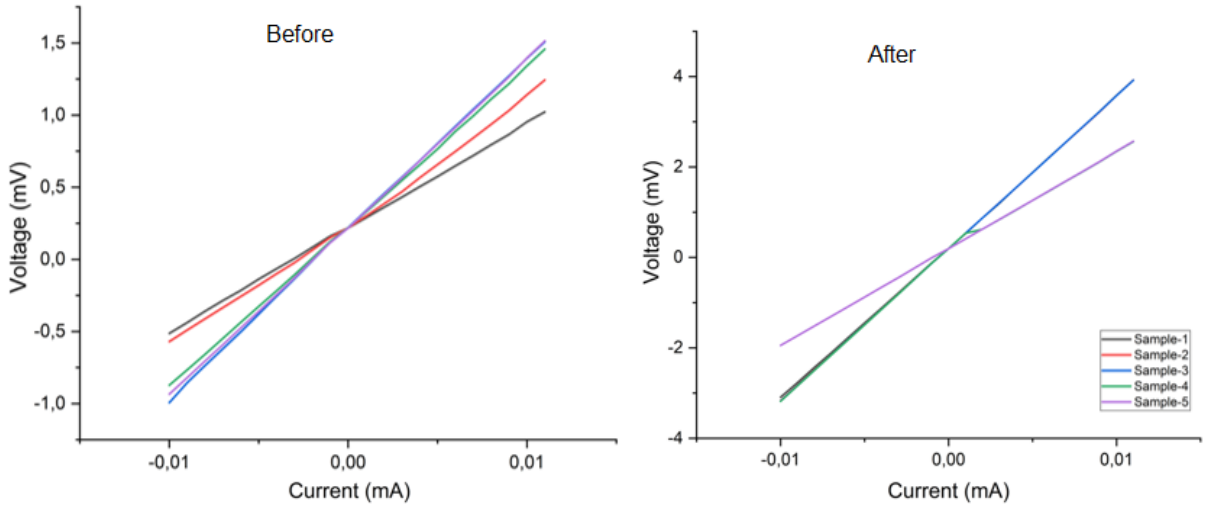


Figure 8. Comparison of electrical resistance test results for uncoated aluminum samples, before and after the corrosion test

Figure 9 presents a comparison of the electrical resistance test results for tincoated aluminum samples before and after the corrosion test. As evident from the graphs, an increase in resistance is observed after the corrosion test.

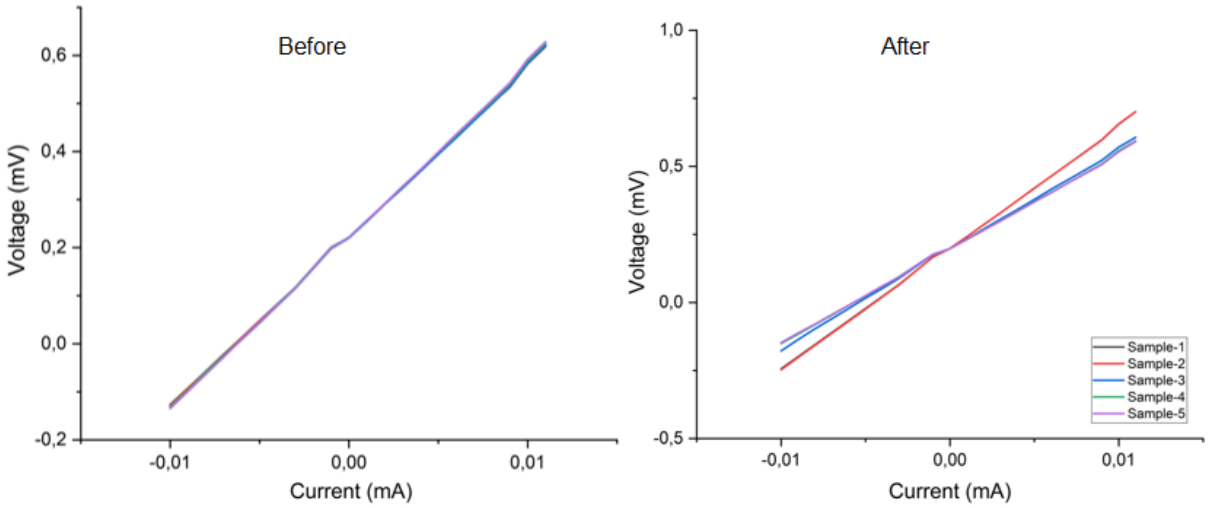


Figure 9. Comparison of electrical resistance test results for tin-coated aluminum samples, before and after the corrosion test

Figure 10 presents a comparison of the electrical resistance test results for graphene-coated aluminum samples before and after the corrosion test. As shown in the graphs, only a very slight increase in resistance is observed following the corrosion test.

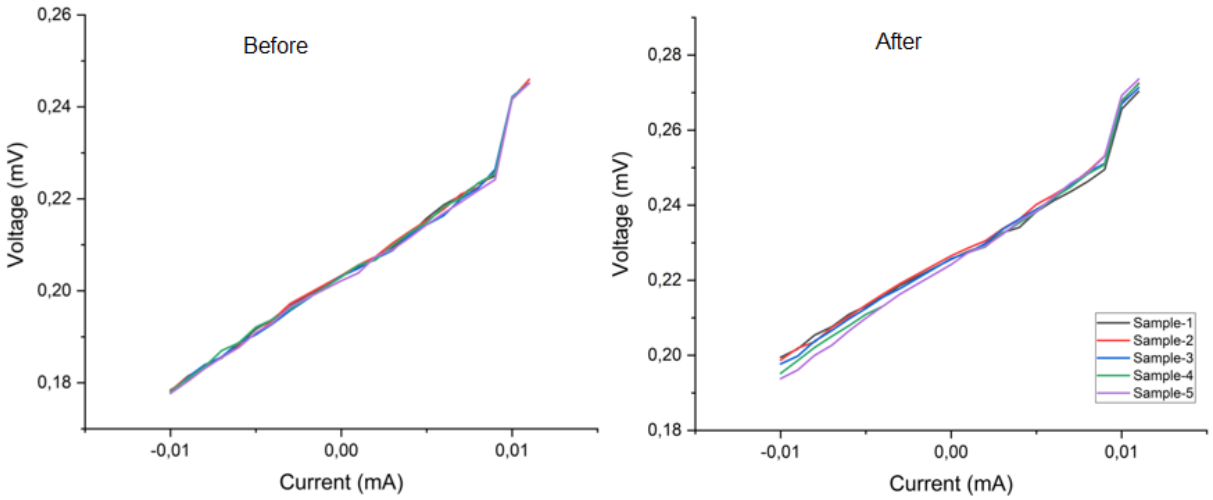


Figure 10. Comparison of electrical resistance test results for graphene-coated aluminum samples, before and after the corrosion test

The electrical resistance results before corrosion show that samples with the same coating methods have similar resistance values, though slight variations exist, likely due to factors like natural oxidation or surface imperfections. Among the samples, graphene-coated aluminum has the lowest resistance, followed by tin-coated aluminum, with uncoated aluminum having the highest resistance. Despite tin being less conductive than aluminum, it offers corrosion protection and maintains lower resistance. Graphene-coated aluminum demonstrates the best conductivity, with approximately 11 times better conductivity than tin-coated samples and 33 times better than uncoated samples.

After the corrosion test, all samples experienced an increase in resistance at varying rates. Graphene-coated aluminum performed the best, with only a 10.71% increase in resistance. Tin-coated aluminum showed a 21.80% increase, while uncoated aluminum exhibited a significant 197.90% increase. These results, detailed in Table 1, indicate that graphene-coated aluminum has the potential for superior performance.

Table 1. Electrical resistance test results of all samples before and after corrosion test

Material	Electrical resistance (Ω) of 5 samples **before** corrosion test					Average
Bare Al	72.28	85.22	118.27	110.28	116.02	100.41
Tin-coated Al	31.32	32.22	32.29	32.42	32.24	32.10
Graphene-coated Al	3.01	3.02	3.01	2.99	3.00	3.01

Material	Electrical resistance (Ω) of 5 samples **after** corrosion test					Average
Bare Al	333.16	336.30	336.64	275.45	214.11	299.13
Tin-coated Al	44.47	44.66	36.72	34.94	34.68	39.09
Graphene-coated Al	3.14	3.28	3.27	3.40	3.55	3.33

In a comparable study, it was found that graphene-coated aluminum retained 12.34% of the resistance values of bare aluminum after 35 days of exposure to a 0.1M NaCl solution [1]. Similarly, a significant improvement in corrosion resistance for graphene-coated aluminum was reported compared to bare aluminum, using a dip coating method; however, differences in experimental conditions, such as the use of a more corrosive 0.5M NaCl solution and unspecified test duration, likely account for the variation in results between the study [11] and ours. Additionally, differences in measurement techniques and experimental setups could have contributed to the differences.

Graphene has proven to be an effective coating option for aluminum. However, it should be noted that some of our samples exhibited poor conductivity, likely due to surface defects. As highlighted by [23], producing defect-free graphene layers remains a challenging issue.

3.3 Contact Angle (Wettability) Results

3.3.1 Results before Corrosion

The wettability test results are presented in Table 2. The data indicate that while tin coating has no significant effect on repelling water molecules from the surface, graphene coating increases the contact angle by an average of 17.47° (23.86%). Although graphene improves wettability, a single-layer graphene coating does not render the aluminum sample fully hydrophobic. The maximum contact angle achieved with graphene coating is 96.18°, and the minimum is 84.23° (Figure 11). Figure 12 displays the contact angle images for uncoated and tin-coated aluminum samples.

Table 2. Wettability test results and measured contact angles for all samples before corrosion testing

Material	Initial Contact angle results (°)					Average (°)
Bare Al	66.41	76.91	73.81	73.83	73.26	72.84
Tin-coated Al	58.94	79.55	74.88	66.11	84.28	72.75
Graphene-coated Al	91.38	84.23	96.18	84.62	94.69	90.22

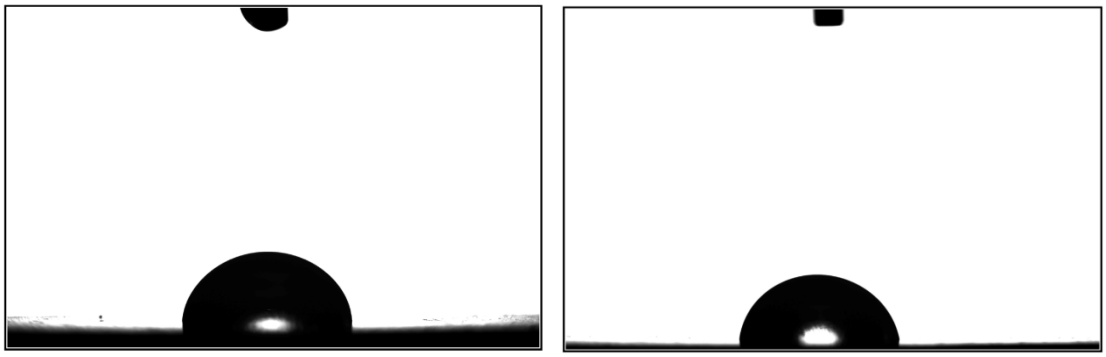


Figure 11. Liquid droplet on the surface of a graphene-coated aluminum sample before the corrosion test, showing a contact angles of 96.18° (left) and 84.23° (right)

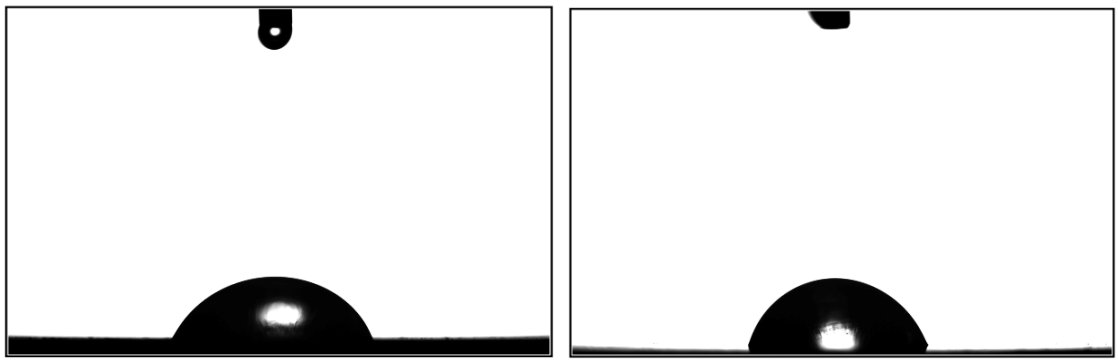


Figure 12. Liquid droplet on the surface of an uncoated aluminum sample before the corrosion test (left) and on the surface of a tin-coated aluminum sample before the corrosion test (right)

A water contact angle of 130.8° was achieved by applying biomimetic hydrophobic patterned graphene on aluminum [7]. The performance was enhanced through biomimetic microstructure processing and surface treatment. Initially, the water contact angle on bare aluminum was 67.1°,

similar to the results in this study, and increased to 78.5° after treatment. These measurements were taken without exposure to a corrosive environment.

3.3.2 Results after Corrosion

Table 3 presents the test results and the impact of corrosion on contact angles. After corrosion, the average contact angle for graphene-coated aluminum is 19.22°, compared to 16.38° for tin-coated aluminum and 10.64° for uncoated aluminum. The contact angle of graphene-coated samples decreased by an average of 71° after corrosion. These findings indicate that while graphene coating initially offers a higher contact angle than other coatings, it is not effective in preventing the reduction in contact angle caused by corrosion. Despite the higher initial contact angles, all samples, including those coated with graphene, remain hydrophilic.

Table 3. Wettability test results, average measured contact angles, and comparison of all samples before and after corrosion testing

	Average Contact Angle (°)	
Material	Before corrosion	After corrosion
Bare Al	72.84	10.64
Tin-coated Al	72.75	16.38
Graphene-coated Al	90.22	19.22

4. Conclusion

This study demonstrates the significant potential of graphene coatings in enhancing both the electrical conductivity and corrosion resistance of aluminum busbars. Through the application of a single layer of graphene, synthesized via the CVD method, the aluminum samples exhibited vastly improved electrical performance on surface-level. Specifically, graphene-coated aluminum showed 11 times better surface-level conductivity than tin-coated samples and 33 times better than uncoated aluminum before corrosion. The results highlight graphene's superior conductivity and its ability to provide a protective layer that helps maintain electrical performance over time. Following exposure to a corrosive environment using NaCl solution, the graphene-coated samples displayed only a 10.71% increase in resistance, significantly outperforming the tin-coated samples, which saw a 21.80% increase, and uncoated aluminum, which experienced a substantial 197.90% rise in resistance. This indicates that graphene not only enhances initial conductivity but also provides notable protection against corrosion, contributing to the long-term reliability of aluminum busbars in harsh environments.

However, despite its enhanced performance, graphene coatings are not completely resistant to corrosion, vulnerable against mechanical damages such as abrasion or impact, and further research is required to improve their long-term durability. Although graphene coatings initially increased the contact angle of aluminum, they did not make the material hydrophobic after corrosion exposure. This indicates that while graphene is highly effective at improving electrical conductivity and anti-corrosive properties, additional research and development are needed to boost its durability and effectiveness in real-world applications. The study confirms graphene's promising role as a coating material for aluminum busbars, though additional optimization is required for widespread industrial use, particularly in corrosive environments.

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