

Article

Investigation of Metal-Graphite Coatings for PEMFC Bipolar Plate Using Atmospheric Plasma Thermal Spraying

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Abstract

To realize the commercial application of metal bipolar plates in proton exchange membrane fuel cells (PEMFCs), it is important to develop coatings that are both durable and have low interfacial contact resistance (ICR). In this study, atmospheric plasma spraying (APS) was utilized to prepare nickel-graphite (Ni-G) and copper-graphite (Cu-G) coatings on titanium bipolar plates. This study investigates the effect of different graphite contents on the phase composition, microstructure, corrosion resistance, and electrical conductivity of the coatings. The results show that higher graphite content leads to better performance. The potentiostatic corrosion current densities of the Ni-G and Cu-G coated bipolar plates are $1.05 \times 10^{-4} \text{ A} \cdot \text{cm}^{-2}$ and $0.91 \times 10^{-4} \text{ A} \cdot \text{cm}^{-2}$, respectively. Similarly, the ICR values of the coated bipolar plates are $25.2 \text{ m}\Omega \cdot \text{cm}^{-2}$ and $38.9 \text{ m}\Omega \cdot \text{cm}^{-2}$ before and after cathodic polarization for Ni-G, and $17.4 \text{ m}\Omega \cdot \text{cm}^{-2}$ and $21.2 \text{ m}\Omega \cdot \text{cm}^{-2}$ for Cu-G. These results suggest that metal-graphite coatings deposited by APS represent a viable strategy for titanium bipolar plates.

Keywords: proton exchange membrane fuel cell; bipolar plates; Ni-G/Cu-G coating; atmospheric plasma thermal spraying

1. Introduction

In recent years, proton exchange membrane fuel cells (PEMFCs) have been adopted in transportation, portable power sources, aerospace, and other economic sectors due to their advantages of cleanliness, high efficiency, fast startup, and long service life [1–3]. Despite substantial advancements in both fundamental and applied PEMFC research, challenges related to cost, durability, and reliability remain key obstacles to their widespread commercialization [4–7].

In PEMFCs, bipolar plates (BPs) are a critical component. Their primary roles include supporting the membrane electrode assembly (MEA), delivering hydrogen and oxygen to the MEA, ensuring uniform gas distribution and complete reaction, collecting current, and facilitating water removal. Based on material composition, bipolar plates are categorized into graphite-based, metallic, and composite types [8,9]. While graphite BPs exhibit superior electrical conductivity and chemical stability, they suffer from complex fabrication, inadequate sealing, and excessive thickness [10]. Composite BPs are fabricated by injection molding of graphite-blended polymer resins. In contrast, metal BPs are widely used due to



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their cost-effectiveness, superior airtightness, and ease of processing [11]. Stainless steel, aluminum alloys, titanium, and titanium alloys are commonly used to fabricate metallic BPs [12,13]. Stainless steel and aluminum alloys are cost-effective materials but offer lower electrical conductivity and corrosion resistance, whereas titanium and its alloys exhibit superior corrosion resistance combined with enhanced mechanical properties [14]. Nevertheless, metal BPs remain vulnerable to corrosion. Leached metal ions can contaminate the membrane and catalyst layers, resulting in severe degradation and reduced lifetime [15,16]. Although forming passivation films on the surface of metallic BPs can improve corrosion resistance to some extent, these films have poor electrical conductivity, which can lead to a significant increase in the contact resistance between the bipolar plates and the gas diffusion layer, and therefore reduce the power output [17–19].

Applying corrosion-resistant conductive coatings is a potential solution to address corrosion and passivation issues in metallic BPs [20]. Tao Li et al. fabricated a monolayer $(\text{Ti}_{1-x}\text{Cr}_x)\text{N}$ coating using multi-arc ion plating, achieving higher conductivity and corrosion resistance [21]. Show et al. employed CVD to deposit amorphous carbon (a-C) coatings on titanium BPs at 600 °C, achieving significantly reduced contact resistance at the membrane-electrode interface [22]. Pingping Gao et al. developed carbon/PTFE/TiN composites via hydrothermal impregnation to enhance hydrophobicity, corrosion resistance, and conductivity [23]. Yi Liu et al. performed cathodic electrophoretic deposition of modified graphene oxide (MGO) on titanium plates, followed by H_2 reduction at 400 °C. The results show that the corrosion current is approximately two orders of magnitude lower than that of bare titanium [24].

Currently, most bipolar plate coating preparation techniques suffer from material limitations or environmental pollution, whereas atmospheric plasma spraying (APS) can process a wide range of materials, including powders, ceramics, metals, and other melts [25,26]. APS has received widespread attention due to its material versatility, simple operation, short preparation cycle, good thickness control, and processing flexibility. Different from other approaches, APS injects coating powder directly into the plasma jet, where particles undergo acceleration, complete/partial melting, and rapid deposition onto substrates. This approach effectively avoids environmental contamination from solvents or high-temperature vapors [27], while enabling large-scale, cost-effective production with significant commercial potential [28].

In this study, APS was employed to fabricate coatings on titanium bipolar plates, and their functional properties were subsequently investigated. APS converts external energy into heat, melting the feedstock materials and depositing them onto the substrate surface to form a corrosion-resistant coating [25]. APS utilizes a plasma arc generator (spray gun) to heat and ionize the gas (commonly Ar, N_2 , H_2 , and others) flowing through the nozzle, thereby generating a high-temperature, high-velocity plasma jet [29]. This process melts and atomizes the spray particles before rapidly depositing them onto the pretreated substrate surface to form a coating. A primary advantage of APS is its applicability to various substrate materials without restriction [30]. It can be used on both composite materials and metal substrates, consistently achieving uniform thickness and excellent coating performance. Currently, APS is a widely used and mature material surface modification process.

Although APS has been widely employed in preparing protective coatings for solid oxide fuel cells (SOFCs) and other high-temperature applications, its application to PEMFC bipolar plate coatings remains relatively unexplored. In particular, the use of metal-graphite composite coatings deposited by APS on titanium substrates for PEMFC bipolar plates has not been systematically investigated.

In this study, Nickel-graphite (Ni-G) and Copper-graphite (Cu-G) were used as coating materials for the preparation and study of bipolar plate coatings. Ni-G and Cu-G

are commonly used to prepare wear-resistant coatings, which can effectively enhance the wear resistance of the coatings [31]. Due to its high electrical conductivity and corrosion resistance, graphite is chosen as the coating material for metallic bipolar plates. However, the difficulty of using graphite directly to prepare coatings by APS lies in its high melting point. To solve this problem, metal components (Copper and Nickel) that can be melted through APS process are mixed with graphite to act as carriers which can wrap the graphite particles in the high-speed flow and form the coating on the surface of the substrate. Coating performance was characterized through microstructural morphology analysis, chemical composition/structure identification, electrochemical corrosion testing, and electrical conductivity measurements.

The novelty of this work lies in (i) demonstrating the feasibility of APS for depositing Ni-G and Cu-G coatings on titanium bipolar plates, (ii) systematically investigating the effect of graphite content (10, 25, and 50 wt.%) on the corrosion resistance and electrical conductivity of the resulting coatings, and (iii) providing a comparative evaluation of Ni-G versus Cu-G systems to identify the optimal coating composition for PEMFC applications.

2. Materials and Methods

2.1. Material Preparation

The 200 mesh Ni-G and Cu-G coating materials with a weight ratio of Ni:G = 90:10, Ni:G = 75:25, Ni:G = 50:50, Cu:G = 90:10, Cu:G = 75:25, Cu:G = 50:50 were purchased from Hebei Xingtai Zhuoyue Alloy Materials Co. (Xingtai, China). These graphite mass fractions (10, 25, and 50 wt.%) were selected based on preliminary screening tests. A minimum graphite content of 10 wt.% was chosen to ensure sufficient electrical conductivity enhancement, while 50 wt.% was set as the highest content to maximize the beneficial effects of graphite on corrosion resistance and electrical conductivity. The intermediate ratio of 25 wt.% was selected to identify the optimal balance between corrosion resistance, electrical conductivity, and coating quality. Ni-G constitutes a composite powder with graphite particle cores enveloped by nickel metallic coatings, whereas Cu-G features copper-based metallic cladding [32,33]. Commercially sourced pure titanium plates (50 mm × 50 mm × 2 mm) served as substrates. Initial surface preparation involved sequential polishing via abrasive papers and polishing cloths. Subsequently, samples underwent ultrasonic cleaning in deionized water followed by anhydrous ethanol immersion and drying. Grit blasting was employed to enhance surface roughness and coating-substrate adhesion via mechanical interlocking [34].

2.2. Coating Preparation Process

Lijia LBP-100 APS (Zhengzhou Lijia Thermal Spray Machinery Co., Ltd., Zhengzhou, China) system was employed for coating fabrication. Process parameters (see Table 1) governed deposition outcomes, where coating thickness was principally controlled through synchronized regulation of powder delivery speed and gun traverse kinematics.

Table 1. APS process parameters.

Parameter	Value
Voltage (V)	50
Current (A)	650
Plasma power (Kw)	32.5
Argon flow rate (L/min)	45
Hydrogen flow rate (L/min)	1
Nitrogen flow rate (L/min)	5
Powder delivery speed (g/min)	30

Table 1. *Cont.*

Parameter	Value
Powder carrier gas	Ar
Spray distance (mm)	100–120
Torch traverse speed (mm/s)	800
Cooling condition	Natural air cooling

2.3. Coating Characterizations

Scanning electron microscopy (SEM), X-ray diffraction (XRD), and X-ray photoelectron spectroscopy (XPS) were performed to analyze the microstructure, phases, and the chemical composition and structure of the coating using The samples were characterized by ZEISS Sigma 500 (Carl Zeiss Microscopy GmbH, Oberkochen, Germany), Shimadzu AXIS SUPRA+ (Shimadzu Corporation, Kyoto, Japan), and Rigaku Smartlab 3 kW X-ray Photoelectron Spectrometer System (Rigaku Corporation, Tokyo, Japan), respectively. After the potentiostatic cathodic polarization tests, the corroded coatings were topographically characterized for comparison.

2.4. Electrochemical Measurements

To accurately simulate the operational environment of a PEMFC cathode, all electrochemical tests were conducted in a 0.5 M H₂SO₄ solution with 2 ppm HF, which was continuously aerated and held at a constant temperature of 25 °C. Measurements were performed on a CHI760E workstation (Shanghai Chenhua Instruments, Shanghai, China) using a standard three-electrode setup, featuring an Ag/AgCl reference electrode, a Pt counter electrode, and the coated sample as the working electrode. Each test immersed 80 mL electrolyte with 1 cm² exposed coating area (The test samples were fabricated by using epoxy resin as the sealant through the method of metallographic cold embedding). Following 60 min Open Circuit Potential (OCP) stabilization, potentiodynamic polarization scans proceeded at 1 mV·s^{−1} (cathodic direction), while potentiostatic holds maintained 0.6 V for 5 h. All electrochemical tests were performed at least three times under identical conditions to ensure the reproducibility of the results.

2.5. Interfacial Contact Resistance Measurements

Coating conductivity was assessed by monitoring interfacial contact resistance (ICR) evolution before and after potentiostatic cathodic polarization. Figure 1 details the measurement schematic. Uniaxial pressure was precisely regulated using an electromechanical press to simulate bipolar plate clamping conditions. The DC low resistance tester used was Merrick RK2511BL (Shenzhen Merrick Electronic Technology Co., Ltd., Shenzhen, China), and the pressure applied ranged from 20 to 300 N·cm^{−2} with a 20 N·cm^{−2} gradient of pressure change. In Figure 1a, the total resistance of the test system R₁ is calculated as follow:

$$R_1 = 2(R_{Cu} + R_C + R_{Cu/C} + ICR) + R_P \quad (1)$$

where R_{Cu}, R_C, R_P and R_{Cu/C} represent the resistance of the copper plate, resistance of the carbon paper, the body resistance of the bipolar plate, and the contact resistance between copper plate and carbon paper, respectively.

After R₁ was measured, the system was rearranged as shown in Figure 1b, and the measured overall resistance value R₂ is calculated as follow:

$$R_2 = 2(R_{Cu} + R_{Cu/C}) + R_C \quad (2)$$

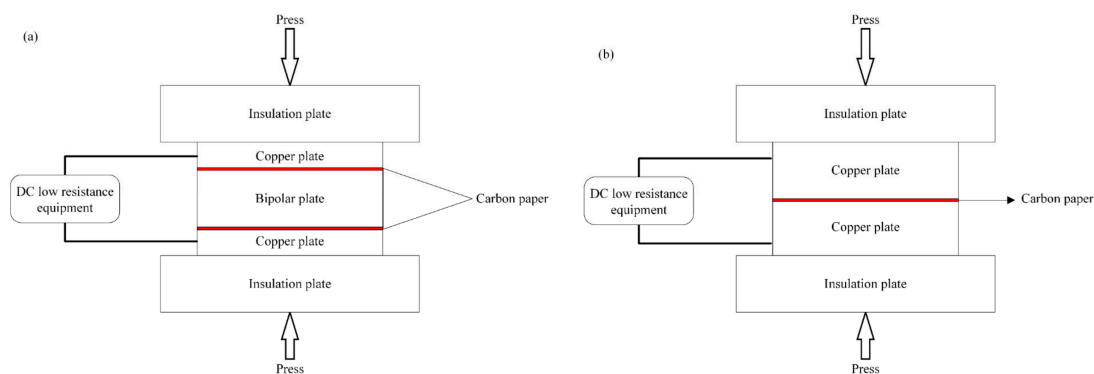


Figure 1. (a) Schematic of the measurement setup for total resistance R_1 (with bipolar plate). (b) Schematic of the measurement setup for resistance R_2 (without bipolar plate).

The body resistances of the carbon paper and the sample were orders of magnitude smaller than the contact resistance and were therefore neglected. Thus, the measured resistance was attributed solely to the interfacial contact resistance.

$$\text{ICR} = (R_1 - R_2)S/2 \quad (3)$$

where S represents the contact area between the copper plate, the sample, and the carbon paper.

The ICR measurements were repeated at least three times for each sample, and the average values were reported.

3. Results and Discussion

3.1. Coating Characterization: Surface and Cross-Sectional Coating Morphologies

Figure 2 shows the surface and cross-sectional morphologies of the Ni-G and Cu-G coatings before corrosion. As shown in Figure 2a, the thermal energy of the plasma arc caused the Ni-G particles to disintegrate, with the nickel component completely melting. The high-speed airflow carried the molten coating material onto the substrate during the APS process, forming a relatively uniform mixture of nickel and graphite. The molten metal uniformly spread over the coating surface upon solidification.

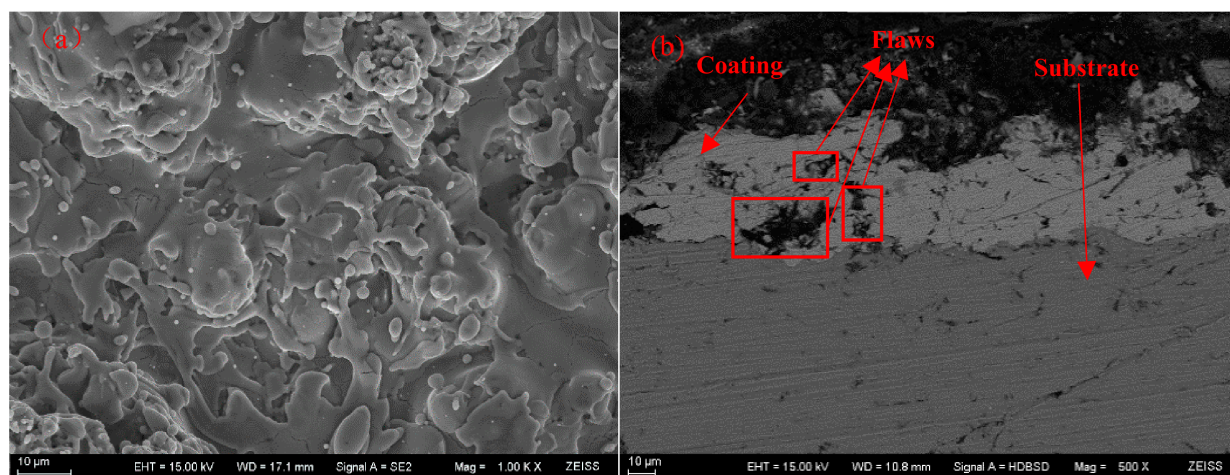


Figure 2. Cont.

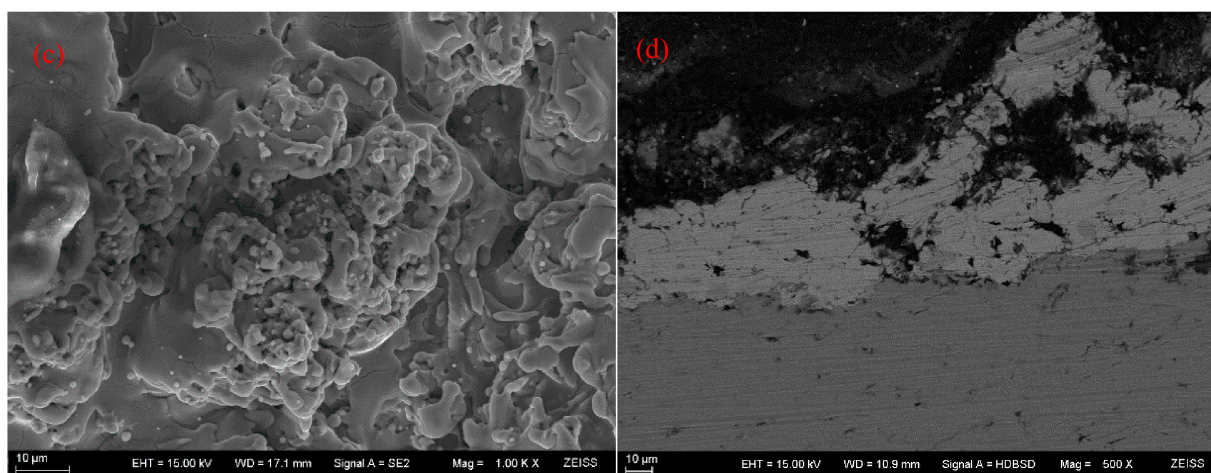


Figure 2. SEM images of (a) Ni-G (c) Cu-G Surface and (b) Ni-G (d) Cu-G cross-sectional coating morphologies before potentiostatic cathodic polarization curve.

Figure 2b reveals the pre-corrosion cross-sectional morphology of the Ni-G coating, revealing robust metallurgical bonding at the coating-substrate interface. Quantitative analysis confirms a uniform coating thickness averaging 30 µm. Since the melting point of graphite is much higher than that of nickel, the graphite particles remained solid during spraying while the nickel melted, resulting in numerous unmelted graphite particles on the surface and causing surface porosity and defects. The porosity and surface defects may also result from the poor surface quality of the substrate. In addition, during the APS process, strong adhesion between the powder particles may lead to uneven and insufficient mixing of the powder, resulting in spraying process instability [35]. Furthermore, the coating thickness was built up by repeated passes of the spray nozzle, and the porosity and defects were exacerbated by the overlapping of deposited layers. Such porosity and surface defects could be mitigated by improving the powder quality, optimizing the spraying parameters, or applying a post-treatment sealing agent [36].

The surface and cross-sectional morphologies of the Cu-G coating before corrosion are shown in Figure 2c,d. The coating quality and the underlying causes are similar to those of the Ni-G coating discussed above.

The cross-sectional SEM images (Figure 2b,d) were further used to quantitatively evaluate the porosity of the Ni-G and Cu-G coatings. Based on visual assessment of the cross-sectional micrographs, the porosity of the Ni-G coatings was estimated to be in the range of 5–10%, while the Cu-G coatings exhibited slightly higher porosity in the range of 8–12%. The higher porosity in the Cu-G coatings is likely attributed to the lower melting point of copper compared with nickel, which may result in different solidification behavior and shrinkage during the rapid cooling process after plasma spraying. The pore size distribution in both coatings was found to be predominantly within the range of 0.5–5 µm, with the majority of pores being smaller than 2 µm. Some larger pores (~5–10 µm) were occasionally observed, which may be associated with the unmelted graphite particles and the overlapping of deposited layers during the multi-pass spraying process. The presence of these pores and defects is consistent with the typical characteristics of APS-deposited composite coatings.

Figure 3 shows the surface and cross-sectional morphologies of the Ni-G and Cu-G coatings after potentiostatic cathodic polarization testing. The surface microstructure was altered, and corrosion products were observed. As shown in Figure 3a,c, more graphite particles were observed after corrosion. This suggests that graphite, which has higher corrosion resistance than the metallic components, remained stable, whereas the nickel,

copper, and their surface oxides were partially corroded during potentiostatic cathodic polarization in the simulated PEMFC environment.

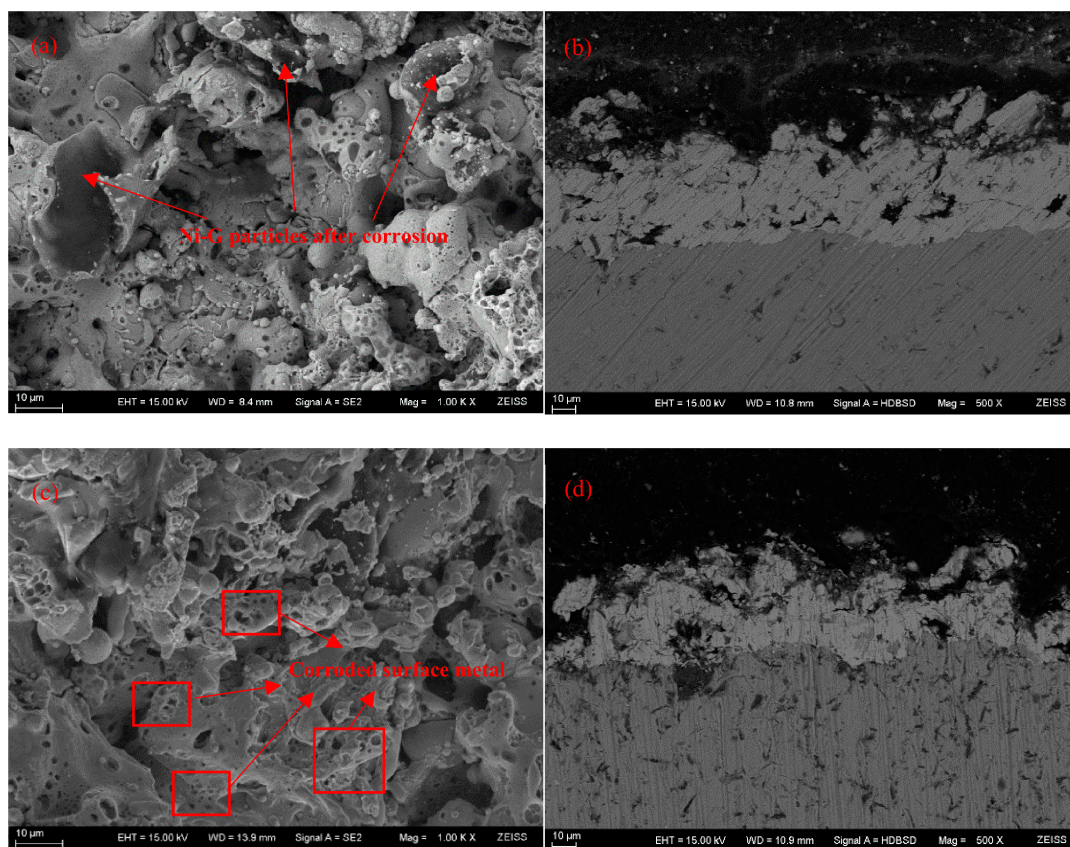


Figure 3. SEM images of (a) Ni-G (c) Cu-G Surface and (b) Ni-G (d) Cu-G cross-sectional coating morphologies after potentiostatic cathodic polarization curve.

The cross-sectional morphologies (Figure 3b,d) reveal that the coating microstructure and uniform substrate coverage were well preserved after testing. This demonstrates that even after prolonged corrosion, the coating quality did not deteriorate significantly, despite the initial surface imperfections.

XRD patterns and XPS spectra

Figure 4a shows the XRD patterns of the Ni-G coatings with different graphite mass ratios. The XRD patterns revealed characteristic diffraction peaks of graphite (002) (PDF#41-1487) and nickel (111), (200), and (220) (PDF#70-0989). As the graphite content increased, the intensity of the graphite diffraction peaks increased, while that of nickel decreased. The NiO phase (PDF#89-7130) was also detected, indicating partial oxidation of Ni to NiO. This oxidation resulted from rapid oxidation in the high-temperature plasma jet, followed by slow oxidation during subsequent air exposure [37].



Figure 4b shows the XRD patterns of the Cu-G coatings with different graphite mass ratios, which exhibit similar trends to those of the Ni-G coatings. Cu (PDF#04-0836) and graphite phases were identified in the sprayed coatings. The intensity of the graphite diffraction peaks increased with increasing graphite content, while that of Cu decreased. A

CuO phase (PDF#45-0937) was also detected, indicating partial oxidation of Cu to CuO. The process can be explained by the oxidation reaction of Cu [38]

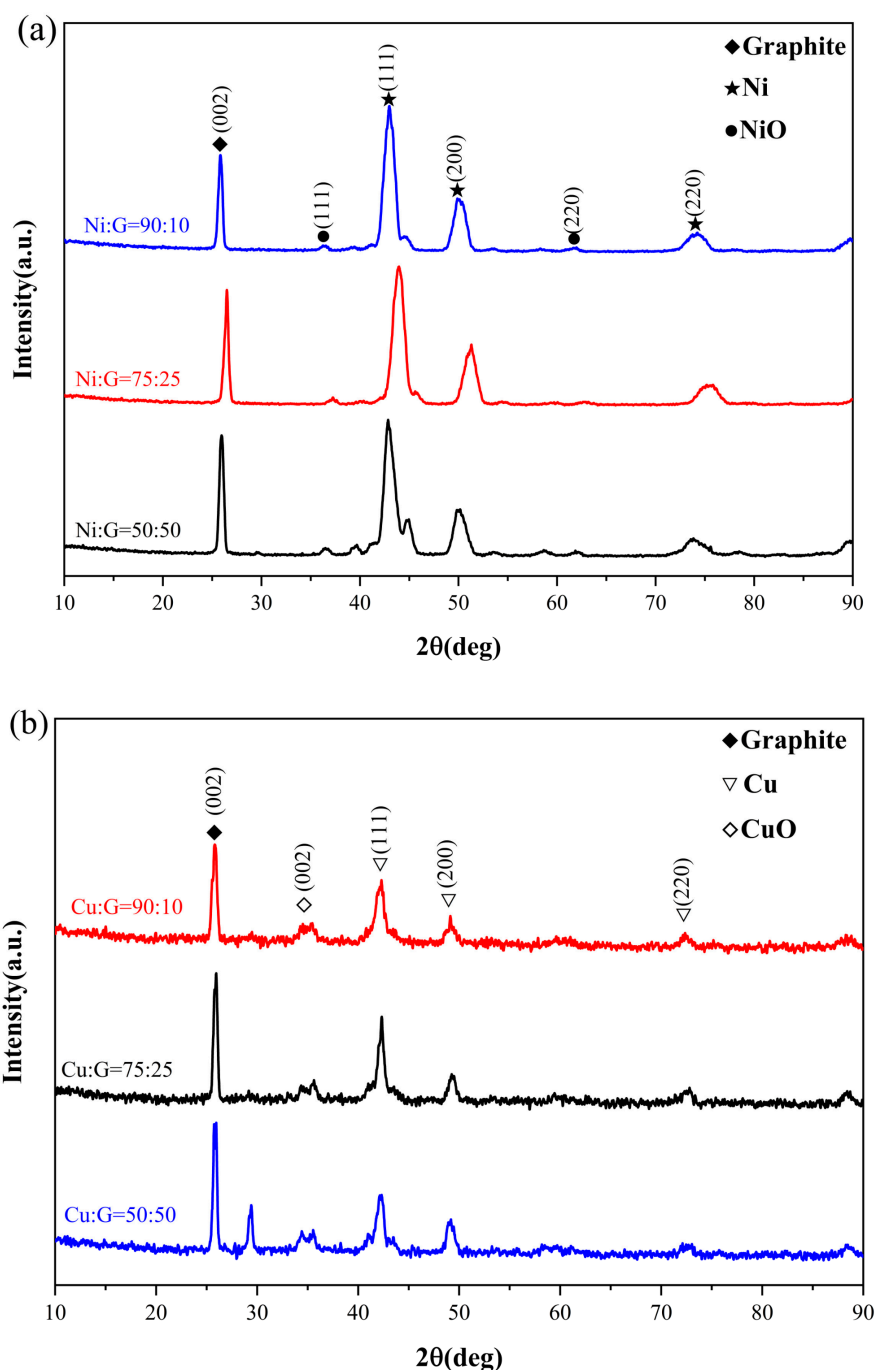


Figure 4. XRD pattern of (a) Ni-G, (b) Cu-G coating.

Figure 5a shows the XPS survey spectrum of the Ni-G coating, and the main elements detected on the surface are C, O, and Ni. C and Ni originated from the coating powder, while O mainly came from atmospheric oxidation. To analyze the chemical bonding states of each element and thus determine the chemical composition and structure of the coating, narrow-scan XPS analysis was performed for each element.

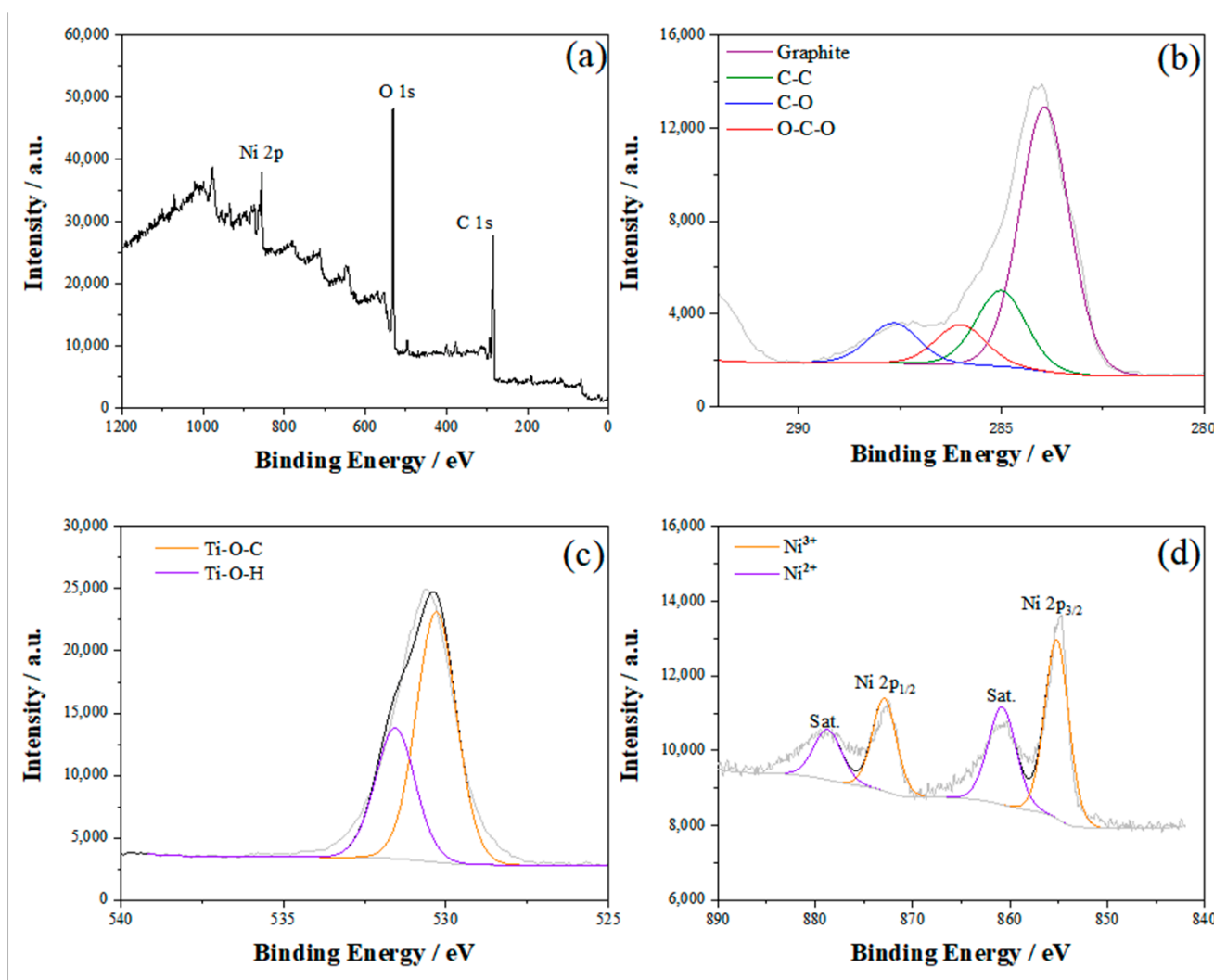


Figure 5. XPS pattern of Ni-G coating: (a) survey spectrum; (b) C 1s spectrum; (c) O 1s spectrum; (d) Ni 2p spectrum.

Figure 5b shows the C 1s spectrum. The spectrum was deconvoluted into peaks corresponding to O–C=O (287.7 eV), C–O (286.1 eV), sp^2 C–C (284.9 eV), and graphite (284.1 eV). The presence of C–O and O–C=O bonds indicates that the graphite was partially oxidized during the spraying process.

Figure 5c shows the O 1s spectrum, which reveals Ti–O–C and Ti–O–H bonds resulting from the oxidation of both the substrate and the coating material.

Figure 5d shows the Ni 2p spectrum, which indicates that Ni was mainly present as Ni^{3+} and Ni^{2+} , resulting from the oxidation of the original Ni powder during the high-temperature APS process.

Figure 6a shows the XPS survey spectrum of the Cu-G coating. The main elements detected on the surface are C, O, and Cu. C and Cu originated from the coating powder, while O mainly came from atmospheric oxidation. Similarly, narrow-scan XPS analysis was performed for each element, and the C 1s, O 1s, and Cu 2p spectra are shown in Figure 6b–d, respectively. Similar to the Ni-G coatings, the graphite and Cu were partially oxidized during the spraying process, as revealed by the C 1s and Cu 2p spectra.

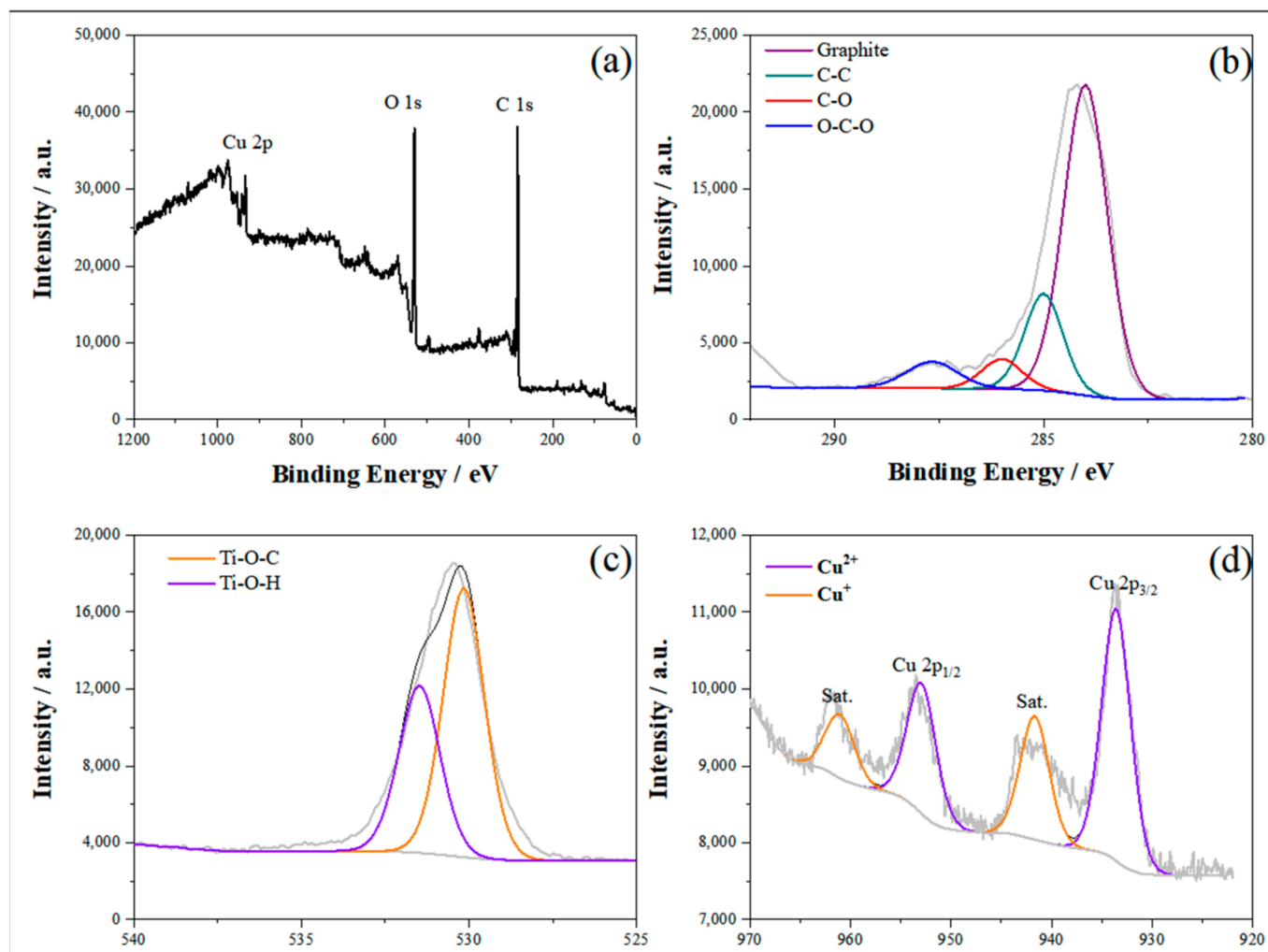


Figure 6. XPS pattern of Cu-G coating: (a) survey spectrum; (b) C 1s spectrum; (c) O 1s spectrum; (d) Cu 2p spectrum.

Regarding the influence of oxide formation on coating performance, several aspects should be considered.

First, the presence of NiO and CuO in the coatings is expected to influence the corrosion behavior. On one hand, these oxides may provide a certain degree of passive protection by acting as physical barriers against electrolyte penetration. On the other hand, the formation of oxides inevitably introduces defects and porosity at the metal-oxide interfaces, which may facilitate electrolyte permeation and lead to localized corrosion. The slightly higher corrosion resistance of Cu-G coatings compared with Ni-G coatings observed in this study may be partly attributed to the higher chemical stability of CuO in the acidic PEMFC environment.

Second, the formation of NiO and CuO adversely affects the electrical conductivity of the coatings. Both nickel and copper are highly conductive metals, whereas their oxides (NiO and CuO) are semiconducting or insulating phases. The presence of these oxide phases increases the contact resistance between coating particles and between the coating and the carbon paper, thereby partially offsetting the beneficial effect of graphite on conductivity. This explains why the ICR values of our coatings, although improved with increasing graphite content, remain higher than those of pure metallic coatings reported in the literature.

Third, the XPS results reveal the presence of C–O and O–C=O bonds (Figures 5b and 6b), indicating partial oxidation of graphite during the APS process. This oxidation may reduce

the intrinsic conductivity of graphite and potentially affect the corrosion resistance of the coatings. The formation of oxygen-containing functional groups on graphite surfaces may also influence the wettability and interfacial properties of the coatings.

Fourth, no carbide phases (e.g., Ni_3C or copper carbides) were detected in the XRD patterns (Figure 4), suggesting that the high-temperature plasma spraying process did not induce significant carbide formation under the current processing conditions. The absence of carbide formation is favorable, as carbides are typically brittle phases that could deteriorate the mechanical integrity of the coatings.

3.2. Corrosion Resistance Test

Figure 7a shows the results of the potentiodynamic cathodic polarization tests for the two coating materials of different mass ratios. The experiments were performed in the Tafel interval. In general, the lower the monitored corrosion current density of the material, the better its corrosion resistance. The fitted data are shown in the table below. It can be observed that the corrosion current density of the coated samples with different mass ratios showed a significant decrease compared with that of the bare titanium plate, indicating that the presence of the coating effectively improved the corrosion resistance of the substrate. Similar trends were observed for the two coating materials. The corrosion current density decreased with the increase in the graphite content in the coated powder material, and the corrosion potential generally remained unchanged. The decrease in corrosion current density indicated the improvement in corrosion resistance due to the existence of more graphite content in the coating material.

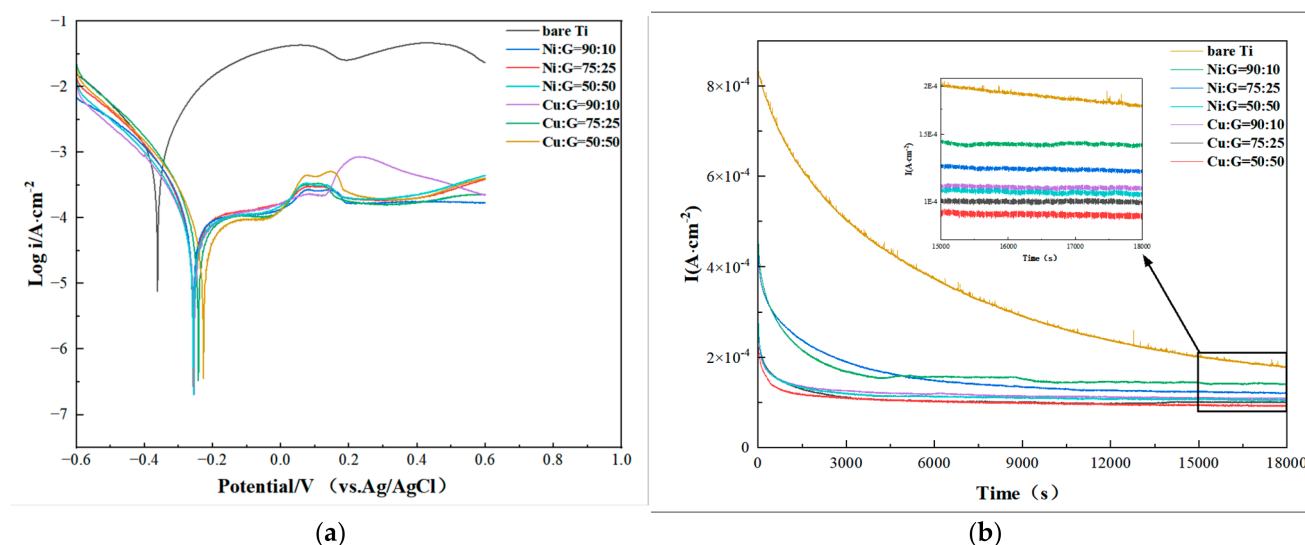


Figure 7. (a) Potentiodynamic cathodic polarization curve (b) Potentiostatic cathodic polarization curve.

The corrosion resistance of the APS-prepared Ni-G and Cu-G coatings is comparable to, or even better than, that of other coating systems reported in the literature. For instance, Joseph et al. [39] demonstrated that coating stainless steel with conducting polymers (PANI and PPY) improved its corrosion resistance. However, the corrosion current density of our Ni-G (50:50) coating ($0.97 \times 10^{-4} \text{ A}\cdot\text{cm}^{-2}$) and Cu-G (50:50) coating ($0.82 \times 10^{-4} \text{ A}\cdot\text{cm}^{-2}$) is significantly lower than that of bare Ti ($1.18 \times 10^{-3} \text{ A}\cdot\text{cm}^{-2}$), showcasing the effectiveness of the metal-graphite composite coating. More recently, a CrN/Nb coated 316L stainless steel prepared by magnetron sputtering achieved a corrosion current density as low as $0.39 \mu\text{A}\cdot\text{cm}^{-2}$ [40]. Although this value is lower than ours, it is important to note that our coatings were deposited on titanium substrates using a simpler and more cost-effective APS process, which is more suitable for large-scale production.

Figure 7b shows the corrosion current density versus time curves of the coatings with different mass ratios in the simulated PEMFC cathode environment at a constant potential of 0.6 V. As the test progressed, the corrosion current density decreased rapidly and then gradually stabilized, which is attributed to the formation of a surface passivation layer [41]. The corrosion current density of the coated samples decreased significantly, by approximately one order of magnitude compared with the bare titanium. This indicates that the coatings maintained better corrosion resistance and stability than the bare titanium plate even after prolonged exposure. The graphite content showed a similar trend to that observed in the potentiodynamic polarization tests, the results of which are summarized in Table 2. The corrosion resistance improved with increasing graphite content.

Table 2. Corrosion parameters obtained in potentiodynamic cathodic polarization tests results.

Samples	E _{corr} (V)	I _{corr} (A·cm ^{−2})
bare Ti	-3.62×10^{-1}	1.18×10^{-3}
Ni:G = 90:10	-2.58×10^{-1}	1.56×10^{-4}
Ni:G = 75:25	-2.57×10^{-1}	1.14×10^{-4}
Ni:G = 50:50	-2.56×10^{-1}	0.97×10^{-4}
Cu:G = 90:10	-2.74×10^{-1}	1.17×10^{-4}
Cu:G = 75:25	-2.42×10^{-1}	1.04×10^{-4}
Cu:G = 50:50	-2.27×10^{-1}	0.82×10^{-4}

It should be noted that post-corrosion EDS and XPS analyses were not performed in this study. The corrosion experiments were conducted some time ago, and the tested samples have been stored under ambient conditions, which may have introduced surface contamination or oxidation, potentially altering the original microstructure. Therefore, additional characterization could not be reliably performed. Future work will include systematic post-corrosion EDS and XPS analyses to further clarify the corrosion mechanism.

3.3. Electrical Conductivity Test

In addition to corrosion resistance, interfacial contact resistance (ICR) is another important performance indicator for bipolar plates. Figure 8 presents the ICR of Ni-G and Cu-G coatings with different mass ratios as a function of applied pressure, measured both before and after potentiostatic cathodic polarization. The ICR decreased with increasing pressure and remained stable at pressures above 100 N cm^{−2}. Typically, the assembly pressure of a PEMFC stack is about 140 N cm^{−2}. As shown in Table 3, at 140 N cm^{−2}, the ICR decreased with increasing graphite content, indicating that higher graphite content improves electrical conductivity. The ICR of all coatings increased after potentiostatic cathodic polarization. However, the negative correlation between ICR and graphite content remained unchanged. The ICR is strongly correlated with the material composition and surface quality [42]. Since the coated samples were not post-treated to improve surface quality, pores and defects remained on the coating surfaces, resulting in relatively high ICR values between the coatings and the carbon paper.

Table 3. ICR at 1.4 MPa before and after potentiostatic cathodic polarization.

Samples	Before Polarization (mΩ·cm ^{−2})	After Polarization (mΩ·cm ^{−2})
Ni:G = 90:10	30.3	47.5
Ni:G = 75:25	29.3	42.9
Ni:G = 50:50	25.2	38.9
Cu:G = 90:10	24.3	26.5
Cu:G = 75:25	20.5	24.4
Cu:G = 50:50	17.4	21.2

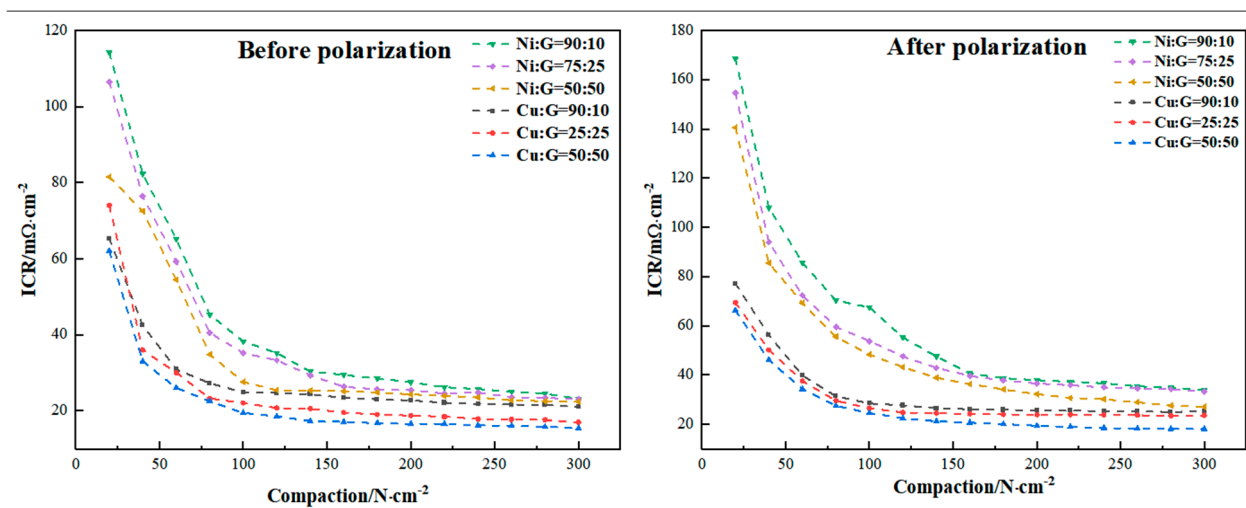


Figure 8. ICR before and after potentiostatic cathodic polarization.

4. Conclusions

In this paper, Ni-G and Cu-G coatings with different mass ratio were prepared on titanium substrate using APS to study the effect of the graphite content of coating materials on the corrosion resistance and electrical conductivity of the coatings. The effect of graphite content in corrosion testes was investigated and the following conclusions were obtained.

- (1) Powdered Ni-G and Cu-G with different graphite contents can be successfully prepared on titanium bipolar plates by APS process.
- (2) The corrosion current densities of the coated bipolar plates decreased significantly compared with those of the bare titanium bipolar plates, indicating that the presence of the coating effectively improves the corrosion resistance. The increase in graphite content in the coatings contributes to the improvement of the corrosion resistance of the coatings.
- (3) The increase in graphite content contributes to the improvement of the electrical conductivity of the coating before and after the potentiostatic cathodic polarization tests.

It should be noted that while the present study focuses on the effect of graphite content on coating performance, systematic optimization of the coating composition and APS process parameters using a design of experiments (DOE) approach would be a valuable direction for future work. Such an approach could further optimize the trade-off between corrosion resistance, electrical conductivity, and coating integrity.

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Conflicts of Interest: Guangji Song was employed by the Xiamen King Long United Automotive Industry Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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