# Original Research Article

# Research Progress on Coatings for Fuel Cell Bipolar Plates

Abstract: The bipolar plate, as one of the key components of a proton exchange membrane fuel cell (PEMFC), significantly impacts the operational efficiency and service life of the fuel cell. Metallic bipolar plates are prone to corrosion during prolonged operation, contaminating the proton exchange membrane, increasing membrane resistance, and degrading PEMFC performance. This paper comprehensively explores the research progress in preparation processes and materials for coatings on automotive fuel cell bipolar plates. It elaborates on the characteristics and applications of various preparation methods and analyzes the performance and applications of multiple coating materials. Research indicates that developing efficient, low-cost preparation processes and high-performance coating materials is crucial for enhancing the performance of automotive fuel cell bipolar plates and holds significant importance for promoting the commercial application of fuel cell vehicles.

Keywords: Proton exchange membrane fuel cell ; Bipolar plate; Surface modification;

## 1. Introduction

In contemporary society, the energy crisis is becoming increasingly severe. The massive consumption of traditional fossil fuels and the resulting damage to the ecological environment have compelled the development of clean, sustainable energy sources to become a global focus. Proton exchange membrane fuel cells (PEMFCs) are widely used in the automotive sector due to their fast start-up, high energy conversion efficiency, and environmental friendliness. The bipolar plate (BPP) is one of the core components of a fuel cell, accounting for 60%-80% of the stack's mass and approximately 40% of its cost. Its primary functions include supporting the membrane electrode assembly (MEA), providing flow channels for hydrogen, oxygen, and coolant, collecting electrons, and conducting heat [1]. The performance of the BPP plays a decisive role in the overall performance, lifespan, and cost of the fuel cell. However, the actual operating environment of fuel cells is harsh and complex, characterized by prolonged exposure to humid conditions at 60°C–80°C, an internal solution pH of 2–3, and the presence of corrosive ions such as SO₄²⁻, F⁻, SO₃²⁻, HCO₃⁻, etc. PEMFCs use hydrogen and oxygen as fuels, requiring their smooth delivery to the MEA for electrochemical reactions. To ensure the effective operation of PEMFCs, bipolar plates must possess excellent electrical conductivity, thermal conductivity, corrosion resistance, gas tightness, and good mechanical properties [2].

Surface modification technology can meet these requirements. By preparing suitable coatings on the bipolar plate surface, not only can the plate's corrosion resistance be enhanced, preventing performance degradation due to corrosion in harsh environments, but the surface conductivity of the bipolar plate can also be improved, reducing contact resistance and thereby increasing the power output and energy conversion efficiency of the fuel cell. Furthermore, optimizing preparation processes and coating materials can reduce the cost of bipolar plates to some extent, promoting the commercial adoption of fuel cell vehicles. Depending on the processing method, surface modification techniques include physical vapor deposition (PVD), chemical vapor deposition (CVD), electroplating, thermal spraying, and electroless plating [3].

Noble metal coatings (e.g., Au, Ag, Pt) were widely used in early research due to their good conductivity and corrosion resistance, but their high cost limited large-scale commercialization [4]. Consequently, research on non-noble metal coatings (e.g., Ni, Cu, Cr) has received increased attention in recent years. The performance of non-noble metal coatings has been significantly improved through alloying and surface modification [5,6]. Metal compound coatings (e.g., carbides, nitrides) possess high hardness, high wear resistance, and good chemical stability, showing great potential in enhancing bipolar plate corrosion resistance and mechanical properties. Conductive polymer coatings offer new approaches for bipolar plate coating research due to their unique electrical properties and good film-forming ability. Additionally, carbon-based coatings (e.g., graphene, carbon nanotubes) have become a hot research topic due to their excellent conductivity, high strength, and good chemical stability [7].

This paper systematically introduces various preparation processes for bipolar plate coatings, analyzes the performance of different bipolar plate coating materials, summarizes current research challenges, and provides an outlook on future development trends for bipolar plate coatings.

## 2. Surface Modification Processes for Metallic Bipolar Plates

### 2.1 Physical Vapor Deposition (PVD)

Physical Vapor Deposition (PVD) refers to the technology where a solid source material is vaporized into gaseous molecules, atoms, ions, or plasma through physical means. After the target material evaporates into gaseous ions, a thin film is deposited onto the substrate surface via a high-speed gas stream. Common PVD techniques include: evaporation coating, sputtering coating, and ion plating [8].

Evaporation coating is one of the earliest developed PVD techniques. Its principle involves heating the coating material (the evaporation source) to its evaporation temperature, allowing its atoms or molecules to gain sufficient energy to transition from solid or liquid state to vapor. This vapor diffuses towards the substrate surface in a vacuum environment and ultimately deposits to form a coating. This method can produce high-purity coatings because, under vacuum, the evaporated source material deposits directly onto the substrate surface, minimizing impurity incorporation. However, evaporation coating becomes unsuitable for materials with high melting points and bipolar plates with complex shapes [9].

Sputtering coating is a commonly used method in PVD. The basic principle involves bombarding the target surface with argon ions in a vacuum environment, causing target atoms or molecules to gain sufficient energy to escape from the target surface and deposit onto the substrate surface to form a coating. During sputtering, argon ions collide with target atoms, transferring part of their energy to the target atoms, enabling them to overcome surface binding forces and be sputtered out. These sputtered atoms or molecules move randomly within the vacuum chamber, with some reaching the substrate surface where they adsorb, diffuse, nucleate, and grow, eventually forming a continuous coating [10]. Depending on the sputtering source, common types include DC sputtering, RF sputtering, and magnetron sputtering. By precisely controlling sputtering parameters such as sputtering power, sputtering time, and gas flow rate, the thickness and composition of the coating can be precisely controlled to obtain coatings with excellent performance[11]. Secondly, sputtering coating can deposit various coating materials (including metals, alloys, compounds) onto bipolar plates made of different materials, demonstrating broad applicability. However, sputtering coating technology has high costs, relatively low deposition rates, low production efficiency, and high equipment and maintenance costs, limiting its large-scale application. Sputtering coating is shown in Figure 1.



Figure 1 Sputtering coating.

### 2.2 Electroplating

Electroplating is a type of metal electrodeposition. The resulting metal deposit not only possesses good physical properties itself but also provides strong protection to the substrate [12]. During electroplating, the anode is made of the metal to be plated or an insoluble conductor, and the cathode is the plate to be plated. These are connected to the positive and negative terminals of the power supply, respectively. The electrolyte is typically a salt solution of the metal to be plated. After energizing the reaction cell, a reduction reaction occurs at the cathode, precipitating the metal ions to be plated. However, because electroplating technology produces large amounts of corrosive waste liquid, polluting the environment, it has been largely replaced by other processes [13].

### 2.3 Thermal Spraying

The principle of thermal spraying technology is to use a heat source such as a flame or plasma to heat the spray material to a molten or semi-molten state. A high-speed gas stream is then introduced to atomize it, and the resulting spray is projected onto a pre-treated part surface to form a protective coating. Thermal spraying technology is simple to operate; the materials used can be metals, ceramics, etc., offering a wide range of choices. Most importantly, it is environmentally friendly, low cost, and suitable for large-scale production. If a part becomes worn or corroded, reducing its size, thermal spraying can also be used to repair its surface [14]. Thermal spraying technology is shown in Figure 2.



Figure 2 Thermal spraying technology.

#### 2.3.1 Flame Spraying

Flame spraying utilizes combustible gas to generate a flame that heats the spray material to a molten or semi-molten state. The material is then atomized by a gas stream and propelled onto the substrate surface to form a coating [15]. Based on the form of the spray material, flame spraying can be classified as: powder flame spraying, wire flame spraying, and rod flame spraying. Flame spraying operates at relatively low temperatures; the substrate surface typically experiences only 200–250°C, resulting in minimal thermal deformation. However, oxidation occurs during spraying, leading to porosity and inclusions within the coating, resulting in poor bond strength between the coating and substrate and poor thermal shock resistance. Flame spraying technology is shown in Figure 3.



Figure 3 Flame spraying technology.

#### 2.3.2 Arc Spraying

Arc spraying technology uses the metal wire material to be sprayed as consumable electrodes, with the arc formed at their tips acting as the heat source. The tips of the wires melt as the arc temperature increases. The molten material is atomized by a gas stream and forms a coating on the substrate surface. Arc spraying offers advantages such as high efficiency, convenience for on-site application, short processing time, low cost, and good safety. However, during spraying, the atomized metal particles can exhibit significant size variation due to accumulation caused by melting at the wire tips.

#### 2.3.3 Detonation Spraying (DS)

Detonation spraying involves mixing oxygen and acetylene gas in a specific ratio and detonating them in a specially designed combustion chamber. This heats the spray particles to a molten state and propels them at high velocity to impact the part surface, forming a coating. Detonation sprayed coatings exhibit high bond strength with the substrate and low porosity within the coating. However, the process generates high noise levels and is difficult to apply to parts with complex shapes or small internal cavities [16].

#### 2.3.4 Plasma Spraying (PS)

The positive terminal of the power supply connects to the plasma spray gun nozzle (anode), and the negative terminal connects to the electrode (cathode). A working gas is fed between the nozzle and electrode, and a high-frequency spark ignites an arc. The arc heats the gas, ionizing it to produce a plasma jet. The heated, expanding gas is expelled from the nozzle, forming a high-velocity plasma stream. Spray powder is accelerated by this plasma jet and simultaneously heated to a molten or semi-molten state. It is then sprayed onto the substrate to form a coating. Plasma spraying offers numerous advantages: convenient adjustment, fast deposition rate, wide range of spray materials, high flame temperature, and strong adaptability. Plasma spraying technology is shown in Figure 4.



Figure 4 Plasma spraying technology.

#### 2.3.5 High-Velocity Oxy-Fuel Spraying (HVOF)

High-Velocity Oxy-Fuel (HVOF) spraying utilizes fuels like propane or propylene combusted with highly compressed oxygen to produce a high-temperature, high-pressure flame stream. This stream heats the spray powder to a molten or semi-molten state and propels it at extremely high velocity to impact the workpiece surface, forming a coating. HVOF coatings possess superior wear resistance, corrosion resistance, and fatigue resistance. Due to the high particle velocity and relatively low particle temperature in HVOF, it is particularly suitable for preparing coatings like metal-ceramics, alloys, and pure metals.

#### 2.3.6 Thermal Spraying + Post-treatment Process

Coatings obtained by spraying often suffer from issues like porosity, oxides, unmelted particles, and interlayer boundaries, which can severely reduce corrosion resistance. Therefore, post-treatment processes are needed to improve the acquired coating.

Sealing treatment is one such post-treatment process. Its principle involves selecting a suitable sealant to treat the coating. To achieve good sealing results, the following points should be considered when choosing a sealant [17]:

Good permeability: Can effectively penetrate into the fine, narrow channels within the coating, preventing corrosive liquids from penetrating and contacting the substrate.

Good chemical resistance: The sealant filling the coating should have good chemical resistance to enhance the overall corrosion resistance of the coating.

Good elasticity: Since coatings often undergo some degree of movement during service, good elasticity is needed to prevent cracking or detachment under mechanical stress.

Good high-temperature resistance: Coatings frequently operate in high-temperature environments; they must avoid melting and losing effectiveness at high temperatures.

Environmental friendliness: Should not cause environmental damage.

### 2.4 Chemical Vapor Deposition (CVD)

Chemical Vapor Deposition (CVD) is a surface modification technology that utilizes the chemical reaction of two or more gases on a substrate surface to form a protective film. In the CVD process, the bipolar plate is typically placed in a reaction chamber, and gaseous coating materials and reactant gases are introduced. Under conditions such as high temperature, plasma, or catalysts, the gaseous reactants undergo chemical reactions on the bipolar plate surface, generating solid coating material that deposits onto the surface. Traditional CVD technology can produce coatings with good chemical stability and uniformity. However, due to its high reaction temperature, it can cause deformation and performance degradation of metallic bipolar plates, limiting its use [18].

Plasma Enhanced Chemical Vapor Deposition (PECVD) builds upon CVD by utilizing plasma to promote chemical reactions, enabling the deposition of high-quality thin films at lower temperatures [19]. The principle involves introducing reactant gases (e.g., silane, ammonia, methane) into the reaction chamber under vacuum (typically between 10⁻³ and 10² Pa). Under a high-frequency electric field, these gases are excited and ionized to form plasma. High-energy electrons within the plasma collide with reactant gas molecules, providing them with sufficient energy to enhance their chemical reactivity, leading to coating deposition on the bipolar plate surface. The primary advantage of PECVD is reducing the reaction temperature from that of traditional CVD to around 100-300°C, meeting the processing requirements for temperature-sensitive bipolar plate materials. Coatings obtained by PECVD exhibit good conductivity, with significantly reduced defects and porosity, greatly improving density and uniformity. Plasma can enhance chemical bonding between the film and the bipolar plate substrate, increasing coating adhesion. PECVD deposition rates are relatively fast, allowing coatings of certain thicknesses to be obtained in a shorter time, improving production efficiency [20]. Chemical vapor deposition is shown in Figure 5.



Figure 5 Chemical vapor deposition.

## 3. Surface Modification of Metallic Bipolar Plates

Commonly used bipolar plates are mainly classified as: graphite bipolar plates, composite bipolar plates, and metallic bipolar plates [21]. Graphite is considered an excellent material for making bipolar plates due to its superior thermal and electrical conductivity. Graphite bipolar plates exhibit good corrosion resistance, hydrophobicity, stability, and low interfacial contact resistance. However, the brittleness and low strength of graphite make the processing of graphite bipolar plates difficult [22,23]. Simultaneously, graphite's relatively high porosity results in poor gas tightness and mechanical strength for graphite bipolar plates, limiting their commercialization. Composite material bipolar plates are primarily made from conductive polymers and conductive fillers, offering advantages like excellent conductivity, good formability, and corrosion resistance. However, localized heating occurs during actual fuel cell operation, leading to excessively high local temperatures, which limits the operating temperature range of composite bipolar plates. Metallic bipolar plates possess good electrical conductivity, thermal conductivity, ease of forming, and relatively low cost. But in the acidic environment of fuel cells, metal corrosion increases the interfacial contact resistance of the fuel cell, reducing output efficiency [24]. The most effective way to solve the problems of poor corrosion resistance and conductivity in metallic bipolar plates is surface modification. Current surface modification coatings for metallic bipolar plates can be divided into three categories: metal-based coatings, conductive polymer coatings, and carbon-based coatings [25].

### 3.1 Metal-based Coatings

Noble metal coatings, such as Au, Ag, and Pt, meet the requirements for conductivity and corrosion resistance of metallic bipolar plates due to their excellent conductivity and inertness. However, their high cost, far exceeding that of the fuel cell itself, prevents large-scale commercialization. Wen et al. deposited a 1μm thick Au coating on 316L stainless steel. After immersion in a simulated fuel cell environment (0.5 mol/L H₂SO₄, 10 mg/L HF, 80°C) for 0, 12, 24, and 48 hours, it was found that the reaction resistance decreased from 3774 Ω·cm² to 1487 Ω·cm², while the corrosion current increased from 1.716×10⁻⁵ A/cm² to 2.243×10⁻⁴ A/cm² as immersion time increased. This indicates an increasing corrosion rate. Due to the corrosive environment (H⁺, SO₄²⁻, F⁻), electrochemical reactions occur on the gold surface, forming pits and pores that accelerate corrosion. Simultaneously, the localized regions of the Au coating film mainly contain Au and O, reducing the corrosion tendency and causing the corrosion potential to increase with immersion time [26]. Feng Kai et al. used ion implantation to inject a thin Ag coating onto the surface of 316L stainless steel. Electrochemical experiments showed that in potentiostatic tests, the corrosion current density decreased from 10 μA·cm⁻² (unmodified plate) to 0.7 μA·cm⁻², and the interfacial contact resistance (ICR) decreased from 312.8 mΩ·cm⁻² to 78.8 mΩ·cm⁻² [27]. To avoid excessive costs, noble metals are now mostly incorporated into coatings as dopants. Yan et al., by studying TiN-Ag nanocomposite coatings obtained at different temperatures, found that the uniform distribution of Ag particles provided new low-resistance pathways in the composite coating, significantly improving its conductivity [28].

Due to the unsuitability of noble metals, some alloy materials have become new research directions. Dong et al. used unbalanced magnetron sputtering to deposit a NiCrCN coating on a stainless steel bipolar plate, studying the coating's microstructure under different Cr target currents (2, 4, 6A) and its corrosion resistance in a simulated PEMFC cathode environment (0.5 mol·L⁻¹ H₂SO₄ + 2 mg·L⁻¹ HF, air bubbling, 70°C). The study showed that as the current increased, the coating became more uniform and dense. However, when the current increased to 6A, the cross-section exhibited a columnar structure again, attributed to excessive current causing nucleation and agglomeration, forming coarse clusters. Potentiostatic polarization revealed corrosion currents of 2.97×10⁻⁷ A·cm⁻² (2A), 1.12×10⁻⁷ A·cm⁻² (4A), and 2.30×10⁻⁷ A·cm⁻² (6A). The lowest value was at 4A, and the polarization curve was stable, indicating good stability. Samples at 2A and 6A showed varying degrees of pitting and spalling, while the 4A sample showed no obvious corrosion marks. The experiment mentioned charge transfer resistance (Rct), related to the hindrance of corrosive ion diffusion; higher Rct makes it harder for corrosive ions to penetrate the coating. Over time, Rct first increased and then decreased. This is because in the initial corrosion stage, a large amount of corrosion products formed at the stainless steel/coating-liquid interface, hindering solution contact. In the middle stage, a stable passive film formed, further protecting the substrate. Later, the passive film was eroded by the solution, becoming loose, allowing corrosive ions to penetrate through defects and cause corrosion. This phenomenon aids in understanding corrosion mechanisms [29]. Wu used plasma spraying to prepare Ni60 alloy coatings, investigating the effects of different spray powers (200A, 300A, 400A), different vacuum heat treatment temperatures, and different sealing treatments on conductivity and corrosion resistance. As spray power increased, the number and size of pores within the coating decreased significantly. Pores mainly resulted from continuous stacking of incompletely melted spray particles on the sample surface, generating localized shrinkage stress that led to pore formation. Potentiodynamic polarization tests showed that as spray power current increased, the corrosion potential increased, while the corrosion current density first decreased and then increased. Corrosion potential indicates the tendency for corrosion to occur; a higher potential indicates a lower tendency. Corrosion current density indicates the coating's corrosion resistance; a lower density signifies better resistance [30]. Xin et al. added boron to a plasma-sprayed Ni-based alloy coating to obtain an oxidation-free coating. Experiments found the new coating was denser, and the stability of Cr₂O₃ was enhanced due to residual borides, giving the Ni20Cr4B coating excellent hot corrosion resistance at 600°C. Based on thermodynamic calculations, this phenomenon is expected to be applicable to other alloys like Fe, Cu, Mn, etc. [31]. Unlike traditional carbon-based or nitride-based coatings, MAX phase coatings are a novel type of ceramic coating. MAX phases have a unique layered hexagonal crystal structure; layers are tightly connected by metallic bonds between M and A atoms (M is an early transition metal like Ti, Ni, Cr; A is a group IIIB or IVB element like Al, Si; X is mainly C or N). MAX phases differ from typical ceramics; they have mixed covalent-ionic-metallic bonding, giving them metallic characteristics like good electrical and thermal conductivity, machinability, low hardness, along with excellent corrosion resistance, thermal resistance, and oxidation resistance. Abbas et al. used magnetron sputtering to prepare Ti₂AlC coatings at different temperatures. They found that conductivity improved as temperature increased to 750°C, and the coating deposited at 750°C had a very low ICR of only 3.27 mΩ·cm², far below DOE standards [32]. Lu et al. prepared Ti₃AlC₂ MAX phase coatings using magnetron sputtering and heat treatment. Results showed that with MAX phase formation, both corrosion resistance and conductivity improved; the contact resistance was only 3.725 mΩ·cm², meeting DOE standards. Among MAX phases, Cr₂AlC has attracted significant attention due to its excellent oxidation and corrosion resistance, along with simple preparation processes. Additionally, Cr₂AlC has a coefficient of thermal expansion similar to SS316L, favoring good adhesion between the substrate and coating [33]. Ma et al. used a combined cathodic arc and magnetron sputtering method to prepare Cr-Al-C coatings on SS316L. Electrochemical and ICR tests showed that coatings with different annealing times exhibited excellent corrosion resistance and conductivity, with interfacial contact resistance far lower than the bare plate [34]. Liu Yun et al. prepared a Cr₂AlC MAX phase coating on an SS304 substrate. Results showed the coating's corrosion current density was 2.43×10⁻⁷ A/cm², two orders of magnitude lower than SS304. After potentiostatic polarization, the anodic current density stabilized at 2.3×10⁻⁷ A/cm², and the cathodic current density decreased to 2.44×10⁻⁸ A/cm², indicating that the Cr₂AlC coating also effectively enhances the corrosion resistance of SS304 bipolar plates [35].

### 3.2 Conductive Polymer Coatings

Besides metal-based coatings, researchers have also developed conductive polymer coatings for surface modification of metallic bipolar plates. Zhou et al. deposited a double-layer protective coating of conductive polyaniline (PANI) and reduced graphene oxide (rGO) on a stainless steel bipolar plate using cyclic voltammetry. Observing the corrosion process in a simulated fuel cell environment, they found that in the initial stage, dissolution and thinning of the outer rGO layer reduced corrosion resistance. In the middle stage, formation, dissolution, and repair of a passive film occurred at the coating/plate interface. In the later stage, partial dissolution of the rGO layer exposed the PANI layer, reducing corrosion resistance and conductivity, but it still performed better than bare 316L [36]. Li et al. also studied the rGO-PANI double-layer protective coating. By introducing O₂ into the PEMFC cathode working environment to study corrosion performance, they found that the continuous, dense rGO layer covering the porous PANI improved the bipolar plate's corrosion resistance. Oxygen significantly affected the corrosion resistance of rGO/PANI/316L SS, aiding in forming a protective passive film at the film/substrate interface, thereby enhancing corrosion resistance [37]. Sun et al. used electrodeposition to prepare polypyrrole (PPy)-based coatings. Studying the effect of doping ions on corrosion performance, they found that using dopants with large molecular structures inhibited ion exchange reactions involving corrosive ions, improving the coating's protective effect on the bipolar plate [38]. Ding et al. investigated the corrosion resistance and conductivity of PPy composite coatings doped with large molecular acids and inorganic nanoparticles deposited on 304SS. Tests at different deposition potentials showed that PPy films prepared at 0.85 V had smaller particle size, lower over-oxidation, and provided the best corrosion protection for 304SS in a simulated PEMFC acidic environment. The experiment further enhanced the conductivity and corrosion resistance of the PPy film by incorporating titanium nitride (TiN) nanoparticles. Results showed that the PPy-0.1TiN composite coating reduced the corrosion current density by about two orders of magnitude compared to uncoated 304SS and significantly reduced interfacial contact resistance, improving conductivity, basically meeting PEMFC bipolar plate requirements [39].

### 3.3 Carbon-based Coatings

Carbon-based coatings and modified carbon-based coatings possess excellent conductivity and corrosion resistance, are relatively low-cost, suitable for large-scale commercial production, and have broad application prospects in the surface modification of metallic bipolar plates. Xu et al. used plasma immersion assisted deposition (PIAD) to prepare a diamond-like carbon (DLC) film on a bipolar plate. Results showed that PIAD could control the growth of sp²-structured graphite layers and sp³-structured diamond layers within the DLC film. The treated bipolar plate's current value was about two orders of magnitude smaller than the bare plate, exhibiting superior corrosion resistance [40]. Wang et al. deposited TiC/a-C:H composite coatings on SS 304 stainless steel using magnetic-filtered vacuum cathodic arc deposition. Studying the effect of different deposition energies on corrosion resistance and conductivity, they found that coatings deposited at substrate negative bias voltages from -100V to -500V were dense with few defects. As the negative bias value increased, the nanograin size of the coating increased. At a bias of -100V, the ICR was 1.49 mΩ·cm² and the current density was 5.25×10⁻⁸ A/cm² (Note: original text says μA/cm², assumed typo), meeting DOE 2025 requirements [41]. Zhou Qinghuan et al. used magnetron sputtering to deposit graphite coatings of different thicknesses on 316L stainless steel bipolar plates by controlling the sputtering time of a graphite target. By comparing the performance of different thickness graphite coatings under the same simulated fuel cell operating environment, the optimal graphite coating thickness was determined. Experiments proved that all graphite coatings improved the corrosion resistance and conductivity of 316L stainless steel; the optimal thickness was found to be 400 nm [42]. Li Jianwei et al. prepared an amorphous carbon coating on a 316L stainless steel bipolar plate using vacuum cathodic arc ion plating. Analysis of the corrosion mechanism showed that the coating's interfacial contact resistance was 7.9 mΩ·cm⁻² and corrosion current density was 0.17 μA·cm⁻². Durability tests at 0.6V (vs. AgCl) and 1.1V (vs. AgCl) in a simulated PEMFC cathode environment showed corrosion current densities below 1 μA·cm⁻², meeting the operational requirements for metallic bipolar plates [43]. Carbon composite bipolar plates are composed of carbon-containing materials compounded with polymer resin materials, offering advantages like low cost, high corrosion resistance, and high durability. The preparation process for carbon composite bipolar plates generally involves vacuum impregnation followed by compression molding or injection molding. Lee et al. used compression molding with graphite powder and carbon black as conductive fillers, and epoxy resin as the polymer matrix, to prepare carbon composite bipolar plates with different carbon black mass fractions. Measurements found that the electrical conductivity of the composite bipolar plate increased with increasing carbon black mass fraction. This is because carbon black particles are much smaller than graphite particles and can act as conductive bridges between them. However, when the carbon black mass fraction exceeded 15%, the conductivity began to decrease [44]. Zhang et al. conducted orthogonal tests on Cr/CrₓC₁₋ₓ/C coatings. They found that at power and gas flow parameters of 3 kW and 120 sccm, the corresponding coating performance was better; coating contact resistance was below 10 mΩ·cm², indicating good conductivity. Subsequently, changing the coating system from Cr/CrₓC₁₋ₓ/C to Ti/TiₓC₁₋ₓ/C revealed that Ti remains stable at high potentials without dissolving, improving corrosion resistance. The coating deposited at -120V bias had a low corrosion current density, indicating better corrosion resistance [45].

## 4. Outlook

Currently, research on fuel cell bipolar plate coatings has achieved significant progress both domestically and internationally. New coating materials continue to emerge, preparation processes are continuously optimized, performance is constantly improving, and commercial applications are gradually advancing. Regarding cost control, many advanced coating preparation processes, such as magnetron sputtering (PVD) and chemical vapor deposition (CVD), involve expensive equipment with high operation and maintenance costs. Production efficiency is another key issue that preparation processes need to address. The deposition rates of some coating processes are low, and the preparation cycle is long, making it difficult to meet the demands of large-scale industrial production. This paper has comprehensively explored the preparation processes and materials for coatings on automotive fuel cell bipolar plates. It has provided detailed analysis of different preparation processes, clarifying the applicable scope and advantages of each, offering strong arguments for process selection in practical applications. It has conducted in-depth analysis of the performance of various coating materials such as metal coatings, conductive polymer coatings, and carbon-based coatings. Through relevant research experiments analyzing the performance of different coatings, it has provided a theoretical basis for the selection and design of coating materials. In summary, current research on bipolar plates remains challenging. The research and development of novel preparation processes and materials, along with new testing methods for materials, remain the direction for scientific research teams.

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