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Advancements in Multilayer Coatings on Aluminium Alloy-Based Bipolar Plates for PEMFC Application

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Abstract

Fuel cells represent a revolutionary and sustainable approach to energy conversion, offering a clean alternative to traditional combustion-based power generation. These electrochemical devices convert the chemical energy of a fuel, typically hydrogen, directly into electricity. The fundamental working principle involves the electrochemical reaction between hydrogen and oxygen, facilitated by a catalyst, to produce electricity, water, and heat as byproducts in Proton Exchange Membrane (PEMFC). This strategic use of aluminum (Al) alloy for Bipolar plates (Bp) aligns with the industry's commitment to advancing materials and design methodologies, ultimately promoting the optimization of fuel cell technology in terms of performance, durability, and economic feasibility. This comprehensive review investigates recent progress in the development of multilayer coatings tailored for Al alloy-Bp in PEMFCs. Al alloys are a preferred substrate material due to their cost-effectiveness, lightweight nature, and high thermal conductivity. However, challenges such as corrosion, electrical conductivity, and interfacial contact resistance have spurred extensive research into innovative coating solutions. The review critically examines various coating materials, deposition techniques, and performance evaluation methods aimed at addressing the challenges associated with al alloy Bp. Special emphasis is placed on corrosion-resistant coatings, conductive layers, and interfacial modifiers. The assessment encompasses both established technologies and cutting-edge approaches, including nanocomposite coatings, self-healing materials, and advanced characterization methods. By synthesizing and analyzing existing literature, this review provides a comprehensive overview for researchers, engineers, and policymakers involved in advancing PEMFC technology. The findings underscore the crucial role of multilayer coatings in augmenting the performance and longevity of al alloy-based Bp, offering valuable insights to guide further research and development in the pursuit of efficient and durable fuel cell systems. In comparing the aluminum grades Al-356, Al-5052, Al-6061, and Al-7075, it is observed that Al 5052 exhibits lower corrosion density, providing greater efficiency compared to other aluminum grades. In the case of Al 356, the potentiostatic result yields a lower value than that of other aluminum grades. Consequently, these findings suggest a tendency for favorable corrosion resistance and electrodeposition in both Al 5052 and Al 356, making them noteworthy choices in applications requiring these particular material characteristics.

Keywords: *Multilayer Coating, Aluminium Alloy, Bipolar plates, PEMFCs.*

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1. Introduction

Fuel cells are cutting-edge and sustainable devices for energy conversion that have garnered significant attention due to their potential to address global challenges related to energy efficiency, environmental sustainability, and the shift away from fossil fuels. These electrochemical systems generate electricity by facilitating a controlled reaction between hydrogen and oxygen, resulting in the production of water and the release of energy. What distinguishes fuel cells from traditional combustion-based power generation is their impressive efficiency, minimal environmental impact, and adaptability, making them a compelling option for various applications, ranging from transportation to stationary power generation. In Figure 1 the basic operation of a fuel cell is illustrated [1]. This overview will explore fuel cells' fundamental principles, types, and potential benefits, emphasizing their crucial role in shaping a cleaner and more sustainable energy future. The Proton Exchange Membrane Fuel Cell (PEMFC) is a state-of-the-art electrochemical device that generates electrical power through the chemical reaction of hydrogen and oxygen, with water as the primary by-product. Recognized for its high energy efficiency and low environmental impact, the PEMFC is a key player in the realm of clean energy. Depicts the typical working principles of PEMFCs [2], they showcase their wide range of potential applications, including powering vehicles, generating stationary energy output, and supplying portable electronics. The core element of a PEMFC is the proton exchange membrane, typically composed of a solid polymer electrolyte enabling the selective passage of positively charged protons (H+ ions) while hindering the flow of electrons. When hydrogen gas is introduced to the anode, a catalytic process separates the gas into protons and electrons. The protons traverse the membrane to the cathode, where they combine with oxygen and electrons and are released into an external circuit, resulting in the generation of water and the release of electrical energy. PEMFCs offer numerous advantages, such as high power density, rapid start-up capabilities, and efficient operation at low temperatures. These features make them suitable for applications requiring quick response and compact, lightweight design, such as automotive fuel cells and portable electronic devices. A primary challenge in PEMFC development involves finding durable and efficient catalysts, often platinum or platinum-group metals, for electrochemical reactions. Additionally, maintaining the integrity of the proton exchange membrane, optimizing water management, and addressing impurities are crucial for sustained operational efficiency and reliability. PEMFCs exhibit significant potential as a versatile technology capable of reducing greenhouse gas emissions and decreasing reliance on fossil fuels. Ongoing research and development efforts aim to enhance the performance, cost-effectiveness, and scalability of PEMFCs, further solidifying their importance in the clean energy landscape [3].

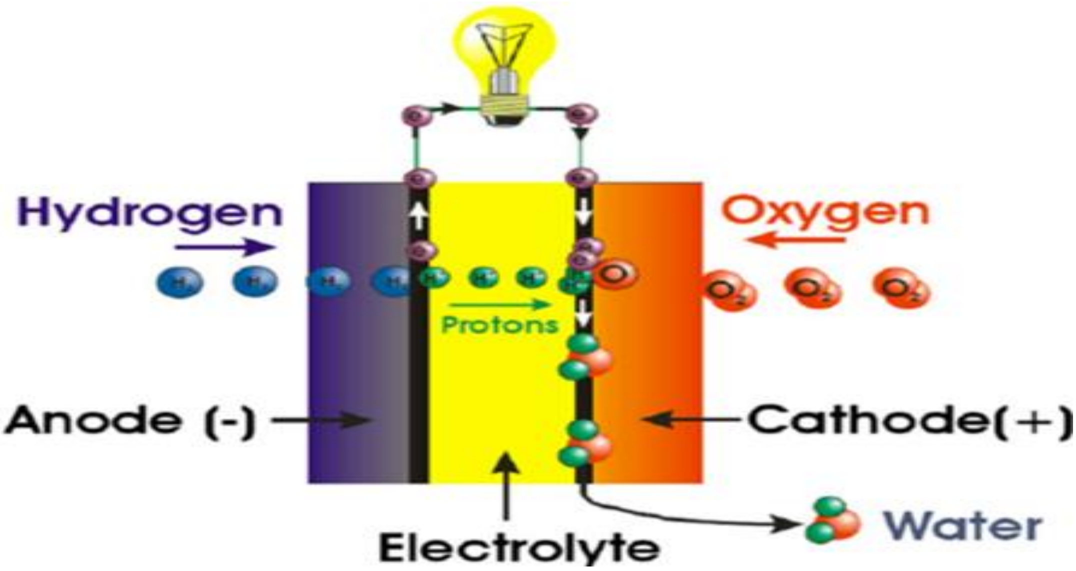

Figure 1 **Basic PEMFC Operation [4]**

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PEMFCs operate through an electrochemical process where hydrogen is oxidized at the anode and oxygen is reduced at the cathode, resulting in the generation of electricity. At the anode, hydrogen gas is introduced and undergoes a catalytic reaction, breaking down into protons and electrons. The protons move through the proton-exchange membrane, a solid polymer electrolyte, while the electrons are forced to travel through an external circuit, creating an electric current. On the cathode side, oxygen is supplied, combining with protons and electrons to form water through another catalytic reaction. This entire process is highly efficient and produces electricity, with water being the sole byproduct. PEMFCs are renowned for their environmental friendliness and potential applications in various sectors due to their clean energy conversion and minimal emissions. Ongoing research aims to further improve their efficiency and practical viability for widespread use.

1.1 Components of Fuel Cells

Fuel cells comprise various essential elements that collaborate to facilitate the conversion of chemical energy into electrical power and heat. Figure 2 presents a simplified diagram illustrating these distinct components of a fuel cell. These integral parts encompass the anode, where hydrogen fuel undergoes catalytic splitting into protons and electrons; the cathode, responsible for the reaction of oxygen with electrons and protons to produce water; an electrolyte, typically a membrane that separates the anode and cathode while permitting the passage of protons; catalysts to accelerate electrochemical reactions at the electrodes; BPs that interconnect and gather current from individual cells within a stack; the fuel cell stack itself, consisting of multiple interconnected cells to enhance voltage and power output; a balance of plant incorporating auxiliary components such as pumps, fans, and humidifiers to uphold optimal conditions; a gas supply system for hydrogen and oxygen; a cooling system to dissipate excess heat generated during operation; hydrogen storage where applicable; and a control and monitoring system to regulate and oversee the fuel cell's performance. Collectively, these components enable fuel cells to efficiently and sustainably generate electricity [5].

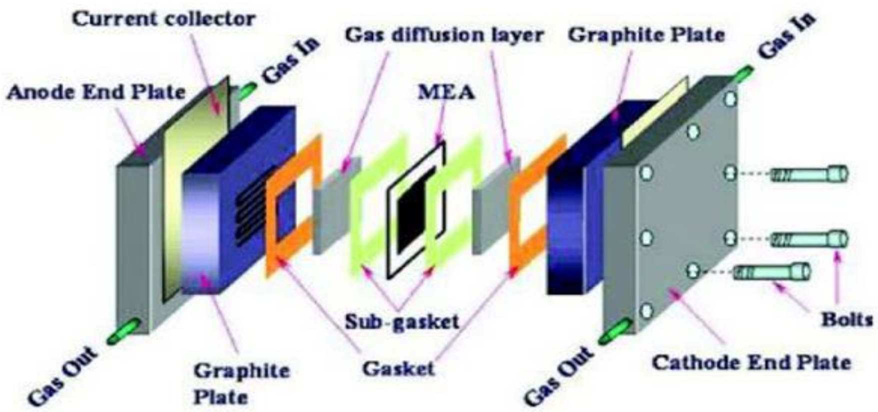

Figure 2 Schematic Picture of The Operating Principle of a Typical PEMFC [6]

Fuel cells consist of key elements, including the anode, cathode, flow field plates, gas diffusion layers, catalyst layers, and PEM. The anode is responsible for the oxidation of fuel, typically hydrogen, while the cathode facilitates oxygen reduction. Flow field plates manage the distribution of reactants and products, ensuring uniform cell operation. Gas diffusion layers facilitate the diffusion of gases to and from the catalyst layers, where electrochemical reactions occur. The catalyst layers play a crucial role in promoting these reactions. Finally, the PEM serves as a selective barrier, enabling the passage of protons while blocking electrons, and ensuring the separation of the oxidation and reduction of half-reactions in the fuel cell [7].

1.2 Bipolar Plates

In Figure 3 it is evident that BPs play a pivotal role in PEMFCs, serving as crucial components integral to the efficient generation of electricity through the electrochemical conversion of hydrogen and oxygen. These plates are indispensable for both maintaining the structural integrity of the fuel cell stack and managing electrical and thermal aspects effectively. BPs act as physical separators between individual cells, establishing a series of interconnected cells within the stack. Their

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primary functions encompass distributing hydrogen and oxygen gases to the anode and cathode sides of each cell, facilitating the removal of water and heat generated during electrochemical reactions. Additionally, BPs are instrumental in creating an electrical connection between adjacent cells, forming a continuous electrical circuit that allows the flow of electrons produced during chemical reactions, ultimately leading to the generation of electrical power. The design and material composition of BPs are critical considerations in PEMFC development. Ideally, these plates must exhibit high electrical conductivity to minimize power losses, corrosion resistance to endure the harsh chemical environment within the fuel cell, and durability to ensure a prolonged operational lifespan. Lightweight characteristics are also desirable to reduce the overall weight of the fuel cell configuration, particularly in applications such as vehicles. Furthermore, effective thermal management properties are crucial for dissipating excess heat generated during operation. Various materials, including graphite, metal alloys, and advanced composites, have been explored for BP construction. Each material choice comes with its own set of advantages and trade-offs, necessitating ongoing research to find the optimal balance of properties while keeping manufacturing costs in check. BPs serve as indispensable elements within PEMFCs, playing a multifaceted role crucial for ensuring the efficient, reliable, and cost-effective operation of these clean energy devices. Ongoing research and innovation in BP design and materials are imperative for advancing the performance and affordability of PEMFCs, contributing to the broader adoption of this technology in various applications, including transportation and stationary power generation [8], [9].

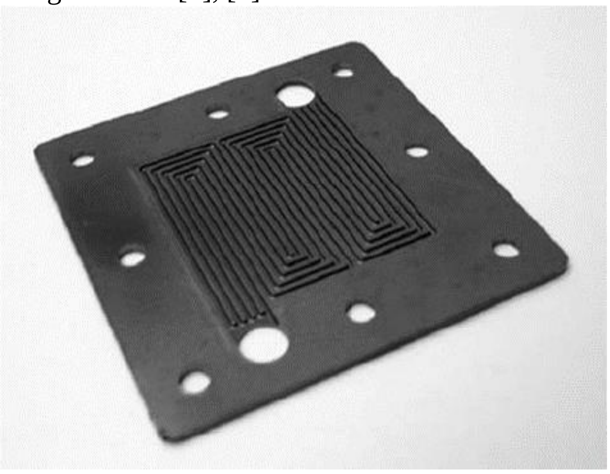

Figure 3 Bipolar Plate [10]

Table 1 DOE Technical Specification Targets for PEMFC Bps

Characteristic	**Units**	**2025 DOE Target [11].**
Electrical conductivity	Scm ^{1}	> 100
Areal specific resistance	Ω cm^2	<0.01
H2 permeability	cm^3sec ^{1}cm ^{2}	2 × 10 6
Thermal conductivity	Wm ^{1}K ^{1}	-
Corrosion, anode	µA cm ^{2}	< 1
Corrosion, cathode	µA cm ^{2}	< 1 & no active peak
Life expectancy	Hours	8000
Plate weight	kg/kW	0.18
price	$kW ^{1}	2
Flexural strength	MPa	> 40

Therefore, it is of utmost importance to develop materials designed for BP's that enable straightforward and cost-efficient manufacturing while meeting specific criteria about electrical, thermal, mechanical, and chemical properties. This is a critical factor for the effective commercialization of PEMFCs. In alignment with the criteria set by the US Department of Energy and other key players in the industry, Table. 1. outlines diverse technical requirements that are pertinent to the advancement of BP in PEMFCs.

2. Aluminium Alloy

Al alloys find limited applications in PEMFCs due to their lower electrical conductivity in comparison to materials commonly utilized for BPs, such as graphite, coated metals, or composites. Despite offering advantages such as lightweight properties and corrosion resistance, the relatively lower electrical conductivity of Al and its alloys makes them less suitable for BP applications in PEM fuel cells. Researchers predominantly emphasize materials with higher electrical conductivity, such as graphite, stainless steel, or titanium, to ensure efficient current collection and overall fuel cell performance. Consequently, Al alloys are not the preferred choice for BPs within PEMFCs. Al metal blends represent versatile metallic materials primarily composed of al, combined with various alloying elements aimed at enhancing specific properties. Engineered for diverse applications,

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these alloys demonstrate a favorable balance in characteristics, including low density, excellent thermal conductivity, and corrosion resistance. The alloying process involves the addition of elements like copper, zinc, magnesium, manganese, and silicon, each contributing unique attributes to the final material. Categorized into wrought and cast alloys, they are further distinguished by series designations using a four-digit numbering system. Alloys of al are extensively utilized in industries such as aerospace, automotive, construction, packaging, and electronics, playing a crucial role in the manufacturing of aircraft components, automotive parts, beverage cans, building facades, and electronic housings. Renowned for their lightweight nature, corrosion resistance, and machinability, Al alloys are favored in diverse applications, although considerations of strength and susceptibility to certain forms of corrosion remain essential in the material selection process [12], [13].

2.1 Electrical Conductivity of Al Alloy-Based Bi-Polar Plate

The electrical conductivity of Al alloy-based BPs is a pivotal factor influencing the performance of fuel cell systems, particularly in PEMFCs and Alkaline Fuel Cells. These plates play a crucial role in facilitating the flow of electrical current between the electrodes of the fuel cell. Al alloys are preferred for BPs due to their advantageous properties, including high conductivity, lightweight nature, corrosion resistance, and cost-effectiveness. The composition of the alloy significantly impacts the electrical conductivity of these plates, with commonly used Al alloys for BPs including the 1xxx series (pure Al), 3xxx series (Al-manganese), and 6xxx series (Al-magnesium-silicon) alloys. Several factors influence the electrical conductivity within Al alloy-based BPs, such as alloy composition, microstructure, processing methods, and surface treatments. Alloying elements like copper and silicon can enhance conductivity, but the overall impact depends on the alloy composition and the presence of other elements. Microstructure plays a critical role in determining the electrical conductivity of Al alloys, and heat treatment processes can be tailored to optimize the microstructure for improved conductivity. Additionally, surface treatments, such as coatings with conductive materials like graphite, can further enhance the electrical performance of BPs. BPs are integral components in fuel cell technology, acting as conductive interfaces between individual cells within a fuel cell stack. Composed of materials like Al alloys, these plates facilitate the movement of electrons between the anode and cathode, essential for the electrochemical reactions powering the fuel cell. The strategic choice of materials, such as Al alloys, takes into account their commendable electrical conductivity, lightweight nature, and corrosion resistance. BPs significantly contribute to enhancing the overall effectiveness of a fuel cell system by providing a conductive pathway for electrons, minimizing electrical resistance, and ensuring the uniform distribution of reactants. Ongoing research in this field focuses on optimizing the design and composition to improve the electrical conductivity of BPs while addressing challenges like mechanical durability and corrosion susceptibility, to continuously improve fuel cell performance [14] – [17].

3. Multilayer Coating

The implementation of a multilayer coating on an al alloy-based BPs in PEMFCs represents a strategic initiative to enhance the overall functionality and durability of the fuel cell system. This coating entails the application of multiple layers of different materials onto the surface of the al alloy. A primary objective of this process is to improve corrosion resistance, a critical factor for extending the lifespan of the BPs within the corrosive surroundings of a fuel cell. Additionally, the multilayer coating is crafted to enhance electrical conductivity, ensuring efficient current flow and distribution throughout the fuel cell. Improved adhesion properties contribute to the structural integrity of the BPs, enhancing the overall dependability of the fuel cell system. Furthermore, the coating has the potential to provide thermal management advantages, assisting in the effective dissipation of heat generated during electrochemical reactions. This comprehensive approach addresses fundamental challenges associated with al alloy-based BPs in PEMFCs, aligning with the ongoing efforts to achieve optimized fuel cell performance and prolonged durability [18], [19].

3.1 Metallic-Based Coating

The utilization of a metallic coating on al alloy-based BPs within PEMFCs stands as a noteworthy progression in the realm of fuel cell technology. This coating involves the application of metallic layers onto the surface of the al alloy, presenting a strategic solution to enhance performance and address key challenges. A primary objective is to bolster the corrosion resistance of the BPs, crucial for extending its operational lifespan amidst the corrosive conditions within a fuel cell. The metallic coating is meticulously designed to optimize electrical conductivity, ensuring the seamless flow and distribution of current throughout the fuel cell system, thereby enhancing electrochemical reactions. This coating contributes to improved adhesion properties, fortifying the structural integrity of the BPs and elevating the overall reliability of the fuel cell. Furthermore, the metallic coating may offer advantageous thermal management characteristics, facilitating the efficient dissipation of heat generated during the electrochemical processes. This comprehensive approach to employing a metallic coating on al alloy-based BPs underscores the commitment to advancing PEMFCs, offering a robust solution to intricate challenges and contributing to the optimization of fuel cell performance and longevity in diverse applications [20], [21].

3.2 Carbon-Based Coating

The application of a carbon-based coating on al alloy-based BPs in PEMFCs represents a strategically significant advancement in fuel cell technology. This coating involves the deposition of layers of carbon-based materials onto the surface of the al alloy, aiming to address critical challenges and enhance overall performance. The primary focus is on augmenting the corrosion resistance of the BPs, a pivotal factor for extending its operational lifespan within the harsh chemical environment of a fuel cell. The incorporation of a carbon-based coating is specifically engineered to improve electrical conductivity, ensuring efficient current flow and distribution throughout the fuel cell, which is essential for optimized electrochemical reactions. Furthermore, the enhanced adhesion properties contribute to the structural integrity of the BPs, bolstering the overall reliability of the fuel cell system. Additionally, the carbon-based coating holds the potential to provide effective thermal management, aiding in the efficient dissipation of heat generated during electrochemical processes. This comprehensive approach underscores the ongoing commitment to advancing PEMFCs, offering a robust solution to the intricate challenges associated with al alloy-based BPs, ultimately contributing to the optimization of fuel cell performance and longevity in diverse applications [22], [23].

3.2.1 Carbon Nano-Tubes

The application of carbon nanotubes (CNTs) as a coating on aluminium alloy-based bipolar plates in PEMFCs represents a promising advancement in fuel cell technology. Al alloys are favored for their lightweight properties and good conductivity, making them suitable for Bp. The integration of CNTs as a coating serves to enhance electrical conductivity, thereby reducing resistive losses and improving overall fuel cell efficiency. Additionally, CNTs act as a protective layer, mitigating corrosion of the Al alloy in the challenging operating conditions of fuel cells. The coating also contributes to improved surface roughness, facilitating enhanced contact with the membrane and subsequently reducing contact resistance. This innovation addresses issues related to water management, thermal conductivity, and overall durability, marking a significant step toward optimizing the performance and longevity of PEMFCs. Moreover, the lightweight design of Al is maintained, and the scalability of the coating process ensures practical applicability in manufacturing at a larger scale. While challenges such as achieving uniform coating and addressing scale-up issues persist, the integration of CNTs onto aluminium alloy bipolar plates holds great potential for advancing the practicality and efficiency of PEMFCs in various applications [24], [25].

3.2.2 Graphene coating

The application of a graphene coating on al alloy-based BPs in PEMFCs represents a groundbreaking advancement in fuel cell technology. Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, is renowned for its exceptional electrical conductivity, mechanical strength, and chemical stability. When applied as a coating on al alloy-based BPs, graphene serves multiple critical functions. Firstly, it significantly enhances the electrical conductivity of the BPs, ensuring efficient current flow and distribution throughout the fuel cell. This property is pivotal for optimizing the electrochemical reactions within the fuel cell, leading to improved overall performance. Secondly, the graphene coating contributes to the corrosion resistance of the BPs, protecting it from the corrosive environment inherent in fuel cells. Thirdly, graphene's lightweight nature adds minimal weight to the bipolar plate, making it an ideal choice for applications where weight is a crucial factor, such as in vehicles. The exceptional mechanical strength of graphene also reinforces the structural integrity of the BPs. Overall, the incorporation of a graphene coating on al alloy-based BPs in PEMFCs holds immense promise in enhancing conductivity, durability, and corrosion resistance, contributing to the advancement and widespread adoption of fuel cell technology [26], [27].

3.3 Polymer-Based Coating

The integration of a polymer-based coating onto all alloy-based BPs within PEMFCs signifies a notable advancement in fuel cell technology. This coating technique involves the application of polymer layers onto the surface of the al alloy, presenting a strategic solution to enhance overall performance and address key challenges inherent to fuel cell systems. A primary objective is to augment the corrosion resistance of the BPs, a critical factor in prolonging its operational lifespan amidst the corrosive environment within a fuel cell. The polymer-based coating is specifically engineered to optimize electrical conductivity, ensuring efficient current flow and distribution throughout the fuel cell, thereby enhancing electrochemical reactions. Additionally, this coating contributes to improved adhesion properties, fortifying the structural integrity of the BPs and elevating the overall reliability of the fuel cell system. The polymer-based coating may also offer benefits in thermal management, aiding in the effective dissipation of heat generated during electrochemical processes. This comprehensive approach to employing a polymer-based coating on al alloy-based BPs exemplifies a commitment to advancing PEMFCs, offering a robust solution to intricate challenges and contributing to the optimization of fuel cell performance and longevity in diverse applications [28], [29].

3.4 Types of Strategies Used for Multilayer Coating

A variety of strategic approaches are employed in the development of multilayer coatings for Al alloy-based Bp in PEMFC applications. One common strategy involves a stepwise deposition process, with each layer serving a specific purpose. The initial layer focuses on corrosion resistance and often incorporates materials like titanium nitride (TiN) or titanium carbide (TiC) using techniques such as PVD or CVD [30]. Subsequent layers may introduce conductive materials like platinum or gold to enhance electrical conductivity. Hydrophobic or hydrophilic layers are applied to manage water distribution and prevent flooding. An interfacial layer is included to improve bonding between the bipolar plate and the membrane/electrode assembly, thereby reducing interfacial contact resistance. Gas barrier layers, composed of materials with low permeability, are integrated to prevent the crossover of reactant gases. The selection of coating techniques, such as electroplating, electroless plating, dip coating, or spray coating, is determined by factors such as scalability and cost-effectiveness. These strategic approaches collectively aim to optimize the corrosion resistance, electrical conductivity, interfacial properties, and gas separation capabilities of Bp, contributing to the overall efficiency and durability of PEMFCs. Ongoing research and development are crucial for refining and advancing these strategies in the pursuit of enhanced fuel cell technology [31], [32].

3.4.1 Physical Vapour Deposition

Physical Vapor Deposition (PVD) techniques employed for the nitride layering on metallic BPs entail the deposition of nitride compounds onto the substrate through physical processes within a vacuum environment. In Cathodic Arc Deposition, a high-current, low-voltage electric arc is generated between a cathode target (composed of the nitride material) and the substrate. The nitride material undergoes vaporization from the cathode target due to the arc discharge, and the resulting vaporized atoms then condense on the BP, forming a nitride coating. Sputter Deposition involves bombarding a target (made of nitride material) with energetic ions, leading to the expulsion of atoms from the target. These ejected atoms then deposit onto the metallic BP, creating a nitride coating. Reactive sputtering, wherein nitrogen is introduced during the process, is frequently employed for nitride coatings. In the Evaporation method, the nitride material undergoes high-temperature heating within a vacuum, causing it to evaporate. The evaporated material subsequently condenses onto the substrate surface, forming a nitride coating, albeit this method is less commonly used for nitride coatings compared to other PVD methods. Plasma Enhanced combines PVD principles with plasma enhancement by creating a plasma in the deposition chamber, enhancing the energy and reactivity of the vaporized nitride material. This results in a more uniform and adherent nitride coating on the BP. Filtered Cathodic Vacuum Arc represents an advanced iteration of cathodic arc deposition incorporating additional filtering mechanisms. These filters aid in controlling the composition of the deposited film, ensuring a high-quality nitride coating on the BP with improved properties [33], [34].

3.4.2 Chemical Vapour Deposition

Chemical Vapor Deposition (CVD) techniques play a pivotal role in enhancing the surface characteristics of metallic BPs, such as improving corrosion resistance and wear durability. Reduced Pressure CVD operates under reduced pressure conditions, allowing meticulous control over the deposition process. Gaseous precursors, containing nitrogen and the desired metal, are introduced into a vacuum chamber at low pressure, instigating a chemical reaction on the surface of the metal BP and culminating in the formation of a nitride coating. Atmospheric Pressure CVD offers a simpler and more cost-effective CVD method functioning at atmospheric pressure. Gaseous precursors are introduced at atmospheric pressure, initiating a chemical reaction on the exterior of the metallic BP and leading to the deposition of a nitride coating. Plasma-enhanced CVD amalgamates traditional CVD with plasma activation to augment the deposition process. A plasma is generated within the deposition chamber, heightening the reactivity of the gaseous precursors. This heightened reactivity facilitates the controlled and adherent formation of a nitride coating on the metallic BP. Metalorganic CVD involves the use of metalorganic precursors that contain the desired metal and nitrogen sources. These precursors are introduced into the deposition chamber, undergoing chemical transformations on the surface of the metallic BP, resulting in the formation of a nitride coating. Hot-wall CVD employs external heating of the substrate, intensifying the chemical reaction between precursors. Gaseous precursors, containing nitrogen and the desired metal, are introduced into the heated chamber, initiating a chemical reaction on the surface of the metal BP and leading to the deposition of a nitride coating [35], [36].

3.4.3 Electrodeposition

The implementation of an electrodeposition multilayer coating on Al alloy-based Bp stands as a significant advancement in the realm of PEMFCs. This process involves the application of multiple layers of material onto the surface of Al alloy substrates through electrodeposition, a technique renowned for its precision in depositing thin films. The Al alloy, serving as the foundation for the Bp, holds a pivotal role within the PEMFC structure. Bp, integral components in fuel cells, not only physically separate individual cells but also facilitate the efficient flow of reactants—namely, hydrogen and oxygen—while concurrently providing a pathway for electrical conductivity. By subjecting these Bp to an electrodeposition multilayer coating, researchers aim to augment their inherent properties. This coating may enhance corrosion resistance, improve electrical conductivity, and fortify overall durability, thereby bolstering the efficiency and lifespan of the PEMFC system. This innovative approach underscores the ongoing efforts in fuel cell technology to optimize materials and processes, paving the way for more robust and reliable energy conversion solutions [37], [38].

3.5 Other Coating Methods

3.5.1 Spray Coating

The spray coating method for Al alloy-based Bp in PEMFCs involves the application of a coating material using a spray gun. This technique is widely utilized for its versatility and efficiency, especially in large-scale production settings. During the process, the Al alloy Bp is exposed to a liquid or powder form of the coating material, which is atomized into fine droplets and propelled onto the surface of the plates. The atomized particles adhere to the substrate, forming a uniform and protective coating. Spray coating offers advantages such as ease of application, adaptability to complex shapes, and the ability to achieve controlled thickness. It is a cost-effective solution for providing corrosion resistance and enhancing the durability of Bp in PEMFCs, contributing to the overall performance and longevity of the fuel cell system [39], [40].

3.5.2 Dip Coating

The dip coating method employed for Al alloy-based Bp in PEMFCs involves immersing the plates into a solution containing the desired coating material. This process allows for the even application of a thin film on the surface of the Al alloy. As the plates are withdrawn from the solution at a controlled rate, the excess coating material drips off, leaving a uniform layer on the substrate. Following this immersion, the coated plates undergo a drying and curing process to ensure the formation of a stable and protective coating. Dip coating is a straightforward and cost-effective technique suitable for small to medium-scale production. It offers advantages such as simplicity, uniform coverage, and the ability to coat intricate shapes. This method contributes to enhancing the corrosion resistance and overall performance of Al alloy Bp in PEMFCs, making them more resilient and durable in the demanding operational conditions of fuel cells [41], [42]. Table 2 The chemical composition of Al alloy materials employed for BPs in fuel cells is carefully tailored to meet specific performance criteria. Typically, Al serves as the predominant constituent, forming a significant proportion of the alloy.

4. Base Material on Al alloy BPs

Table 2 Chemical Composition (Wt.%) Of Al Alloy Metal Materials for Bps

Series / Grade	Mg	Cr	Mn	Si	Cu	Zn	Fe	Ti	Al contents	Ref
Al 356	0.20-0.45		0.35	6.5-7.5	0.25	0.35	0.60	0.25	Balance	[43]
Al 5052 (magnesium)	2.60	0.25	0.10	0.23	0.12	0.15	0.28	-	Balance	[44]
Al 6061 (Magnesium & silicon)	0.8-1.2	0.04-0.35	<0.15	0.4-0.8	0.15-0.4	<0.25	0.7	<0.15	Balance	[45]
Al 7075 (zinc)	2.376	0.238	0.273	0.22	1.605	5.572	0.275	0.020	Balance	[46]

To improve conductivity, copper is commonly added, with strict control over its concentration to prevent adverse effects on corrosion resistance. Silicon is introduced to enhance strength and casting fluidity, while manganese contributes to both strength and corrosion resistance. The incorporation of magnesium is utilized to augment the overall strength of the alloy, particularly in heat-treatable variations. Zinc and titanium may also be included to further enhance strength and hardness, and the precise alloy composition is dictated by the desired balance of properties. Beyond these primary elements, trace amounts of chromium, nickel, and other elements may be present based on specific alloy formulations. This tailored composition allows for the customization of Al alloy materials, ensuring they meet the exacting requirements for Bp in fuel cells without compromising essential properties.

5. Multilayer Coating on Al alloy BPs

5.1 Surface Modification

5.1.1 Titanium

The utilization of Titanium (Ti) coating in Al alloy-based bp for PEMFC's signifies a notable progression in fuel cell technology. Bp is instrumental in ensuring the effective distribution of reactants and the removal of byproducts within the fuel cell stack. Al alloys, chosen for their lightweight properties, are prone to corrosion and wear under the demanding operational conditions of fuel cells. The incorporation of a Ti coating acts as a protective barrier, providing robust corrosion resistance and wear resilience. This coating not only prolongs the life of the Bp but also enhances conductivity and reduces interfacial contact resistance, thereby optimizing the overall efficiency of the PEMFC's system. The amalgamation of Al alloys with Ti coating exemplifies a significant leap in material engineering, contributing to heightened performance and reliability [11].

5.1.2 Titanium Nitride

The utilization of Titanium nitride (TiN) coating in Al alloy-based bp for PEMFC's is a pivotal advancement in fuel cell technology. Bp are integral components that enable efficient reactant distribution and byproduct removal within the fuel cell stack. Al alloys, chosen for their lightweight properties, are susceptible to corrosion and wear in the demanding conditions of fuel cell operation. The integration of TiN coating acts as a protective barrier, offering exceptional corrosion resistance and wear resilience. This coating not only ensures the prolonged life of the bipolar plates but also enhances conductivity and reduces interfacial contact resistance, ultimately optimizing the overall efficiency of the PEM fuel cell system. The strategic combination of aluminum alloys and TiN coating exemplifies a significant stride in material engineering, contributing to the improved performance and dependability of PEMFC [32].

5.1.3 Titanium Nitroxide

The incorporation of Titanium Nitroxide (TiNO) coating in Al alloy-based Bp for PEMFC's signifies a noteworthy progression in fuel cell technology. Bp plays a pivotal role in facilitating the efficient distribution of reactants and the removal of byproducts within the fuel cell stack. Al alloys, chosen for their lightweight properties, are susceptible to corrosion and wear in the challenging operational conditions of fuel cells. The introduction of a TiNO coating acts as a protective layer, offering enhanced corrosion resistance and wear resilience. This coating not only extends the lifespan of the Bp but also contributes to improved conductivity and reduced interfacial contact resistance, ultimately optimizing the overall efficiency of the PEMFC's system. The amalgamation of Al alloys with TiNO coating reflects a significant leap in material engineering, contributing to the heightened performance and reliability [47].

5.1.4 Chromium Nitride

The application of Chromium nitride (CrN) coating in Al alloy-based Bp PEMFC'S marks a noteworthy development in fuel cell technology. Bp are critical components facilitating the efficient distribution of reactants and removal of byproducts within the fuel cell stack. Al alloys, chosen for their lightweight characteristics, are susceptible to corrosion and wear in the demanding operational conditions of fuel cells. The incorporation of CrN coating acts as a protective layer, providing excellent corrosion resistance and wear durability. This coating not only ensures prolonged bp life but also enhances conductivity and reduces interfacial contact resistance, thereby optimizing the overall efficiency of the PEMFC's system. The integration of Al alloys and CrN coating represents a significant stride in material engineering, contributing to enhanced performance and reliability [11].

5.1.5 Carbon

The integration of Carbon (C) coating in Al alloy-based bp for PEMFC's constitutes a notable advancement in fuel cell technology. Bp plays a crucial role in ensuring the efficient distribution of reactants and removal of byproducts within the fuel cell stack. Al alloys, favored for their lightweight properties, are susceptible to corrosion and wear in the challenging operational conditions of fuel cells. The incorporation of a C coating serves as a protective layer, offering excellent corrosion resistance and wear protection. This coating not only extends the lifespan of the bipolar plates but also improves conductivity and reduces interfacial contact resistance, ultimately optimizing the overall efficiency of the PEMFC's system. The synergy between Al alloys and C coating underscores the significance of material innovation in advancing performance and dependability [32], [47].

5.1.6 Nickel Phosphorus

Applying Nickel Phosphorus (Ni-P) coating in Al alloy-based Bp for PEMFC's represents a noteworthy advancement in fuel cell technology. Bp are critical components responsible for the efficient distribution of reactants and the removal of byproducts within the fuel cell stack. Al alloys, chosen for their lightweight characteristics, are susceptible to corrosion and wear in the demanding operational conditions of fuel cells. The integration of Ni-P coating acts as a protective layer, providing robust corrosion resistance and wear durability. This coating not only extends the lifespan of the Bp but also enhances conductivity and reduces interfacial contact resistance, thereby optimizing the overall efficiency of the PEMFC's system. The incorporation of Al alloys with Ni-P coating highlights a significant stride in material engineering, contributing to improved performance and reliability [47].

5.2 Corrosion Current Density

The corrosion current density of an Al alloy is a critical parameter that indicates the rate at which corrosion occurs on the alloy's surface. This current density measurement is a key factor in assessing the alloy's susceptibility to corrosion, a common concern given Al's propensity to corrode in certain environments. Researchers and engineers employ various electrochemical techniques, such as polarization tests, to determine the corrosion current density. A low corrosion current density suggests better corrosion resistance, indicating that the Al alloy can withstand corrosive conditions more effectively. Understanding and monitoring the corrosion current density are crucial for industries where Al alloys are employed, as it helps in designing and implementing corrosion protection strategies to enhance the longevity and reliability of components and structures made from these alloys [48].

5.3 Potensiostatic Result

The potentiostatic results of an Al alloy provide valuable insights into its electrochemical behavior under controlled voltage conditions. In potentiostatic experiments, the alloy is subjected to a constant potential, allowing researchers to analyze its corrosion resistance and other electrochemical properties. The potentiostatic results typically include measurements such as polarization curves and corrosion rates. These findings are crucial for assessing the alloy's performance in corrosive environments, aiding in the development of effective corrosion protection strategies. Lower corrosion rates and favorable polarization characteristics in potentiostatic tests suggest enhanced corrosion resistance, which is vital for applications where Al alloys are exposed to aggressive conditions. Overall, potentiostatic analysis of Al alloys contributes significantly to materials engineering, guiding the design and selection of corrosion-resistant materials for diverse industrial applications [49].

5.4 Interfacial Contact Resistance

The ICR of an Al alloy is a crucial parameter that characterizes the electrical contact quality at interfaces within the alloy. In the context of Al alloys, ICR is often evaluated in applications like electrical connectors or bipolar plates in fuel cells, where efficient electrical conductivity is essential. High-quality interfacial contact is critical for minimizing resistive losses and ensuring optimal performance. The ICR measurement involves assessing the electrical resistance at the interface between the Al alloy and other materials. Lower interfacial contact resistance is indicative of improved conductivity and better overall electrical performance. Researchers and engineers utilize techniques such as impedance spectroscopy to quantify ICR, enabling a comprehensive understanding of the alloy's electrical behavior. By addressing and optimizing interfacial contact resistance, it becomes possible to enhance the efficiency and reliability of electrical systems employing Al alloys [50,51].

Table 3 Al Alloy Data Reported in The Literature

Sl. No.	Sub-strate	Surface modi-fication	Electrolyte	Corrosion Current Density (µA/cm²)	Potentiostatic result (µA/cm²)	ICR (mΩcm²)	Ref
1	Al 356	TiN/CrN (PVD)	0.5 M H_2SO_4 H2 bubbled	-	4.6 at -0.1 V (vs. SCE)	-	[50]
			0.5 M H_2SO_4 air bubbled	-	29.03 at 0.6 V (vs. SCE)	-	[50]
2	Al 5052	C/TiN (PVD)	0.001 M H_2SO_4 + 0.1 ppm NaF at 70 ◦C	0.4 (H_2) 36 (air)	-	-	[29]
		C/CrN (PVD)	0.001 M H_2SO_4 + 0.1 ppm NaF at 70 ˚C	0.5 (H_2) 40.7 (air)	10 at -0.47 V (vs. MSE)	4.08 at 150 N/cm²	[29]
3	Al 6061	TiN/Ti (PVD)	0.5 M H_2SO_4	0.5	-	-	[47]
		Ni-P/ TiNO (PVD)	0.5 M H_2SO_4 + 0.1 ppm HF	4.23	0.6 V_{SCE}	50.5	[51]
4	Al 7075	TiN/CrN (PVD)	0.5 M H_2SO_4 H_2 bubbled	-	60.29 at -0.1 V (vs. SCE)	-	[50]
			0.5 M H_2SO_4 air bubbled	-	89.68 at 0.6 V (vs. SCE)	-	[50]

Table. 3. offers a succinct summary of data pertaining to Multilayer-based coatings on Al alloy Bp in PEMFCs applications. The focus is on essential aspects such as the Al substrate, surface modifications achieved through nitride coatings, their impact on the electrolyte, corrosion current density, potentiostat results, and Internal Contact Resistance (ICR). The "Al Substrate" column specifies the type of Al alloy employed as the substrate for Bp. The "Surface Modification" category outlines the specific nitride-based coating applied to enhance the properties of the plates. In the "Electrolyte" column, details regarding the type of electrolyte utilized in the PEMFC setup are provided. The "Corrosion Current Density" entry offers insights into the corrosion rate, a pivotal parameter for assessing the effectiveness of the nitride coating. The "Potentiostat Results" section encapsulates the outcomes of potentiostatic tests, shedding light on the coating's performance under controlled electrochemical conditions. Finally, the "ICR" section highlights the Internal Contact Resistance, a crucial metric reflecting the coating's impact on the electrical conductivity of the Bp. This table serves as a comprehensive reference, offering researchers and practitioners a consolidated overview of critical data points in the realm of Multilayer-based coatings on Al alloy Bp for PEMFC applications. Al alloy 5052 exhibits lower corrosion density, providing greater efficiency compared to other grades of Al. On the other hand, Al alloy 356 shows a potentiostatic result with a lower value than alternative aluminium grades, indicating a propensity for favorable corrosion resistance and electrodeposition. These distinctive characteristics make both alloys promising choices for applications where corrosion resistance and electrodeposition performance are critical.

Conclusion

In conclusion, the exploration of advancements in multilayer coatings for Al alloy-based Bp in PEMFCs unveils a dynamic landscape of innovative strategies aimed at enhancing the overall performance and durability of fuel cell technology. The comprehensive review highlights the pivotal role of multilayer coatings in addressing critical aspects such as corrosion resistance, electrical conductivity, interfacial properties, and gas separation capabilities. Strategies, including PVD methods like Cathodic Arc Deposition and Sputter Deposition, as well as CVD showcase diverse approaches tailored to meet specific criteria. The chemical composition of Al alloys, meticulously customized to achieve optimal balance and properties, forms the foundation of these coatings. Key alloy constituents such as copper, silicon, manganese, magnesium, zinc, and titanium play vital roles in enhancing conductivity, strength, and corrosion resistance. Beyond the primary elements, trace additives like chromium and nickel further refine the alloy formulations. The presented data in Table. 3. provides a valuable resource for researchers and practitioners, offering a consolidated overview of crucial parameters in the context of Multilayer-based coatings on Al alloy Bp. This comprehensive review underscores the collective efforts to advance the understanding and implementation of multilayer coatings, paving the way for the continued evolution of Al alloy-based Bp in PEMFC applications. As research in this field progresses, these advancements hold promise for realizing more efficient, durable, and sustainable fuel cell systems, contributing significantly to the ongoing development of clean energy technologies. In comparing the aluminium grades Al-356, Al-5052, Al-6061, and Al-7075, it is observed that Al 5052 exhibits lower corrosion density, providing greater efficiency compared to other aluminium grades. In the case of Al 356, the potentiostatic result yields a lower value than that of other aluminium grades. Consequently, these findings suggest a tendency for favorable corrosion resistance and electrodeposition in both Al 5052 and Al 356, making them noteworthy choices in applications requiring these particular material characteristics.

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