Advancements in Polymer Coatings on Enhanced Electric Conductivity of Metallic Bipolar Plates for PEMFC application

S. J. Narasimharaju[1] , Poorna Chandra Rao B[2] , K. Annamalai[3]

{narasimharajusj@mitindia.edu[1], poorna6567@gmail.com[2], drkam@mitindia.edu[3]}

Department of Automobile Engineering, Madras Institute of Technology Campus, Anna University, Chennai, Tamil Nadu, India [1,2,3]

Abstract. Proton Exchange Membrane Fuel Cells (PEMFCs) hold immense promise as a clean and efficient energy technology. At the core of these fuel cells, metallic bipolar plates (BPs) play a critical role in facilitating efficient electron and ion transfer, thus profoundly impacting the overall performance of the system. This review article offers a comprehensive analysis of recent innovations in polymer coatings tailored to enhance the electric conductivity of metallic BPs within PEMFC applications. The abstract begins by highlighting the growing importance of PEMFCs in the transition to sustainable energy solutions, characterized by their high energy efficiency and environmental friendliness. It underscores the pivotal role played by metallic BPs in optimizing electrical conduction and PEMFC efficiency. The review delves into the latest advancements in the field of polymer coatings, encompassing various strategies and materials employed to enhance the electric conductivity of metallic BPs. These innovations include conductive polymers, and diverse coating techniques, each offering unique advantages and challenges. Their applicability in different operating conditions of PEMFCs is assessed, providing a comprehensive understanding of their potential. Furthermore, the review underscores the critical significance of electric conductivity in improving the overall efficiency of PEMFCs. It explores the mechanisms through which polymer coatings augment the conductivity of metallic BPs and discusses the influence of factors such as temperature, exposure to reactive species, and material compatibility. In conclusion, this review article encapsulates the significant progress made in the development of polymer coatings for enhancing the electric conductivity of metallic BPs in PEMFCs. These advancements hold the promise of elevating the performance and durability of PEMFCs, thus contributing to the broader transition to clean and sustainable energy technologies. This review serves as a valuable resource for researchers, engineers, and stakeholders invested in the advancement of PEMFCs as a pivotal element in the clean energy landscape.

Keywords: Proton exchange membrane fuel cells, Metallic Bipolar plates, Electric conductivity, Polymer coating, sustainable energy.

1. Introduction

In recent times, the declining condition of the environment and the rising incidence of natural calamities have become more apparent the effects of environmental degradation closer to humanity. Hydrogen fuel, recognized by many nations for its sustainability, cleanliness, lack of

ICAMDMS 2024, February 23-24, Coimbatore, India

DOI 10.4108/eai.23-2-2024.2347027

pollution, and abundant reserves, has become a preferred energy source. PEMFCs are energy conversion systems that exclusively utilize pure hydrogen as fuel. They have found applications in diverse fields, including energy storage, aerospace, aviation, and automotive fuel cell vehicles developed by manufacturers like Toyota, Hyundai, Honda, and others [1], [2]. In a typical PEMFC, the polymer electrolyte membrane plays a critical Playing a crucial role in enabling proton conductivity, these membranes facilitate the transfer of protons from the anode to the cathode. Perfluoro sulfonic acid polymers, particularly perfluoro sulfonic acid-based membranes, have emerged as prominent choices among different fuel cell types due to their exceptional conductivity, as well as superior chemical and mechanical characteristics. Operating efficiently at temperatures lower than 90°C and in environments with high relative humidity, these membranes demonstrate notable effectiveness. Hydrogen, being a simple atom with just one electron and one proton, is readily excited and can be easily separated into positive and negative charges. In a fuel cell, the hydrogen consumed is used to excite other hydrogen atoms, and the resulting protons are directed into the proton exchange membrane. While the excited electrons flow out, creating electrical energy, the protons move across the membrane. Any presence of oxygen is disrupted by electrons, and when they react with protons, water is produced. For a visual representation of this process, please refer to Fig. 1. [3], [4].

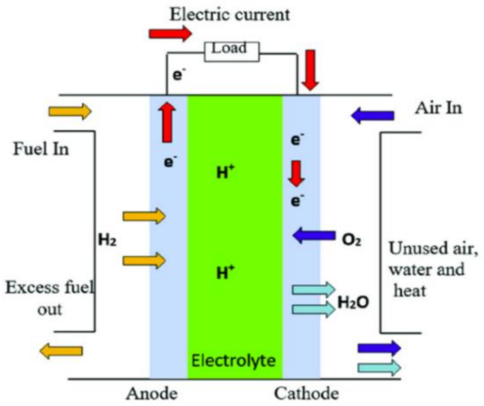


Fig. 1. Working principles of PEMFC [5].

A PEMFC consists of several key components, including the Graphite plate or BPs, Membrane Electrode Assembly (MEA), gaskets, gas-diffusion layer, current collectors, and end plate. Figure 1 provides a simplified schematic representation of these individual fuel cell components. Fuel cells typically employ anode and cathode electrodes, which drive an electrochemical reaction between an oxidant and a fuel to generate electricity. This reaction also yields heat and water as byproducts. Differences among various types of fuel cells arise from the choice of membrane and electrolyte used in their construction. The primary objective of most fuel cell research endeavours is to explore ways to enhance the electrochemical reaction, thereby achieving improved cell efficiencies while reducing operating costs [6], [7].

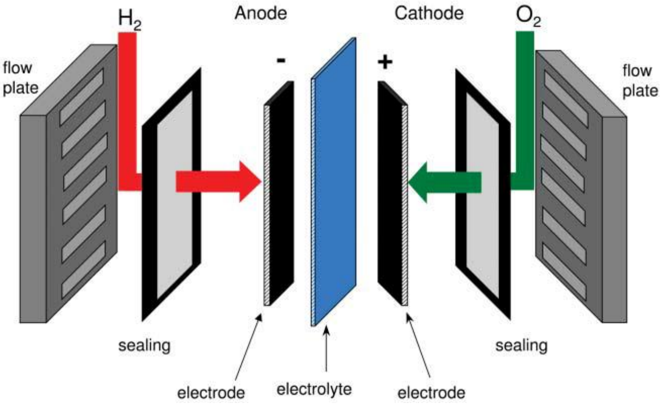


Fig. 2. A schematic illustration of a single PEMFC functional component [8].

A. Bipolar Plate

In the configuration of PEMFC stacks, BPs play a crucial role. They serve the important function of uniformly distributing reactant gases across multiple cells and electrodes, ensuring uniform current density distribution. This uniformity also contributes to maintaining an even operating temperature within the cell stack. Additionally, an efficiently designed BP geometry aids in effective water management by facilitating eliminating the water produced during the electrochemical process reaction, thereby reducing the risk of flooding. Furthermore, a well-designed BP helps alleviate mechanical stress on the membrane electrode assembly. As most BPs are currently made from metals, it is imperative to consider coating these plates with materials that provide corrosion resistance while enhancing electrical and thermal conductivity [9], [10].

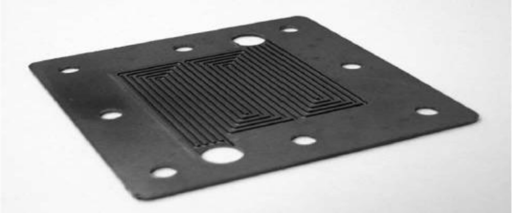


Fig. 3. Bipolar Plate in PEM Fuel Cell Stack [11].

Furthermore, The functionality of fuel cells is negatively impacted by corrosion. Metallic BPs, when utilized in fuel cells operating in acidic environments, are susceptible to corrosion, resulting in the dissolution of metallic ions. This, in turn, can lead to contamination of the membrane, catalyst, and electrode components. In order to counteract the harmful consequences of metallic corrosion while preserving electrical conductivity, multiple surface modification methods and coatings resistant to corrosion have been devised. [12], [13].

Table 1. DoE Technical Specification Targets for PEMFC BPS [14].

Characteristic	**Units**	**2025 DoE Target**
Electrical conductivity	Scm^{1}	> 100
Areal specific resistance	Ω cm^{2}	<0.01
H2 permeability	cm^{3}sec ^{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	$\$\text{ kW}^{1}$	2
Flexural strength	MPa	> 40

Hence, it is crucial to develop appropriate materials for bipolar plates (BPs) that can be readily and affordably manufactured, while also satisfying specific criteria for their electrical, thermal, mechanical, and chemical characteristics. This is essential for the effective commercialization of Proton Exchange Membrane Fuel Cells (PEMFCs). Adhering to the guidelines established by the US Department of Energy (DOE) and other industry participants, Table I delineates certain technical prerequisites pertinent to the progression of BPs in PEMFCs.[15].

B. Metallic BPs

The existing metallic BPs in a PEMFC are a fundamental component critical to the efficient operation of the fuel cell system. This metallic plate is designed to play a crucial role in facilitating the electrochemical reactions within the PEMFC, ensuring proper distribution of reactant gases, and maintaining the electrical circuit necessary for power generation. Typically composed of highly durable and corrosion-resistant materials such as stainless steel or titanium, the metallic BPs are engineered to withstand the demanding conditions inside the fuel cell, where it is exposed to high temperatures, humidity, and chemical interactions. This robust construction ensures the longevity and reliability of the fuel cell system.

The primary function of the metallic BPs is to act as both a current collector and a reactant gas distributor. It is strategically positioned between adjacent MEAs, which consist of a proton exchange membrane, an anode, and a cathode. The BPs allow for the uniform distribution of hydrogen and oxygen gases to the respective electrodes, where electrochemical reactions occur.

Furthermore, the BPs serve as an electrical conductor, enabling the flow of electrons generated during the electrochemical reactions. Electrons travel from the anode to the cathodethrough an external circuit, thus producing electric power. The design of the BPs includes channels and flow pathways that help maintain a uniform distribution of gases, preventing issues like reactant starvation or flooding, which can compromise the efficiency and performance of the PEMFC [12], [16], [17].

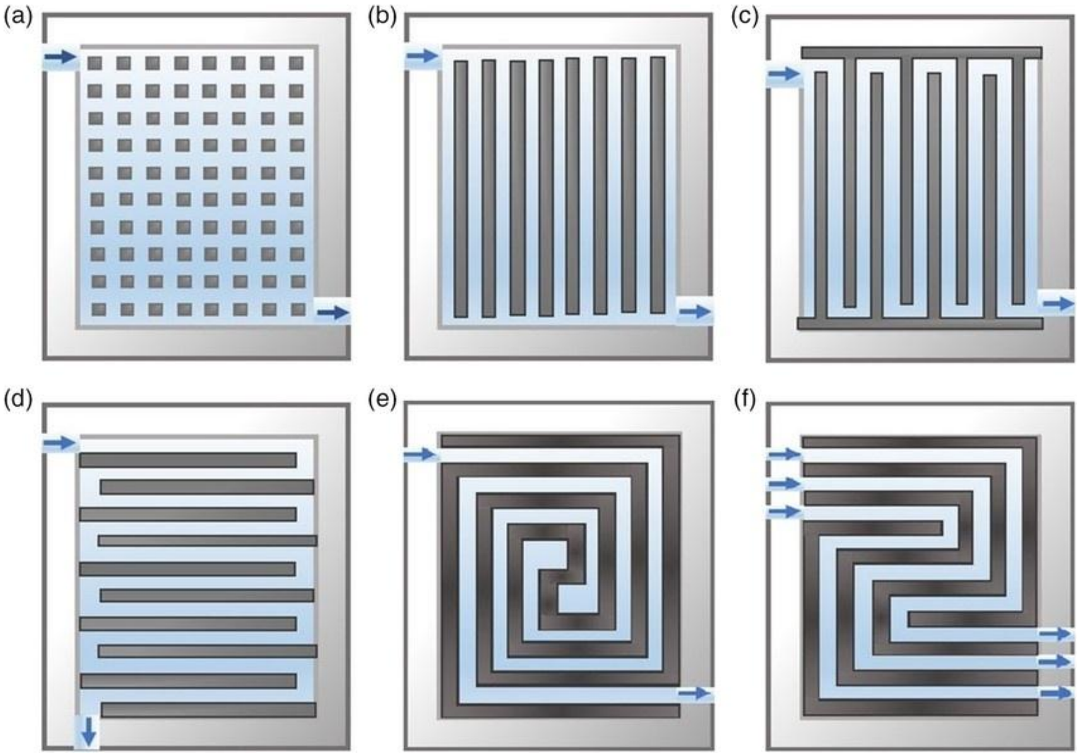
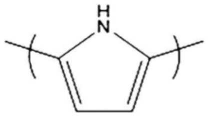
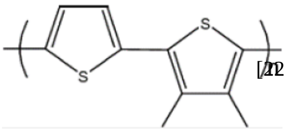
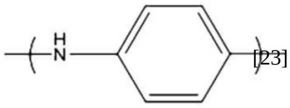


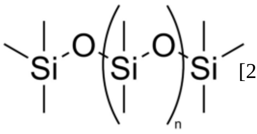
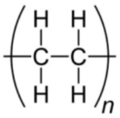
Fig. 4. Different types of conventional flow field designs (a) pin-type (b) straight parallel (c) interdigitated (d) single-channel serpentine (e) spiral (f) multiple-channel serpentine [18].

BP flow field designs in various fuel cell systems, including PEMFCs, are critical components that play a pivotal role in optimizing the distribution of reactant gases and the removal of water and other byproducts. These designs are crucial for enhancing the overall efficiency and performance of the fuel cell. BP flow fields are typically characterized by a pattern of channels and serpentine pathways that are intricately etched or stamped onto the surface of the BPs. The primary purpose of these flow fields is to facilitate the even and controlled flow of reactant gases, such as hydrogen and oxygen, across the catalyst layers on the MEA. By ensuring uniform gas distribution, these flow fields help prevent reactant starvation or flooding, both of which can impair the fuel cell's efficiency. The design and geometry of these flow fields can vary significantly depending on the specific application and type of fuel cell. Common configurations include serpentine, parallel, interdigitated, and variations thereof. Each design has unique advantages and is selected based on factors such as the desired level of gas distribution uniformity, pressure drop constraints, and manufacturing considerations.

For example, serpentine flow fields consist of meandering channels that maximize gas exposure to the catalyst layers. They are known for their uniform gas distribution, making them suitable for applications where gas distribution uniformity is crucial, such as in PEMFCs. Parallel flow fields, on the other hand, consist of straight channels that may be simpler to manufacture and are often used in high-power-density applications. Interdigitated flow fields are designed with alternating gas distribution channels and gas removal channels. This design helps to promote even gas distribution while efficiently removing water and other byproducts. Such flow fields are commonly employed in fuel cells designed for automotive applications. Additionally, designers consider other factors, such as flow channel depth, width, and spacing between channels, which all influence the distribution of reactant gases and the removal of water from the fuel cell. The aim is to strike a balance between achieving optimal gas distribution and minimizing pressure drops within the system [12], [16], [17]. Conductive polymers (CPs) exhibit a unique molecular structure characterized by conjugated bonds along their polymer backbone. Unlike conventional thermoplastic polymers, CPs lack thermoplasticity and are not readily moldable under heat. The question of their solubility has been a matter of debate, with most scientists categorizing solvent-CP mixtures as solutions, while a minority defines them as 'dispersions.' CPs are available in various forms, including powders, dispersions, and coatings. They are typically derived from conjugated organic polymers recognized for their low hydrogen content, aromatic structure, and outstanding chemical and thermal stability. These characteristics contribute to enhanced electrical conductivity in their oxidized or reduced states. The origins of electrical CPs trace back to the early 1960s, with significant breakthroughs occurring in the late 1970s, particularly driven by pioneering experiments involving polyacetylene doping. These materials encompass a wide range of properties, including semi conductivity, luminescence, bioelectronic effects, and electrochemical redox activity, making them valuable for applications like field-effect transistors, solar cells, thermoelectric devices, electrochromic systems, and electrical energy storage [19], [20].

Table 2. Conjugated Conductive Polymer Chemical Structure and Electrical Conductivity

Conductive Polymer	**Abbreviation**	**Formula**	**Electrical Conductivity (S cm^{-1})**	**Chemical Structure of _-Conjugated Polymers**	**Ref.**
Polypyrrole	Ppy	$[C_4H_2NH]_n$	From 42 to 6.4 × 10^{-10}		[21]
Poly(3,4-Ethylene dioxythiophene)	PEDOT	$[C_6H_4O_2S]_n$	6259		[22]
Polyaniline	PANI	$[C_6H_4NH]_n$	From 0.1×10^{-10} up to 100		[23]
Polyacetylene	PA	$[C_2H_2]_n$	1. 8 X 10 $^{-14}$ Ω^{-1} cm^{-1}		[24],[25]

Polydimethylsiloxane	PDMS	$[C_2H_6OSi]_n$	From $10^{-2,}$ 0.1 to 7.8 (with the use of fillers)		[26],[27]
Polyethylene	PE	$[C_2H_4]_n$	From 0.1 to 100 (with the use of fillers)		[28],[29]

CPs can serve as a fundamental material in a variety of forms, such as films, particles, matrices, and fillers. Table II highlights the connection between the chemical structure of π-conjugated CPs and their electrical conductivity. The use of signal-amplified conjugated polymers on a solid substrate provides an effectiveness to enhance the performance of tactile sensors, and the aforementioned polymers are notable for their conductivity [30].

A. Polypyrrole

Ppy, derived from the oxidative polymerization of pyrrole, is a notable member of the CPs family. Its distinctive feature lies in its conjugated backbone, comprised of alternating single and double bonds, which facilitates the movement of electrons along the polymer chain. Ppy synthesis can be achieved through various methods, including chemical oxidation, electrochemical polymerization, and enzymatic catalysis. The utility of Ppy extends across a spectrum of advantages when compared to traditional metals and semiconductors. These advantages encompass affordability, ease of processing, flexibility, tunability, and compatibility with biological systems, making it an attractive choice for a wide array of applications. Some notable applications for Ppy include its use in sensors, supercapacitors, batteries, corrosion protection, and the development of smart materials. Its adaptability and diverse range of applications make Ppy a compelling material in both research and industry settings [31].

B. Polyaniline

PANI stands out as a prominent conductive polymer celebrated for its remarkable electrical and mechanical attributes. Its synthesis can be achieved through diverse approaches, including chemical oxidation, electrochemical polymerization, and enzymatic catalysis. A defining feature of PANI is its conjugated backbone, comprising alternating single and double bonds, which creates pathways for electron mobility within the polymer structure. Moreover, PANI exhibits the capacity for doping with either acids or bases, a process that bolsters its conductivity and stability. This versatile polymer finds extensive utility across various domains. It contributes significantly to applications in fields such as sensor technology, supercapacitors, energy storage in batteries, corrosion prevention, and the development of innovative smart materials [31].

C. Polyacetylene

Polyacetylene, an organic polymer with a repeating unit of [C2H2]n, is synthesized through the polymerization of acetylene, represented by the chemical formula C2H2. This unique polymer possesses a distinct structure characterized by a sequence of alternating single and triple carbon-carbon bonds. This structural feature creates a conjugated or delocalized system, enabling the free movement of electrons along the polymer chain, thereby conferring electrical conductivity. In its pure form, polyacetylene does not exhibit substantial electrical conductivity. However, its electrical properties can be significantly altered through a process known as doping, which involves the introduction of foreign substances, such as iodine or arsenic. This doping process transforms polyacetylene into either a conductor or even a semiconductor, making it a versatile material for various electronic applications [32].

2 Conductive Polymer Coating Strategies

A. Chemical vapour deposition

CPs have garnered substantial attention across diverse applications, thanks to their remarkable blend of electrical conductivity and polymer characteristics. One prominent method for coating CPs onto substrates involves employing chemical vapour deposition (CVD) techniques. CVD polymerization proves advantageous for several reasons in the context of depositing conductive polymers. To begin, CVD polymerization demonstrates exceptional compatibility with a wide array of substrates, eliminating concerns about potential solvent or plasma-induced damage to the underlying materials. This substrate-independence simplifies the process of device fabrication and extends the utility of CVD to innovative substrates. Furthermore, CVD polymerization facilitates the deposition of conformal films with precise control over thickness, a critical feature for electronic or sensing devices featuring high-aspect-ratio components. Another noteworthy advantage of using CVD techniques to coat CPs is the capacity to introduce diverse functional groups into the polymer structure. These functional groups offer the potential for covalently anchoring various sensing elements like metal nanoparticles or proteins. As a result, CVD stands out as a versatile platform for applications in chemical and biological sensing [33].

B. Electrochemical polymerization

CPs have garnered considerable interest in the realm of electrochemical polymerization, owing to their remarkable attributes and wide-ranging potential applications in electronic devices. Electrochemical polymerization, also known as electropolymerization, emerges as a cost-effective and user-friendly method for crafting conductive polymer films. This technique involves the oxidation of a monomer within an electrochemical cell, leading to the formation of a polymer film on the surface of the working electrode. The working electrode can be crafted from materials such as carbonaceous substances, metals, or conductive glass. Significantly, electrochemical polymerization aligns with the principles of green chemistry, as it eliminates the requirement for toxic oxidants and enables real-time control over the production of high-purity conductive polymer films. These films showcase exceptional electrical, electronic, magnetic, optical, and rheological properties. This chapter predominantly focuses on the electrochemical polymerization of PANI films, as well as films composed of other CPs. [34], [35].

C. Solution casting

CP coatings have gained considerable attention in a range of industries due to their ability to tailor electrical and mechanical properties. Among the methods employed to apply CP films to flexible substrates, solution casting is a popular choice. This technique offers several advantages for the large-scale production of flexible devices and the creation of thin films. In the solution casting process, CPs are initially dissolved in appropriate solvents and then applied to the substrate's surface. To enhance adhesion, the substrate is often pre-treated with additives. Solution casting is a versatile and cost-effective approach that allows for the optimization of coating efficiency, making it a widely used method in the production of flexible sensors and various electronic devices based on CP technology [36], [37].

D. Spin coating

CPs have garnered substantial interest within the field of spin coating, particularly for the production of transparent conductive films (TCFs) crucial to various optoelectronic devices, including solar cells and displays. Traditional TCFs, such as those employing indium tin oxide (ITO) films, are encumbered by high costs and the utilization of rare metal elements. In contrast, low-cost alternatives for TCF fabrication involve metal nanowires (NWs) deposited on substrates through solution processes. Spin coating stands out as a widely used method for applying thin films to substrates. Nevertheless, when employing spin coating with solutions, challenges can arise in achieving strong adhesion between the NWs and the polymer-coated substrates. Insufficient contact area between the NWs and the substrates can lead to NWs peeling off during the spin coating process. This issue can be addressed by enhancing the contact area between the NWs and the polymer-coated surfaces, primarily by utilizing capillary immersion forces.

The selection of an appropriate polymer binder plays a pivotal role in improving the durability of NW films during spin coating. For instance, polyvinylpyrrolidone (PVP) thin films are deemed effective adhesive layers due to their low surface roughness and substantial surface energy changes. Nonetheless, the solubility of PVP in ethanol can result in NWs peeling off during the spin coating process. PVP variants with higher K values, such as PVP K120, have demonstrated lower solubility and superior adhesion to substrates [38], [39].

3 Base Materials

Table 3. Chemical Composition (Wt.%) Of SS Alloy Metals For BPS

Series / Grade	***C***	***Si***	***Mn***	***P***	***S***	***Cr***	***Ni***	***Mo***	***N***	***Ref***
SS 303	0.15	1.00	2.00	0.2	0.15	17.0 - 19.0	8.00-10.0	-	-	[40]
SS 304	0.07	0.75	2.00	0.045	0.030	17.5–19.5	8.0–10.5	-	*0.10*	
SS 316	0.08	0.75	2.00	0.045	0.030	16.0–18.0	10.0–14.0	2.00–3.00	*0.10*	*[41]*
SS 316L	0.03	0.75	2.00	0.045	0.030	16.0–18.0	10.0–14.0	2.00–3.00	*0.10*	

Table 3 presents the chemical compositions of the CPs that have been the primary focus of recent studies as coatings on stainless steel (SS) based BPs. The corrosion resistance of stainless-steel substrates in simulated PEMFC environments depends significantly on their chromium (Cr) and nickel (Ni) composition. Typically, increased Cr and Ni content enhances corrosion resistance. However, it's important to consider that increasing Cr and Ni content also results in higher manufacturing costs for the substrate. Furthermore, the incorporation of appropriate amounts of vanadium, molybdenum, and manganese into the stainless-steel substrate enhances its corrosion resistance and reduces the potential toxic effects on the Membrane Electrode Assembly [42].

Table 4. Chemical Composition (Wt.%) of Cu Alloy Metals For BPS

Series / Grade	***Cu***	***Other***	***Ref***
Cu	99.89	0.11	*[43]*

Table 4 provides the chemical compositions of the CPs that have been predominantly studied as coatings on Copper (Cu) based BPs in recent years. Copper has long been a preferred material for thermal management and electrical conduction across various industrial sectors, thanks to its remarkable thermal and electrical conductivity. However, the modern electronic industry's rapid growth has led to an increased demand for copper components with intricate and complex structures [44].

Table 5. Chemical Composition (Wt.%) Of Al Alloy Metals for BPS

Series/ Grade	***C***	***Si***	***Mn***	***Mg***	***Fe***	***Cu***	***V***	***Ti***	***Ref***
Al 6061	0.32	0.63	0.52	*1.08*	*0.17*	*0.32*	*0.01*	*0.02*	*[45]*

Table 5 provides the chemical compositions of the CPs that have been predominantly studied as coatings on Aluminium (Al) based BPs in recent years. When compared to stainless steel, aluminum alloy presents a more cost-effective and practical option for BP materials. Al BPs offer the significant advantage of being 65% lighter than stainless steel. This reduction in weight holds particular significance in transportation applications, given that each automobile's PEMFC stack, with an 80-kWh capacity, contains a substantial number of 740 BPs [46], [47].

4 Conductive Polymers Coating

We have gathered the corrosion resistance and Interfacial Contact Resistance (ICR) test results from recent literature, conveniently presented in Table 6 for your convenience. A comprehensive summary has been prepared by analyzing and structuring the latest literature on the surface modification of stainless steel.

Table 6. Chemical Composition (Wt.%) Of Conductive Polymer Coatings on Metallic BPS.

Sl. No	**Substrate**	**Coating**	**Method**	**Electrolyte**	**ICR *(mΩ cm^2)***	**Potentiostatic result *(mA/cm^2)***	**Corrosion Current Density *(mA/cm^2)***	**Ref**
1	SS 303	PANI	Spray gun – followed by curing for 1hr at 343 K	1.0 M H_2SO_4	-	-	150 ± 20	[48]

2	SS 304	PANI &Ppy	Cyclic voltammetry	0.1 M H_2SO_4	PPY (80), PANI (80)	-	PPY (10^{-3}) PANI (10^{-4})	[49]
		PANI	Doped sodium dodecylbenzene sulfonate	1 M H_2SO_4	-	0.1 at 0.45 V	0.05	[50]
		Ppy/C-PDA	Electropolymerized	0.1 M H_2SO_4	10	0.925 at 110 N/cm^2	9.25	[51]
		Ppy	Electro polymerization	0.4 M pyrrole & 0.15 M sodium dodecylsulfate	19	1.5V	1.3	[52]
		Ppy/G	Electrodeposition	0.3 M H_2SO_4	9.25	-	19	
		Go reinforced Ppy	Constant Voltage electro polymerization	0.1 M py& SGO aqeous	78	1.27	0.18	[53]
		Ppy/C	Electrodeposition	-	16	-	0.49	[54]
3	SS 316	Ppy&Ppy/C	Potentiostatic	0.1 M py& 0.3 M oxalic acid	51 - Ppy 22– Ppy/C	-	5.150 2.140	*[55]*
		PANI	Doped Nb and TiO_2	1 M H_2SO_4 at 25°C	-	9 at 0.6 V	12.9	*[56]*
4	SS 316L	PTFE	Electrodeposited	0.5 M H_2SO_4 + 5 ppm F−	Ag-PTFE (2.88 – 3.94) Ag (3.24 – 4.54)	-	10^{-2}	[57]
5	Cu (Essentially pure)	Ppy	Cyclic voltammetry	0.2 M H_2SO_4 + 0.1 M HCl 3ppm HF solutions at 25°C	16 at 180 N/cm^2	0.7 at 0.6V	4.59	[43]
		Ppy/ PANI	Galvanostatic		14 at 180 N/cm^2	0.7 at 0.6 V	1.62	
6	Al 6061	Ppy	Electrodeposition	0.1 M pyrrole in 0.1 M oxalic acid	25	-	-	[58]
		PANI	Electrodeposition	0.1 M py in 0.1 M nitric acid	25	-	-	

Where: Ppy - Polypyrrole, py – pyrrole, PANI - Polyaniline, GO - Graphene oxide, G – Graphene, PTFE - Poly tetra fluoroethylene, PDA – polydopamine

CPs, including variants like Ppy, PANI and their derivatives, offer remarkable chemical and physical stability coupled with high conductivity, rendering them highly promising for applications in the realm of metal corrosion prevention. Notably, a groundbreaking discovery was made when it was observed that electrochemically synthesized PANI coatings effectively mitigated the corrosion of stainless steel, garnering widespread attention from the research community. As of now, numerous studies have delved into the protective capabilities of polymer-coated metal BPs. In a specific investigation, the corrosion resistance of Ppy and PANI coatings on SS304 BPs was examined. The outcomes revealed that, over time, these coatings exhibited rapid degradation due to issues like inadequate adhesion and a loose structural arrangement. Consequently, it became evident that the reduction of the coating's porosity held significant importance in enhancing its corrosion resistance [59] – [61]. CP coatings have the potential to offer increased polarization resistance and reduced corrosion current density. Nonetheless, a quantitative assessment of their conductivity quality remains a subject for future investigation [50], [56], [62]

5 Conclusion

This review article offers a comprehensive insight into the evolving landscape of polymer coatings within the PEMFC domain. As we stand on the cusp of a significant shift towards cleaner and more sustainable energy solutions, the role of metallic BPs in enhancing the performance of PEMFCs becomes increasingly vital. The exploration of recent innovations in polymer coatings, discussed within this review, reveals the dynamic nature of this field. From CPs to nanocomposites and a spectrum of coating techniques, the advancements have the potential to revolutionize the electric conductivity of metallic BPs. This, in turn, promises to significantly improve the efficiency and durability of PEMFCs. Understanding the mechanisms behind these innovations, considering factors such as temperature and material compatibility, is imperative in harnessing the full potential of these enhancements. As we seek to address the pressing global challenges of energy efficiency and environmental sustainability, the insights presented in this review hold the key to unlocking the true capabilities of PEMFCs in clean energy applications. In essence, this review serves as a beacon for researchers, engineers, and stakeholders, guiding them towards a more efficient, eco-friendly, and sustainable energy future through the advancements in polymer coatings for enhanced electric conductivity of metallic BPs in PEMFCs.

Acknowledgment. This work was supported by the Centre for Excellence in Automobile Technology, Madras Institute of Technology Campus, Anna University, Chennai, Tamil Nadu, India. It was also financially supported by the Centre for Research, Anna University Chennai, Tamil Nadu, India.

References

[1] Zhao, Y., Mao, Y., Zhang, W., Tang, Y., Wang, P.: Reviews on the effects of contaminations and research methodologies for PEMFC. International Journal of Hydrogen Energy. Vol. 45, pp. 23174–23200 (2020)

[2] Xu, Z., Qiu, D., Yi, P., Peng, L., Lai, X.: Towards mass applications: A review on the challenges and developments in metallic bipolar plates for PEMFC. Progress in Natural Science: Materials International. Vol. 30, pp. 815–824 (2020)

[3] Tellez-Cruz, M.M., Escorihuela, J., Solorza-Feria, O., Compañ, V.: Proton exchange membrane fuel cells (Pemfcs): Advances and challenges. Polymers. Vol. 13 (2021)

[4] Malik, V., Srivastava, S., Bhatnagar, M.K., Vishnoi, M.: Comparative study and analysis between Solid Oxide Fuel Cells (SOFC) and Proton Exchange Membrane (PEM) fuel cell - A review. Materials Today: Proceedings pp. 2270–2275 (2021)

[5] Li, C., Liu, Y., Xu, B., Ma, Z.: Finite time thermodynamic optimization of an irreversible proton exchange membrane fuel cell for vehicle use. Processes. Vol. 7 (2019)

[6] Zhan, Z. et al.: Microstructure Reconstruction and Multiphysics Dynamic Distribution Simulation of the Catalyst Layer in PEMFC. Membranes (Basel). Vol. 12 (2022)

[7] Alaswad, A. et al.: Technical and commercial challenges of proton-exchange membrane (Pem) fuel cells. Energies. Vol. 14 (2021)

[8] De Bruijn, F.: The current status of fuel cell technology for mobile and stationary applications. Green Chemistry. Vol. 7, pp. 132–150 (2005)

[9] Wilberforce, T. et al.: A comprehensive study of the effect of bipolar plate (BP) geometry design on the performance of proton exchange membrane (PEM) fuel cells. Renewable and Sustainable Energy Reviews. Vol. 111, pp. 236–260 (2019)

[10] Wilberforce, T. et al.: Technical evaluation of proton exchange membrane (PEM) fuel cell performance – A review of the effects of bipolar plates coating. Renewable and Sustainable Energy Reviews. Vol. 113 (2019)

[11] Dobrovol'skii, Y.A. et al.: Materials for bipolar plates for proton-conducting membrane fuel cells. Russ J Gen Chem. Vol. 77, pp. 752–765 (2007)

[12] Madadi, F., Rezaeian, A., Edris, H., Zhiani, M.: Improving performance in PEMFC by applying different coatings to metallic bipolar plates. Mater Chem Phys. Vol. 238 (2019)

[13] Manso, A.P. et al.: Corrosion behavior of tantalum coatings on AISI 316L stainless steel substrate for bipolar plates of PEM fuel cells. Int J Hydrogen Energy. Vol. 45, pp. 20679–20691 (2020)

[14] Song, Y. et al.: Review on current research of materials, fabrication and application for bipolar plate in proton exchange membrane fuel cell. Int J Hydrogen Energy. Vol. 45, pp. 29832–29847 (2020)

[15] Ramírez-Herrera, C. A., Tellez-Cruz, M. M., Pérez-González, J., Solorza-Feria, O., Flores-Vela, A., Cabañas-Moreno, J. G.: Enhanced mechanical properties and corrosion behavior of polypropylene/multi-walled carbon nanotubes/carbon nanofibers nanocomposites for application in bipolar plates of proton exchange membrane fuel cells. Int J Hydrogen Energy. Vol. 46, pp. 26110–26125 (2021)

[16] Wang, H., Turner, J. A.: Reviewing metallic PEMFC bipolar plates. Fuel Cells. Vol. 10, pp. 510–519 (2010)

[17] Karimi, S., Fraser, N., Roberts, B., Foulkes, F. R.: A review of metallic bipolar plates for proton exchange membrane fuel cells: Materials and fabrication methods. Advances in Materials Science and Engineering. Vol. 2012 (2012)

[18] Pedram, S., Batool, M., Yapp, K., Bonville, L., Jankovic, J.: A Review on Bioinspired Proton Exchange Membrane Fuel Cell: Design and Materials. Advanced Energy and Sustainability Research. Vol. 2 (2021)

[19] Elsenbaumer, R. L., Jen, K. Y., Oboodi, R.: Processible and Environmentally Stable Conducting Polymers. (1986)

[20] Dědek, I., Kupka, V., Jakubec, P., Šedajová, V., Jayaramulu, K., Otyepka, M.: Metal-organic framework/conductive polymer hybrid materials for supercapacitors. Applied Materials Today. Vol. 26 (2022)

[21] Stejskal, J. et al.: Polypyrrole salts and bases: Superior conductivity of nanotubes and their stability towards the loss of conductivity by deprotonation. RSC Adv. Vol. 6, pp. 88382–88391 (2016)

[22] Gueye, M. N. et al.: Structure and Dopant Engineering in PEDOT Thin Films: Practical Tools for a Dramatic Conductivity Enhancement. Chemistry of Materials. Vol. 28, pp. 3462–3468 (2016)

[23] Ziadan, K. M., Saadon, W. T.: Study of the electrical characteristics of polyaniline prepeared by electrochemical polymerization. Energy Procedia. Vol. 14, pp. 71–79 (2012)

[24] Basescu, N., Liu, Z. X., Moses, D., Heeger, A. J., Naarmann, H., &Theophilou, N.: High electrical conductivity in doped polyacetylene. Nature. Vol. 327, pp. 403-405 (1987)
[25] Ebisawa, F., Kurokawa, T., Nara, S.: Electrical properties of polyacetylene/polysiloxane interface. J Appl Phys. Vol. 54, pp. 3255–3259 (1983)
[26] Quinsaat, J. E. Q. et al.: Conductive silicone elastomers electrodes processable by screen printing. Sci Rep. Vol. 9 (2019)
[27] Jun, Y. S. et al.: The conductivity of polydimethylsiloxane/graphene nano-ribbon foam composite with elongation. Carbon N Y. Vol. 162, pp. 328–338 (2020)
[28] Adamect, V., Calderwoodt, J. H.: On the determination of electrical conductivity in polyethylene. (1981)
[29] Alo, O. A., Otunniyi, I. O.: Electrical conductivity of polyethylene/epoxy/graphite/carbon black composites: synergy of blend immiscibility and hybrid filler. Polymer-Plastics Technology and Materials. Vol. 60, pp. 2075–2088 (2021)
[30] Bubniene, U. S. et al.: Conducting Polymers for the Design of Tactile Sensors. Polymers. Vol. 14 (2022)
[31] Varghese, A., Devi K R, S., Kausar, F., Pinheiro, D.: Evaluative study on supercapacitance behavior of polyaniline/polypyrrole – metal oxide based composites electrodes: a review. Materials Today Chemistry. Vol. 29 (2023)
[32] Namsheer, K., Rout, C. S.: Conducting polymers: a comprehensive review on recent advances in synthesis, properties and applications. RSC Advances. Vol. 11, pp. 5659–5697 (2021)
[33] Wang, M. et al.: CVD Polymers for Devices and Device Fabrication. Advanced Materials. Vol. 29 (2017)
[34] Fomo, G., Waryo, T., Feleni, U., Baker, P., Iwuoha, E.: Electrochemical Polymerization. (2019)
[35] De Paoli, M.-A., Gazotti, W. A.: Electrochemistry, Polymers and Opto-Electronic Devices: A Combination with a Future. (2002)
[36] Van Tran, V., Lee, S., Lee, D., Le, T. H.: Recent Developments and Implementations of Conductive Polymer-Based Flexible Devices in Sensing Applications. Polymers. Vol. 14, no. 18 (2022)
[37] Gao, W., Ota, H., Kiriya, D., Takei, K., Javey, A.: Flexible Electronics toward Wearable Sensing. Acc Chem Res. Vol. 52, pp. 523–533 (2019)
[38] Mutiso, R. M. et al.: Integrating simulations and experiments to predict sheet resistance and optical transmittance in nanowire films for transparent conductors. ACS Nano. Vol. 7, pp. 7654–7663 (2013)
[39] Langley, D. et al.: Flexible transparent conductive materials based on silver nanowire networks: A review. Nanotechnology. Vol. 24 (2013)
[40] Shen, T. H.: The Cleaning of 303 Stainless Steel. (2004)
[41] Leng, Y., Ming, P., Yang, D., Zhang, C.: Stainless steel bipolar plates for proton exchange membrane fuel cells: Materials, flow channel design and forming processes. Journal of Power Sources. Vol. 451 (2020)
[42] Coms, F. D., Liu, H., & Owejan, J. E.: Mitigation of Perfluorosulfonic Acid Membrane Chemical Degradation Using Cerium and Manganese Ions. ECS Trans, vol. 16, pp. 1735–1747 (2008)
[43] Pan, T. J., Zuo, X. W., Wang, T., Hu, J., Chen, Z. D., & Ren, Y. J.: Electrodeposited conductive polypyrrole/polyaniline composite film for the corrosion protection of copper bipolar plates in proton exchange membrane fuel cells. J Power Sources, vol. 302, pp. 180–188 (2016)
[44] Yan, X. et al.: Microstructure and mechanical properties of pure copper manufactured by selective laser melting. Materials Science and Engineering: A, vol. 789 (2020)
[45] Christy, T. V., Murugan, N., & Kumar, S.: A Comparative Study on the Microstructures and Mechanical Properties of Al 6061 Alloy and the MMC Al 6061/TiB 2 /12 P. (2010)
[46] Chiang, T.-Y., Tsai, L.-C., Sheu, H.-H., & Lu, C.-E.: Corrosion Resistance of 5052 Al-alloy with a Zirconia-Rich Conversion Coating Used in Bipolar Plates in PEMFCs. (2014).
[47] Horita, Z., Fujinami, T., Nemoto, M., & Langdon, T. G.: Improvement of mechanical properties for Al alloys using equal-channel angular pressing. Journal of Materials Processing Technology, Vol. 117, pp. 288-292 (2001)
[48] Deyab, M. A., & Mele, G.: Stainless steel bipolar plate coated with polyaniline/Zn-Porphyrin composites coatings for proton exchange membrane fuel cell. Sci Rep, vol. 10 (2020)

[49] Joseph, S., McClure, J. C., Chianelli, R., Pich, P., & Sebastian, P. J.: Conducting polymer-coated stainless steel bipolar plates for proton exchange membrane fuel cells (PEMFC). International Journal of Hydrogen Energy (2005)

[50] Ren, Y. J., Chen, J., & Zeng, C. L.: Corrosion protection of type 304 stainless steel bipolar plates of proton-exchange membrane fuel cells by doped polyaniline coating. J Power Sources, vol. 195, pp. 1914–1919 (2010)

[51] Chen, Z. et al.: Superior conducting polypyrrole anti-corrosion coating containing functionalized carbon powders for 304 stainless steel bipolar plates in proton exchange membrane fuel cells. Chemical Engineering Journal, vol. 393 (2020)

[52] Liu, S., Pan, T. J., Wang, R. F., Yue, Y., & Shen, J.: Anti-corrosion and conductivity of the electrodeposited graphene/polypyrrole composite coating for metallic bipolar plates. Prog Org Coat, vol. 136 (2019)

[53] Sun, Y., Hu, C., Cui, J., Shen, S., Qiu, H., & Li, J.: Electrodeposition of polypyrrole coatings doped by benzenesulfonic acid-modified graphene oxide on metallic bipolar plates. Prog Org Coat, vol. 170 (2022)

[54] Luo, X. et al.: Design and fabrication of bipolar plates for PEM water electrolyser. Journal of Materials Science and Technology, vol. 146, pp. 19–41 (2023)

[55] Li, X., Sun, W., Zheng, Y., Long, C., & Wang, Q.: New Strategy for the Design of Anti-Corrosion Coatings in Bipolar Plates Based on Hybrid Organic–Inorganic Layers. Molecules, vol. 28, no. 7 (2023)

[56] Wang, Y. et al.: Synthesis and corrosion protection of Nb doped TiO2 nanopowders modified polyaniline coating on 316 stainless steel bipolar plates for proton-exchange membrane fuel cells. Prog Org Coat, vol. 137 (2019)

[57] Fu, Y. et al.: Ag-polytetrafluoroethylene composite coating on stainless steel as bipolar plate of proton exchange membrane fuel cell. J Power Sources, vol. 182, pp. 580–584 (2008)

[58] Joseph, S., McClure, J. C., Sebastian, P. J., Moreira, J., & Valenzuela, E.: Polyaniline and polypyrrole coatings on aluminum for PEM fuel cell bipolar plates. J Power Sources, vol. 177 , pp. 161–166 (2008)

[59] Akula, S., Kalaiselvi, P., Sahu, A. K., & Chellammal, S.: Electrodeposition of conductive PAMT/PPY bilayer composite coatings on 316L stainless steel plate for PEMFC application. Int J Hydrogen Energy, vol. 46, pp. 17909–17921 (2021)

[60] Deberry, D. W.: Modification of the Electrochemical and Corrosion Behavior of Stainless Steels with an Electroactive Coating.

[61] Gonzalez-Rodriguez, J. G. et al.: Improvement on the corrosion protection of conductive polymers in pemfcenvironmets by adhesives. J Power Sources, vol. 168, no. 1 SPEC. ISS., pp. 184–190 (2007).

[62] Jiang, L. et al.: Enhanced anticorrosion performance of PPY-graphene oxide/PPY-camphorsulfonic acid composite coating for 304SS bipolar plates in proton exchange membrane fuel cell. Journal of Industrial and Engineering Chemistry, vol. 80, pp. 497–507 (2019)