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Electrodeposition of Functional Coatings on Bipolar Plates for Fuel Cell Applications – A Review

Peter Odetola, Patricia Popoola, Olawale Popoola and David Delport

Additional information is available at the end of the chapter

Abstract

The issue of corrosion and degradation has been evaluated as one of the major sources of concern in the history and trend of materials development and their applications in engineering. Design, process, and production consideration of materials hinge on the motive of built-to-last technology in their lifetime applications. The "World Corrosion Organization" has calculated that the direct cost of corrosion worldwide is over 3% of global gross domestic product (GDP)—approximately US $2.2 trillion—every year.

Natural materials tend to return to their original stable states after being conformed through processes into engineering applications. In order to conserve materials' integrity, usability, safety, and performance, the materials have to be subjected to processes that will keep them in its optimal functionalities.

The finishing phase of most materials for engineering applications is usually done with protective barrier in the form of coating, paint, or furnishes to conserve the materials' integrity and inhibit its susceptibility to interact with the environment.

Complete overhauling of a whole corrosion-invaded device is capital intensive. Corrective maintenance through repair work on damaged parts is not economically viable. To minimize or avoid these costs, adoption of functional composite coatings using electrodeposition can be effective.

Bipolar plate of fuel cell is a key performance component with corrosion challenge. This chapter will focus on electrodeposition as one of the corrosion inhibition techniques on bipolar plate of fuel cell [1, 2]. Through electrodeposition, bipolar plate can be protected with appropriate functional coatings to enhance surface quality and impart good surface properties that will prolong lifespan application in fuel cell vehicles.

Keywords: Fuel cell, Bipolar plate, Coatings, Electrodeposition, Corrosion

1. Introduction

The study of fuel cell is highly relevant to solving ongoing worldwide threats of pollution as well as meeting up with the future energy demands for technological advancement. Fuel cells have been proposed for use in automobiles as a replacement of the conventional internal combustion engines. Fuel cells produce power in an entirely different way compared to internal combustion engines and storage batteries. Fuel cell is an electrochemical system that works on reverse electrolysis combining hydrogen from fuel with oxygen from air to produce electric power directly. Heat and non-polluted water vapor are the only by-products of these systems. Internal combustion engines[3] are powered from the combustion of hydrocarbon fuel through the Carnot cycles. The combustion process releases harmful gases such as CO, CO_2, SO_2, etc., into the environment, polluting it and affecting the energy balance of the ecosystem through global warming and damaging the protective ozone layers. Conversely, batteries are chemical energy storage devices that only produce power intermittently, as they must be recharged after being exhausted. The recharging process is always lengthy and inconvenient.

1.1. Timeline for fuel cell development

Fuel cell was first discovered by William Grove in 1839 when he thought it possible to produce electric current through reverse electrolysis by combining hydrogen and oxygen together. This awareness made scientists throughout the 19th century to conduct several studies until Francis Thomas Bacon, a British scientist, worked on developing alkaline fuel cells in 1958. This technology was utilized for NASA Apollo spacecraft program and was licensed to Pratt and Whitney. Through the research work of Thomas Grubb and Leonard Niedrach in 1960, polymer electrolyte membrane (PEM) technology was invented at General Electric (GE). A small fuel cell was further developed in the mid-1960s by General Electric for US Army Signal Corps and US electronic division of the Navy's Bureau of ships. In the year 1970, GE developed a novel water-electrolysis technology for undersea life support leading to the US Navy Oxygen Generating Plant. The British Royal Navy adopted this technology in the early 1980s for their submarine fleet. In the 1990s, Los Alamos National Lab and Texas A&M University researched different ways of reducing platinum load required for PEM cells.

1.2. Definition of fuel cell

A fuel cell is an electrochemical device that converts the chemical energy of a fuel (e.g., hydrogen, methanol, etc.) and an oxidant (air or pure oxygen) in the presence of a catalyst into electricity, heat, and water[4].

Economy benefits of fuel cells are possible as a result of its fantastic flexibility and features over conventional energy sources:

- Fuel cells produce clean energy through electrochemical conversion of the fuel. Therefore, they are environmentally friendly because of the zero or very low emissions.

- Fuel cells are high-power generating system from a few watts to hundreds of kilowatt with efficiencies much higher than conventional internal combustion engine.

- Fuel cells have low noise production because of few moving parts.

- Fuel cells can be used as a power source for mobile applications such as fuel cell vehicles and boats and also in stationary applications such as laptops and phones.

1.3. Component of a fuel cell

The fuel cell assemblage which comprises bipolar plate (BP), membrane electrode assembly (MEA), gas diffusion layers (GDL), catalyst layer (Nafion®), seal, and the end plates function together as heat and electrical generating system[5].
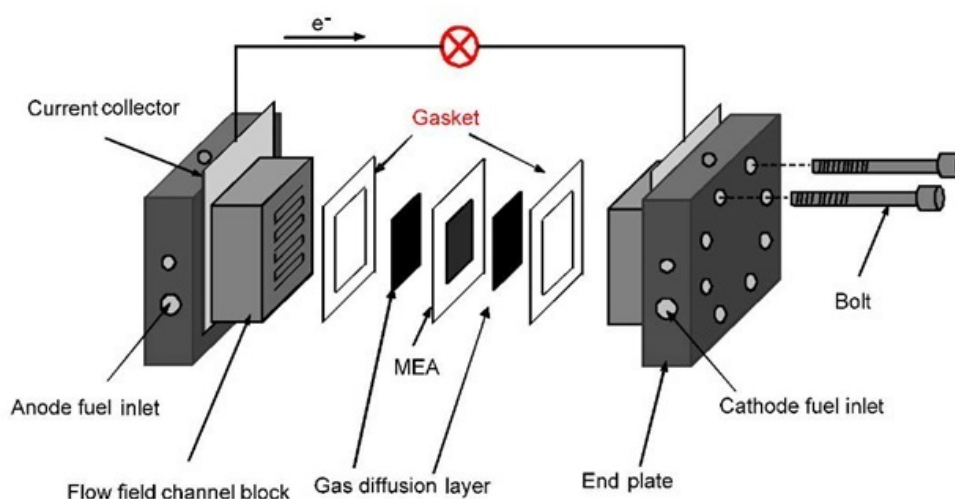

Figure 1. Showing components made up of bipolar plate stacks (www.what-when-how.com)

1.3.1. Membrane electrode assembly

"Membrane Electrode Assembly (MEA)" is the heart of a fuel cell consisting of polymer membrane electrolyte and two electrodes (anode and cathode) that sandwich the polymer membrane. It has three components fused and compressed together by high pressure and temperature. The industry standard of polymer membrane is Nafion developed in the 1970s by DuPont. Nafion consists of polytetrafluoroethylene (PTFE) chains commonly known as Teflon forming the backbone of the membrane. MEA plays the role of separating electrons and protons from fuel and therefore moves the protons (hydrogen ions) to the cathode side where it recombines with the air to form water and heat. It enhances proton conduction and improves stability in terms of chemical, mechanical, and dimensional alteration[6].

1.3.2. Catalyst

"Platinum" is a common noble metallic that acts as a catalyst in the acidic fuel cell environment. The platinum catalyst in the form of tiny particles is deposited on the large surface area of the

carbon cloth for a better reaction. The platinum catalyzes the conversion of hydrogen molecule of the fuel into electrons and protons at the anode side. Moreover, at the cathode side, it helps to split oxygen molecule into two atoms and then combines with the electrons and protons from hydrogen to produce water. Platinum catalyst is extremely sensitive to CO poisoning from the fuel gas derived from hydrocarbon fuel[7].

1.3.3. Gas diffusion layers

"Gas Diffusion Layers (GDL)" is responsible for uniform distribution of the reactants from the bipolar plates into the active catalyst sites. It helps in membrane humidification[8]. It helps in effective current assemblage and water-heat removal as well.

1.4. Fuel cell stack

The amount of power produced by a fuel cell is dependent on several factors, such as the size, type, operating temperature, and pressure of the gas supplied into the cell. However, a single fuel cell produces enough electricity for only the smallest applications. Therefore, to realize sufficient operational power output, individual fuel cells are typically combined in series to form fuel cell stack[4,5,9]. A typical fuel cell stack may consist of hundreds of fuel cells.
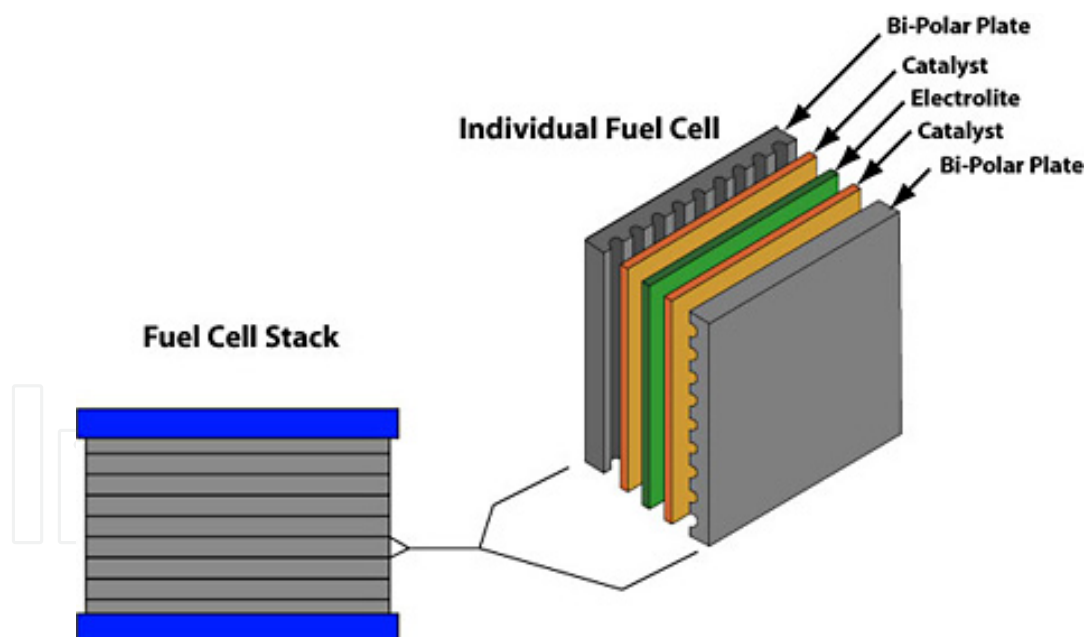

Figure 2. Showing components of fuel cell stack (www.tech-etch.com)

1.5. Types of fuel cell

Fuel cells are broadly classified into the following types:

- Alkaline fuel cell (AFM)

- Direct methanol fuel cell (DMFC)

- Molten carbon fuel cell (MCFC)

- Phosphoric acid fuel cell (PAFC)

- Polymer electrode membrane fuel cell (PEMFC)
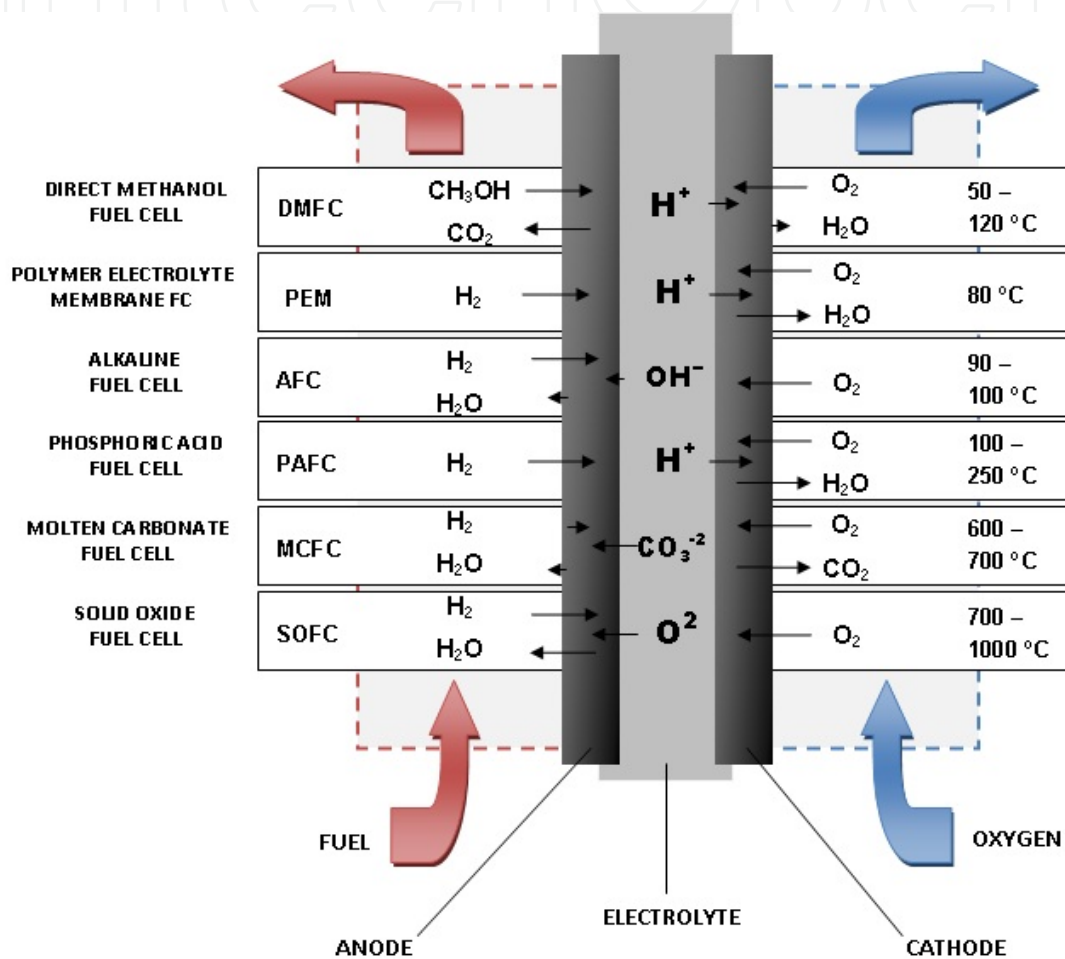
- Solid oxide fuel cell (SOFC)

Figure 3. Showing different types of fuel cells (www.fuelcells.org)

1.6. Brief Description of Fuel Cell Type

1.6.1. AFC

"AFC" was one of the first fuel cell technologies developed and was originally used by NASA space shuttle missions to produce electrical energy and water onboard spacecraft. The fuel cell uses a solution of potassium hydroxide as an electrolyte and can use a variety of non-precious metals as a catalyst at the electrodes. This fuel cell has high performance due to the rate at

which chemical reactions take place in the cell. They are also very efficient in space applications with efficiencies up to 60%[10].

The major setback of this fuel cell is carbon dioxide poisoning of the electrolyte. Even little concentration of carbon dioxide in air can adversely affect its operation, making it necessary to purify the hydrogen and oxygen before use. This affects the cell's lifetime and incurs additional cost. AFC stacks have at least 8000 average operating hours and to make it economically viable for large-scale utility operations, operating times exceeding 40,000 hours are needed. This is possibly the most significant hindrance to its commercialization.
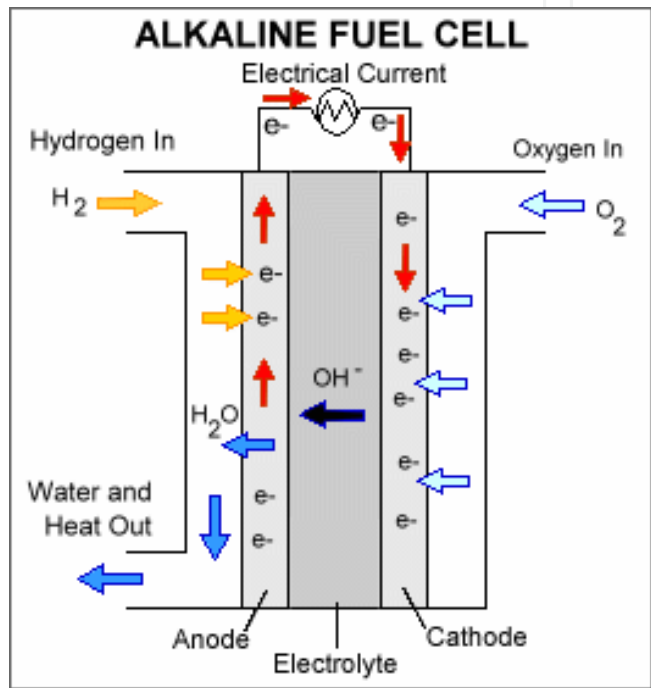

Figure 4. Showing components of alkaline fuel cell (www.fuelcellmarkets.com)

1.6.2. DMFC

"DMFC" uses polymer membrane as an electrolyte such as the polymer electrolyte membrane fuel cells (PEMFC). The distinction lies in the anode catalyst that draws hydrogen from the liquid methanol[11], eliminating the need for reformer. Therefore, pure methanol can be used as fuel.

1.6.3. MCFC

"MCFC" uses molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide ($LiAlO_2$) matrix as the electrolyte. In molten carbonate fuel cells, negative ions travel through the electrolyte to generate water and electrons[4]. They operate at extremely high temperatures of about 650°C and beyond. MCFCs offer significant reduction in cost by using non-precious metals as catalysts at the electrodes. The efficiency level is up to
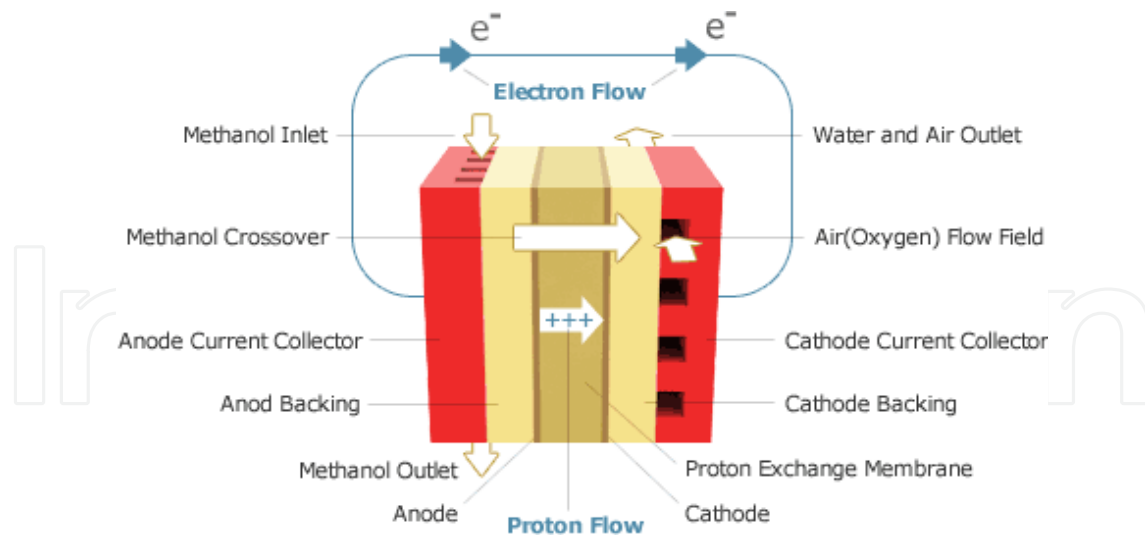
Figure 5. Showing components of direct methanol fuel cell (www.daviddarling.info)

60% which is considerably higher than 35–50% efficiencies of a phosphoric acid fuel cell. Overall, fuel efficiencies mount up to about 85% when the waste heat is captured and used. As a result of the elevated temperature at which it works, the fuels are converted to hydrogen by a process known as internal reforming within the fuel cell. This also makes it economical.
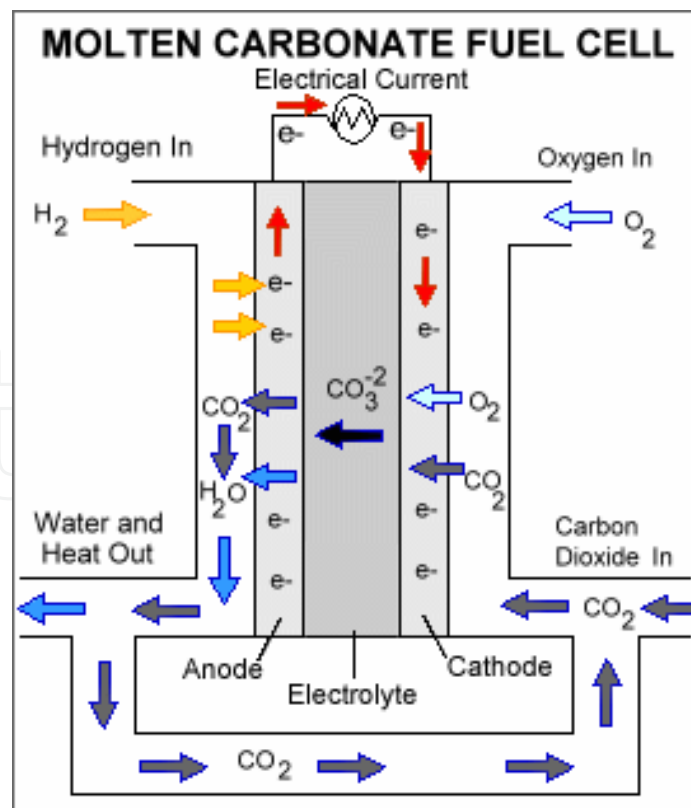

Figure 6. Showing components of molten carbon fuel cell (www.fuelcellmarkets.com)

1.6.4. PAFC

"PAFC" uses liquid phosphoric acid as an electrolyte contained in a silicon carbide matrix bonded in Teflon and has finely dispersed platinum catalyst inside its porous carbon electrodes.

Phosphoric acid fuel cell is considered as the first-generation modern fuel cells. It is the first most commercially developed fuel cell used to power many commercial premises and large buses such as city buses. The major challenge of PAFC is the costly platinum catalyst which makes it uneconomical.
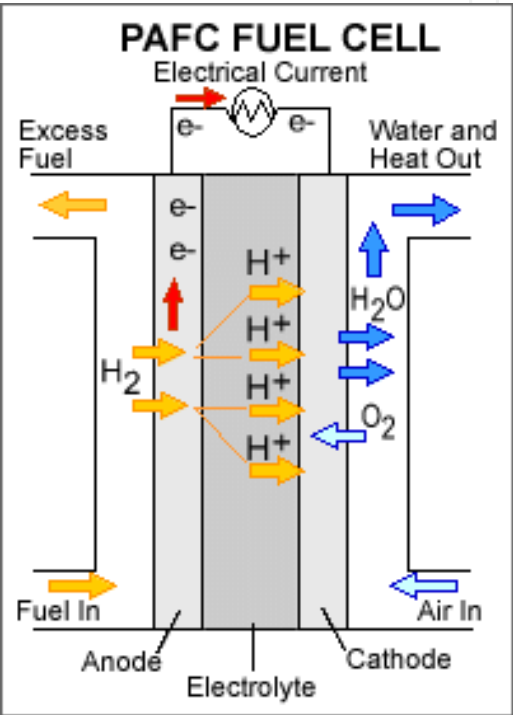

Figure 7. Showing components of phosphorus acid fuel cell (www.fuelcellmarkets.com)

1.6.5. PEMFC

"PEMFC" uses a solid polymeric membrane as the electrolyte and platinum catalyst contained in porous carbon electrodes. Polymer electrolyte membrane fuel cells[2,4& 12]operate at moderately low temperature range of 80°C to 100°C. The low operating temperature range enables them to quick start (short warm-up time) and results in better durability (lesser wear on system components).

PEMFC utilizes the platinum catalyst on its membrane. Platinum catalyst[7]is very expensive even in small quantity and also very sensitive to carbon monoxide poisoning, making application of reactor that will reduce its concentration in hydrogen fuel gas-derived fossil fuel necessary. This adds to the overall cost. In recent times, researchers are exploring platinum/ruthenium catalysts that are more resistant to CO, as better substitutes.

Another significant challenge to suitability of fuel cells for vehicles is low hydrogen storage capacity. Hydrogen is a very light gas with low energy density and will require a very large storage tank to store it onboard to power the fuel cell vehicles over a considerable distance, typically 300–400 miles like the gasoline-powered vehicles before refueling. Higher-density liquid fuels such as methanol, ethanol, natural gas, liquefied petroleum gas, and gasoline cannot be used directly unless they are processed into hydrogen through an onboard reformer unit. This increases costs and maintenance requirements.
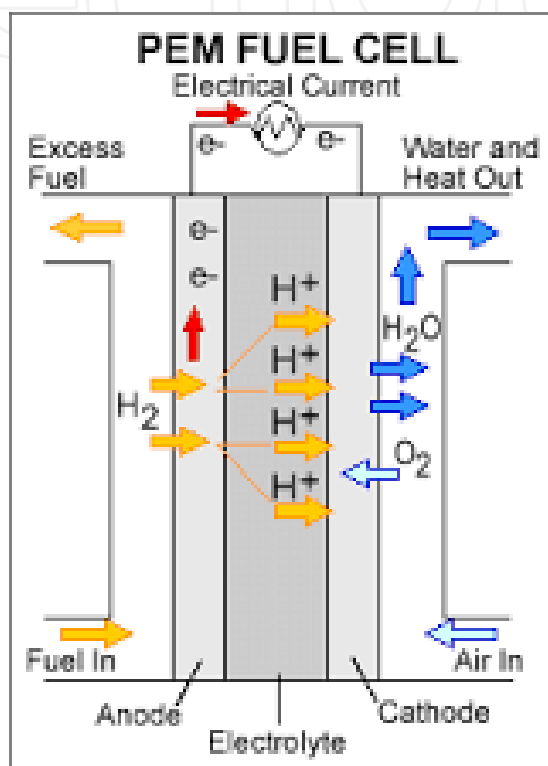

Figure 8. Showing components of polymer electrolyte fuel cell (www.daviddarlin.info)

1.6.6. SOFC

"SOFC" uses a hard, nonporous solid ceramic compound as the electrolyte, such as zirconium oxide stabilized with yttrium oxide, instead of a liquid. It works at a higher temperature range of 800°C to 1000°C and can attain efficiencies around 60%. This makes it suitable for providing auxiliary power in vehicles and also for industrial electricity and heat generation. The high-temperature operating conditions allow fuels to reform internally and also nullify the need for any precious metal catalyst, thereby saving cost. The high operating temperature results in a slow start-up and requires huge thermal shielding which renders it unsuitable for transportation and small portable applications. The development of moderate cost materials that will be stable under the stringent operating conditions is the major challenge facing this technology. Research and development are currently developing lower-temperature SOFCs operating at or below 800°C with minimal durability problems and lesser cost.
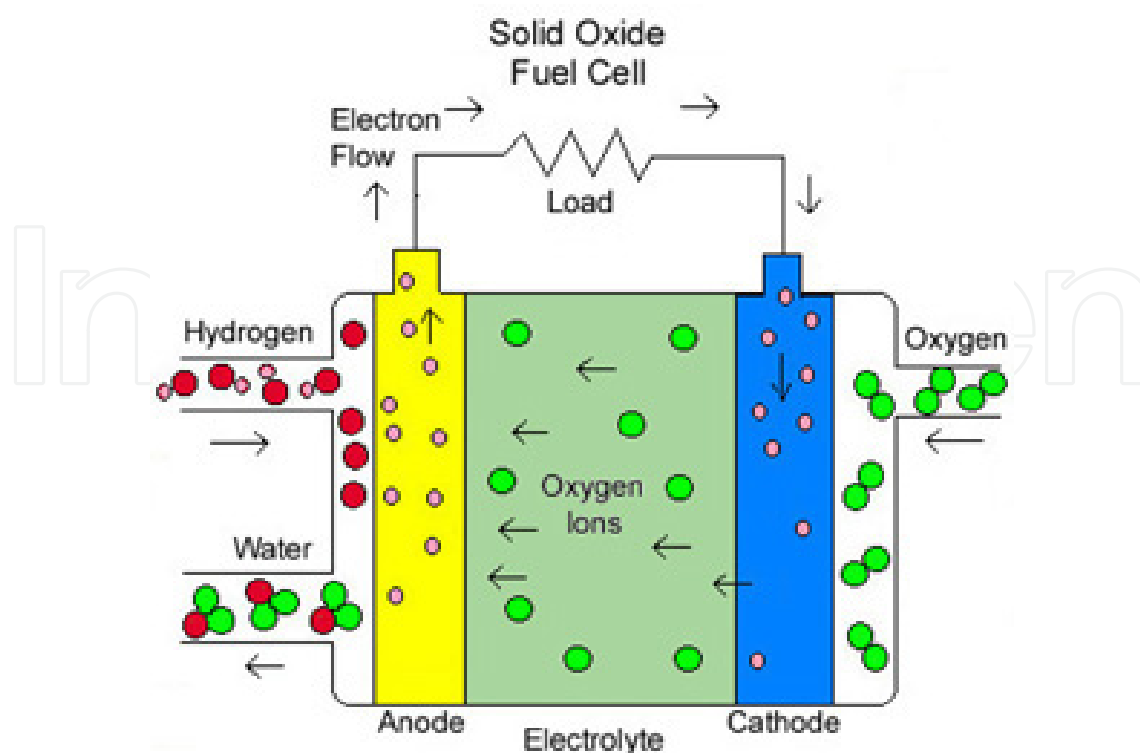
Figure 9. Showing components of molten carbon fuel cell (www.iit.edu)

1.7. Polymer electrolyte membrane fuel cell: A case study

Polymer electrolyte membrane fuel cell also known as proton exchange membrane fuel cell has been proposed to be a suitable candidate for use in fuel cell vehicles[2].

The major portion of the fuel comprises hydrogen (H_2) and oxygen (O_2) from air which together acts as an oxidant. Both react together electrochemically producing electricity and water as by-products.

The different components of PEMFCs are as follows:

• Bipolar plates

• "Anode" is the negative electrode that conducts freed electrons to an external circuit.

• "Cathode" is the positive electrode that distributes oxidant to the surface of the catalyst and it also conducts the electrons back from the external circuit to the catalyst where they can recombine with the hydrogen ions and the oxygen to form water and heat.

• "Catalyst" usually made up of platinum serves the purpose of splitting fuel and oxidant at the anode and cathode interface.

• "The electrolyte" is the proton exchange membrane that is only permeable to hydrogen ions serving as its transport medium.

• Gas diffusion layers (GDL)

1.8. Mode of operation of PEMFC

- Hydrogen gas is fed to the anode side of the fuel cell, while oxygen or air enters through the cathode side of the cell.

- At the anode side, a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged electrons.

- The polymer electrolyte membrane allows only the proton to pass through it to the cathode while the electrons are moved away to an external circuit to do useful work.

- At the cathode side, the electrons from the external circuit attract the hydrogen ions through the membrane with an oxygen atom to form water molecule which flows out of the cell.

1.9. Bipolar plates: The key performance component of PEMFC

The successful commercialization of fuel cell for future use and its suitability to compete on economical scale above other energy sources still depend on the performance of the bipolar plates. The bipolar plate accounts for more than 40% of the total stack cost and about 80% of the total weight[13].

As a result of this, there have been significant esearchresearch and evelopmentdevelopment activities in the past few years to lower their cost, reduce their size, and improve their performance and lifetime in applications.

2. Functions of bipolar plates

Bipolar plates perform a number of critical functions simultaneously in a fuel cell stack to ensure acceptable levels of power output and a long stack lifetime[14]as described in the following:

- They collect and transport electrons from the anode to cathode.

- They connect individual fuel cells in series to form a fuel cell stack of the required voltage.

- They separate fuel gas (hydrogen) and oxidant (oxygen or air) feeding hydrogen to the anode and oxygen to the cathode while removing water and unreacted gases. Hence, they are impermeable to gases.

- They contain the gas flow field channels, thereby providing a flow path for gas transport to uniformly distribute the gases over the entire electrode area.

- They provide thermal conduction to help regulate fuel cell temperature and remove heat from the electrodes to the cooling channels or media.

- They provide structural support for the fuel cell stack.

2.1. Bipolar plate materials

The materials [12, 15] required for bipolar plates fall into two categories:

- Non-metallic materials, for example, graphite or polymer-based composites.

- The metallic materials, for example, stainless steel, aluminum, titanium, nickel, copper, etc.

Substrate	Conductivity (S/cm)	Density (g/cm³)	Thickness (mm)
Aluminum	370,000	2.7	1–2
Stainless Steel	10,000	8.0	1–2
Graphite	110–680	1.8–2	5-6

Table 1. Showing properties variation of bipolar plates materials

2.1.1. Aluminum

It has a relatively low density, good strength, and higher thermal conductivity than stainless steel. Aluminum bipolar plates can be produced by casting, machining, and etching methods. This leads to lower production time and costs when compared to graphite. The major setback of aluminum lies in the formation of an electrically insulating oxide layer which impedes bipolar plate performance.

2.1.2. Stainless steel

Stainless steel has been shown to have the potential to meet all of the requirements for bipolar plates. It has a relatively low cost with high electrical and thermal conductivity, good mechanical properties, and ease of machining. Stainless steel bipolar plates[16] can be rapidly manufactured in large quantities by stamping. In the acidic environment within the fuel cell, stainless steel passivates forming Cr_2O_3 which elevates the interfacial contact resistance.

Most conventional coatings for stainless steel have shown to add to overall cost and also leave surface defects which result in local corrosion, damaging the fuel cell. The development of cost-effective coatings is the most significant research area in metallic bipolar plates. Despite the excellent physical properties and high-volume manufacturing processes available for metal bipolar plates, current technology places the estimated cost at $60–100/kW or 6 to 10 times the current target for transportation[17].

2.2. Bipolar plate DOE performance targets

As defined by the US Department of Energy (DOE), an ideal material for bipolar plates must meet the following requirements[18]:

- Bulk electrical conductivity (in-plain):

- Hydrogen permeability:

- Corrosion rate:

- Interfacial contact resistance: at

- Tensile strength:

- Flexural strength:

- Thermal conductivity:

- Thermal stability: up to for PEMFC

- Cost: 2005,

- Chemical and electrochemical stability in acidic environments

- Low thermal expansion

- Acceptable hydrophobicity

- Rapid and inexpensive manufacture

2.3. Performance control strategies for fuel cell

2.3.1. Corrosion management

Corrosion problem is only associated with metallic bipolar plate materials such as stainless steel, aluminum, nickel, and titanium. The bipolar plate works in an acidic environment and is therefore susceptible to corrosion attack[19, 20] through the electrochemical processes. The corrosion products of the metallic ions from the substrate at first will increase the surface contact resistance, then reduce the ionic conduction of the proton via the membrane electrode, and eventually poison it. Metallic coatings through electroplating can be used to address these problems. It will act as a protective barrier between the substrate and the aggressive acidic environment.

2.3.2. Water management

It has been well established that at the anode interface, the fuel undergoes a splitting process whereby only protons are permitted to pass through the membrane electrode assembly. Fuel cell performance is a function of effectiveness of the Nafion membrane to conduct the protons through it which also depend on the temperature and the level of relative humidity.

The proton conductivity of the Nafion membrane is highly influenced by the quantity of water absorbed in the membrane[21] and the maximum proton conductivity is attained when the membrane is fully saturated with water. Overflooding of water has an adverse effect of blocking the reaction sites of the neighboring electrodes, thereby preventing access of reactant gases into their cell. On the other hand, under low relative humidity, the absorbed water in the membrane vaporizes which remarkably reduces the proton conductivity and drastically increase the ohmic overpotential. To create balance, there is need for incorporation of water retention fillers in the electrolyte membrane such as TiO_2, SiO_2, ZrO_2 and heteropolyacids

which are both hygroscopic and proton conductors. Functionalized one-dimensional carbon nanotubes can also be incorporated into the Nafion membrane to improve the membrane performance operated under low relative humidity and dry conditions [22, 23].

2.4. Surface modification through coating

By definition, coating is a covering that can be applied to the surface of substrate for enhancement, functional, and modification purposes. The major purpose of coating on bipolar plate is to serve as corrosion resistance interface between the substrate and the environment, thereby reducing or eliminating the interfacial contact resistance that affects the overall power output of the fuel cell. They impact special surface properties of hardness, wear control, corrosion, and oxidation resistance without changing the substrate bulk properties. Therefore, improves surface properties.

Coating is mostly needed for application of metallic bipolar plates because of the possible interaction with the stringent acidic fuel cell environments that affects its overall performance. Oxide formation and ion dissolution as a result of metal bipolar plates can be prevented by applications of various coatings. Metallic bipolar plates[24, 25] are often coated with protective coating layers which serve as a barrier between its substrate and the corrosive media thereby preventing corrosion. The coating must be able to satisfy the following important criteria:

- It must have good adhesion to the substrate material without exposing its corrosive media. Proper adhesion of coating to the substrate is achieved by selecting coating materials with thermal expansion coefficients similar to those of the chosen bipolar plate's material to minimize micro- and macro-crack formation.

- It must be impermeable to the fuel cell reactant gases.

- It must be chemically stable or inert and give low contact resistance.

- It must be conductive so as to enhance electron conduction through it to the external circuit.

In the absence of corrosion, there will be no formation of metallic ions poisoning the membrane assembly electrode and reducing its potency for proton transport. Formation of oxide films in stainless steel as a self-protection against progression of corrosion that eventually result into high surface contact resistance will also be eliminated.

Two types of coatings[26–29] that have been investigated over the years as suitable candidates for bipolar plates are as follows:

- Carbon-based coatings: includes conductive polymer, graphite, diamond-like carbon, and organic self-assembled monopolymers.

- Metal-based coatings: comprises metal nitrides, metal carbides, metal oxides, and noble metals like gold, platinum, and ruthenium.

The investigation of metallic bipolar plates is divided into two major parts:

- Stainless steel and their coatings

• Aluminum, nickel, and other non-ferrous alloys and their coatings

2.5. Stainless steel and their coatings

Bare or uncoated stainless steel cannot satisfy DOE criteria for bipolar plate. There are three types of stainless steel with varying chromium contents: austenitic (AISI SS300)[30] has 18–20% Cr, ferritic (AISI SS400)[31, 32] has 17% Cr, and martensitic Cr quantities ≥ 11.5%. Chromium acts to produce a thin layer oxide of Cr_2O_3 which gives it self-surface protection and stop progression of corrosion. The passive layer of the thick oxide film however increases interfacial contact resistance between the bipolar plates and the gas diffusion layers which amount to the overall voltage drop. As a result of this, majority of studies[33, 35] on bipolar plates use measurements of interfacial contact resistance as the main criteria for material suitability.

In the stainless steel group, austenitic stainless steel is the most corrosion resistant due to its high Ni composition coupled with substantial level of chromium that gives it a higher formability at all temperatures from the cryogenic region to the melting point of the alloy.

They are the largest produced stainless steel accounting for about 70%. As a result, the grades 316, 310, and 304 SS have been investigated by many researchers as suitable candidates to replace nonporous graphite bipolar plates.

The primary selection criterion for austenitic stainless steel bipolar plates is the Cr, N, and Mo content that comes in different compositions and therefore makes them to behave differently in various environments. Addition of Mo and N is intended to enhance crevice and pitting corrosion resistance. Nickel and chromium addition is to improve strength and high-temperature oxidation resistance.

Over the years, ferritic stainless steel has been considered as bipolar plate material due to its low nickel content that reduces the overall cost of the material and eliminates the potential problem of Ni ion contamination of the membrane.

2.6. Titanium and their coating

Titanium[33] has been investigated as a suitable material for bipolar plates because of its properties such as low density, good mechanical strength, and high corrosion resistance. Titanium can form an insulating oxide film such as stainless steel. This surface passive film formed significantly increases ohmic losses with the stack resulting in lower power output compared to uncoated 316 SS. To tackle these challenges, further studies on titanium alloys with niobium and tantalum as viable bipolar plate materials showed that the resistivity of their surface oxides were lower than that of pure Ti. It was also found out that INEOS CHLOR patent PEMcoat™ coated on titanium offered an interfacial contact resistance similar to graphite.

2.7. Aluminum and their coating

In terms of cost and density, aluminum offers a better substitute compared to other bipolar plate materials. It also has an inherent problem of developing an oxide film like stainless steel

and titanium. This reduces its surface conductivity and rendered it incompetent as bipolar plate material except used in combination with other metals or with suitable coating blend.

2.8. Nickel and their coatings

Nickel is comparatively inexpensive, and it exhibits good ductility and ease of manufacturing. Pure nickel does not form protective oxide layer like other known bipolar plate materials but is very susceptible to severe corrosion. Therefore, there is need for alloying it with chromium to be very stable at minimum corrosion rate and low electrical resistivity compared to stainless steel alloys.

2.9. Copper and their coatings

Copper emerges as the only bipolar plate material with the highest possible electrical and thermal conductivity. Studies have shown that in a stimulated PEMFC environment, copper beryllium alloy Ce17200 has a corrosion rate of approximately 0.28 μm year at 70°C.

Materials such as Al, Cu, Sn, Ni, and Ni-phosphorous are very susceptible to electrochemical corrosion in acidic solutions that are typical of PEMFC operating conditions. However, gold shows very high resistance to electrochemical corrosion, in comparison to graphite, the traditional bipolar plate material.

In order for its multifunctional roles to be actualized, its material requirement has to be one of excellent electrical and thermal conductivity, good gas permeability, high mechanical strength, high corrosion resistance, and low weight. Having all these required properties locked up in a single material has ever been a challenge facing the research and development community on bipolar plates. As a result, different materials suited for different applications for bipolar plates such as metal, coated metal, graphite, flexible graphite, carbon–carbon composite, and carbon–polymer composites have been adopted over the years. None of these has been able to fulfill at once all the performance requirements and targets set by the US Department of Energy for fuel cell.

3. Electrochemical methods of applying coatings on metals

Techniques here include electrophoretic deposition, electrospray, electrodeposition, and electroless deposition.

3.1. Electrodeposition

This is a technique of using electrochemical processes to apply metallic coatings on metals or other conducting surfaces. Electrodeposition is done for the following purposes:

- Impartation of special surface properties like harness for wear control, toughness for tribology control, surface roughness for frictional control

- Protection and barrier intermediary between a material and the environments of influence

- Appearance as seen in aesthetic outlook and beautification of materials

- Engineering or mechanical properties

Electrodeposition works on the principle of electrolysis. Electroplating utilizes electrolytic cell setup whereby plating metal (anode) and metal to be plated (cathode) are inserted in plating bath containing the solution of a salt of the metal that is to form the coating. The object to be coated is connected to the negative terminal of an electric battery as cathode while the plating metal is connected to the positive terminal of the electric power source as anode. As the electroplating process continues, the metal salts in the bath are used up. If the anode is a bar of the coating metal, the bar dissolves in the bath at the same rate that the bath gives up its metal to the cathode. If the anode is made of another metal, salts of the coating metal must be added to the bath as metal becomes deposited on the cathode. The longer the process continues, the greater the thickness of the coating on the cathode.

3.2. Electroless deposition

Electroless deposition is mainly different from electroplating by not using external electrical power. It is purely chemical or autocatalytic plating that involves a reaction whereby hydrogen is released by reducing agent, normally sodium hypophosphite or thiourea and becomes oxidized, thus producing a negative charge on the surface of the part. The most common electroless plating method is electroless nickel plating, although silver, gold, and copper layers can also be applied in this manner, as in the technique of Angel gilding.

Electroless nickel plating, according to several studies, is a suitable method of coating metallic bipolar plates. Electroless nickel plating layers are known to provide extreme surface adhesion when plated properly.

3.3. Existing literature review on coating of bipolar plates of fuel cell

Corrosion resistance has always been the ultimate goal for bipolar plate of fuel cell. Actualizing this through correct application of surface barrier coating will minimize interfacial contact resistance of the fuel cell. Using electrochemical method TiN has been successfully coated on stainless steel 316L bipolar plate for proton-exchange membrane fuel cell [36]. The result of investigation showed that the TiN-coated 316L exhibits promising interfacial contact resistance and improved corrosion resistance in simulated aggressive PEMFC environments. Slight increase in the ICR was also observed after the potentiostatic polarization. This was due to the formation of stable passive film on the surface of the TiN-coated 316L.

Composite coatings are an excellent corrosion inhibitor and can be suitably formed through electrodeposition. To gain high hardness, good thermal stability, and corrosion resistance, multicomponent TiAlSiN coating has been developed by Li and colleagues using different deposition methods [37]. The authors demonstrated the influence of Al and Si on the electro-chemical properties of TiN-coated 316L stainless steel bipolar plate in simulated PEMFC environment. The corrosion inhibiting efficiency was improved by incorporation of the Al and Si in TiN coating.

According to research conducted by Nam and colleagues, electroplating Cr-C coatings on SS304 offers an excellent conductivity and corrosion resistance [38]. The deposition was done under different current densities, and it was discovered that carbon content of the composite coating decreased with increasing current density. The surface roughness of Cr-C plated at current density of was observed to be smooth and crack-free. In addition, the lowest contact resistance was recorded at this value. Beyond this current density was formation of cracks and pinholes in the coating network.

A novel epoxy resin (EP)-based system containing polyaniline (PANI) was developed in the research work carried out by Baldissera and Ferreira [39] The PANI serves as an anticorrosive agent to monitor corrosion behavior of mild steel samples. It was found out that the addition of three different forms of PANI-undoped, sulfonated, and fibers to the epoxy resin increased its corrosion protection capacity. Based on the good outcomes, paints prepared with EP and PANI is able to be used as protective coating to metals even when exposed to aggressive marine environment.

In the study conducted by Hung et al. (2009) [40], coated aluminum and graphite composite bipolar plates were installed in separate single PEM fuel cells and tested under normal operating conditions and cyclic loading. After 1000 hours of operation, samples of both the bipolar plates and the membrane electrode assembly (MEA) were collected and characterized. The purpose was to examine the stability and integrity of the plate's coating and evaluate possible changes of the ionic conductivity of the membrane. The SEM/EDX analysis showed very small variation in the surface composition of the coated aluminum bipolar plate after 1000 hours of operation. Chromium was observed in one of the three cathode samples of the MEA. However, it was confirmed that the released Cr did not react with Pt. The microcracks that were observed in the corrosion resistance coating did not seem to completely penetrate through the substrate layer. Aluminum was also detected in the GDLs that were used in both coated aluminum and graphite composite fuel cell which is believed to come from aluminum oxide carried by the reactant gases from the uncoated back plate and gas manifold.

Conducting polymers as a new type of material have high redox potential complimented with properties of both metals and polymers. Polypyrrole coatings have gained outstanding recognition over the years as one of the most important conductive polymers successfully used in fuel cells, chemical sensors, batteries, anti-corrosion coatings, and drug delivery systems. Graphite-polypyrrole has been successfully coated on SS316L substrate as the bipolar plate for polymer electrolyte membrane electrode [41]. Synergy of graphite and polypyrrole as composite imparts good surface barrier and conductive properties. The polypyrrole enhances good corrosion resistance and electrical conductivity. The graphite further improves the electrical conductivity of the bipolar plate.

4. Summary

It has been shown that metallic bipolar plates are prone to corrosion attack in the fuel cell environment. In addition, the use of precious noble metals is not economical in meeting the

future cost projection of fuel cells to successfully compete with combustion engine vehicles. Though noble metals offer excellent conductivity and good corrosion resistance, they are phased out as viable bipolar plate materials over difficulty in forming them into thin strips. Composite-based bipolar plates are known for brittleness which in the long run may easily fail in operation of the fuel cell.

Metallic bipolar plates were proven to surpass the mechanical strength of graphite composite plates as well as giving acceptable electrical conductivity with minimal production cost on commercial scale. As indicated earlier, metallic plates are prone to corrosion in the fuel cell environment. Considerable research work has been conducted to enhance the material's corrosion resistance and interfacial contact resistance. It is concluded that metallic bipolar plates hold a promising potential as more research and development studies progress on its surface modification through different functional coatings.

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