Performance Optimizing Strategies For PEMFC And Electrode Materials

Yixian Yang [1, *, #], Xinyu Lou [2, #], Gewangcairang Ge [3, #]

[1] School of Materials Science Engineering, Changchun University of Technology, Changchun, China, 130012

[2] School of New Energy and Materials, SouthWest Petroleum University, Chengdu, China, 610599

[3] School of Materials Science and Engineering, Lanzhou University of Technology, Lanzhou, China, 730050

* Corresponding Author Email: yang78yi90xian@foxmail.com

[#]These authors contributed equally.

Abstract. Traditional fossil fuel-based power generation methods suffer from various drawbacks including high pollution, energy consumption, and so on. Metal bipolar plates are essential for corrosion resistance, excellent mechanical properties, high conductivity, and impermeability, and this makes them typically produced through stamping. The performance of Proton Exchange Membrane Fuel Cell electrode materials can be improved via the use of different welding methods and coating technologies. Welding techniques, such as thermo-elastic-plastic simulation, can be used to control the heat input, laser overlay welding, and protection gas-enhanced joint strength, and thus improving the welding quality and efficiency of fuel cells. Based on the implementation of ZrC coating modified Ti bipolar plates in proton exchange membrane fuel cells, the battery's lifespan experiences an increase of approximately 1.5 times, while performance sees enhancements of over 30%. Metal carbon-based coatings and metal nitride coatings come with long-lasting protection for metal plates, accompanied by good conductivity, corrosion resistance, and strong adhesion. In the future, these technologies hold promise for applications in renewable energy and contribute to sustainable development.

Keywords: PEMFC, Bipolar Plate, Surface Modification, Welding Technique.

1. Introduction

Recently, traditional fossil fuel power generation methods had many disadvantages, including high pollution, high energy consumption, and the growth of non-renewable resource consumption and the lack of renewable resources. With a high energy density and environmental friendliness, many new energy sources, such as fuel cells, are typically characterized by an abundant source of renewable energy. Fuel cells, as a form of new energy, contribute to the reduction of greenhouse gas emissions, operate quietly, and efficiently convert energy, thereby playing a pivotal role in fostering a sustainable and clean energy economy.

Fuel cells, with their capability to directly transform chemical energy into electrical energy, offer a host of benefits including high energy density, zero emissions, and high efficiency. Fuel cells can be broadly classified into proton exchange membrane fuel cells (PEMFC), solid oxide fuel cells, alkaline fuel cells, molten carbonate fuel cells and so on. The principle behind fuel cells involves the oxidation of fuel, resulting in the production of electrons. This process generates an electric current in the external circuit, converting chemical energy into electrical energy, and simultaneously producing water and heat. However, conventional fuel cells suffer from drawbacks such as high costs, limited catalyst availability, low durability, and stability issues. Thus, enhancing fuel cell performance is crucial.

Fuel cell bipolar plates need to have extreme corrosion resistance, excellent mechanical properties, high electrical conductivity, and impermeability [1]. The main production method of metal bipolar plates is press forming [2], and metal bipolar plates with higher mechanical properties, electrical conductivity and machinability can help to achieve high-precision and high-complexity flow field design and preparation. The smaller heat capacity of metal bipolar plates and their light weight and small size make the thermal conductivity faster [3]. It effectively improves the cold-start performance of power stacks. For example, MS-SOFCs have low material cost, high strength, and heat cycle resistance [4]. The low cost of metals facilitates mass production and fabrication of thin plates. Metal bipolar plates play an important role in fuel cells as conductive, catalytic and heat dissipation and improve the efficiency of fuel cells. It meets the requirements of commercial applications with high mechanical properties, good processability and abundant reserves, and practical applications with excellent electrical. The use of metals can effectively control the thickness of bipolar plates. This way reduces the mass and volume of the PEMFC, contributing to the improvement of the power density of the cell and mass transfer performance of PEMFC in the field of mobile power supply [5].

Therefore, this paper summaries PEMFC bipolar plates to improve their performance and efficiency, and it mainly relies on advancements in two primary areas. First, surface modification techniques address the vulnerability of metal bipolar plates to oxidation. This challenge is exacerbated by the high temperature and acidic conditions within fuel cells. Techniques like DC magnetron sputtering or plasma surface modification deposit uniform and dense a-C films on stainless steel substrates. Secondly, advanced welding techniques, such as pulsed laser welding, address issues of deformation and weld quality in battery bipolar plates. These advancements in surface modification and welding techniques signify significant progress in improving the performance and longevity of PEMFC. Moreover, broadening the utilization of metal bipolar plates in various domains could further contribute to the achievement of sustainable development goals.

2. Surface modification

Metal bipolar plates, as the core building blocks of a PEMFC, directly determine the manufacturing cost and performance of the cell. Nevertheless, when exposed to the elevated temperatures and acidic conditions within fuel cells, the surfaces of metal bipolar plates are prone to oxidation. This leading to a significant decline in conductivity and corrosion resistance characteristics. Presently the main solution is the surface modification of the metal bipolar plate. This ensures the metal bipolar plate’s optimal performance while enhancing its conductivity, corrosion resistance, and other attributes.

Li et al. [6] deposited a uniform and dense amorphous carbon (a-C) film on 316L stainless steel using DC magnetron sputtering deposition technique and adjusted the composition and structure of the a-C film by changing the sputtering power. Then, the composition, microstructure, interfacial contact resistance and corrosion resistance of a-C films were systematically investigated in Figure 1. (a-b). Under PEMFC simulated environmental conditions, all a-C films significantly improve the performance of 316L stainless steel. The a-C film deposited at 0.9 KW sputtering power has the best performance with the lowest corrosion current density of 7.52×10^{-3} $\mu A\cdot cm^{-2}$ and has the smallest interfacial contact resistance of 2.91×10^{-3} $\Omega\cdot cm^2$ and 4.00×10^{-3} $\Omega\cdot cm^2$ before and after the test in Figure 1. (c-d). Corrosion resistance was significantly improved and exceeded DOE 2025 bipolar plate performance specifications. Li et al. [7] deposited amorphous carbon (a-C) films with different Ti doping levels on SS316L substrates by DC balanced magnetron sputtering technique. The effect of Ti doping on the electrical conductivity and corrosion resistance of a-C films was investigated. The increase of Ti doping can promote the sp^2 hybridization rate of a-C films, and the doped Ti atoms can also form a low-resistivity TiC phase with carbon, decreasing the ICR of a-C films from 5.64×10^{-3} $\Omega\cdot cm^2$ to 3.47×10^{-3} $\Omega\cdot cm^2$. This improved performance of fuel cells.

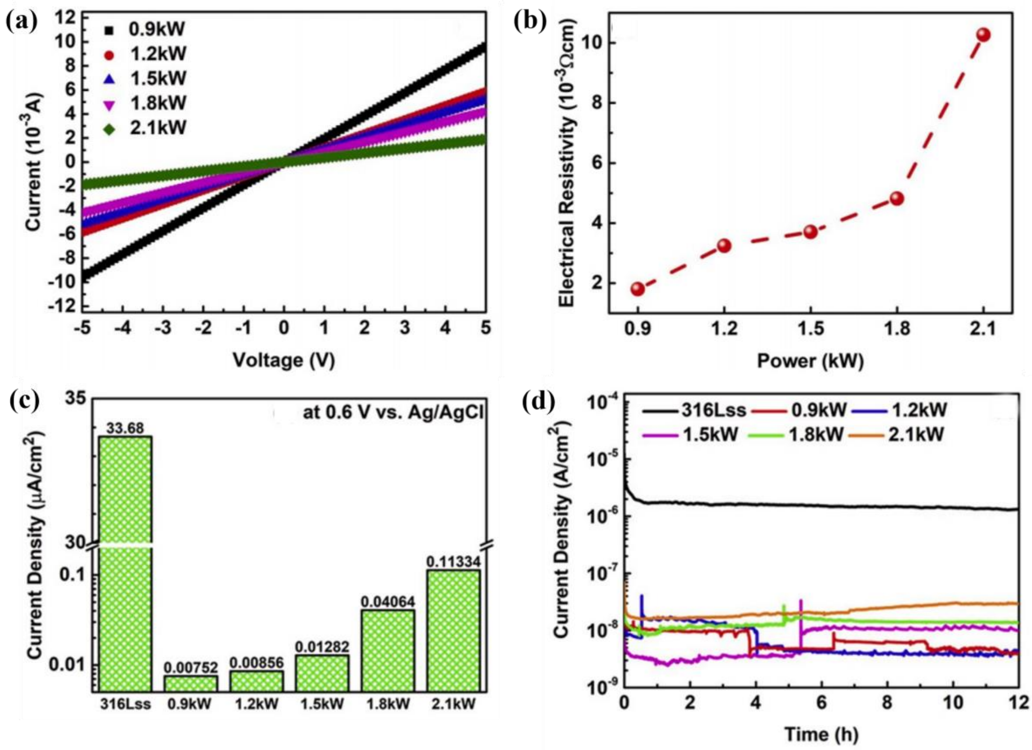

Figure 1. (a) I-V characteristics of a-C films; (b) Resistivity of a-C films; (c) Passivation current density of a-C films; (d) Prolonged constant potential of a-C films [6]

Zhang et al. [8] prepared smooth and dense zirconium carbide (ZrC) coatings on the surface of titanium bipolar plates by using the plasma surface modification technique. Potentiodynamic polarization and electrostatic potential polarization testing in a simulated PEMFC environment, and the corrosion current densities of the ZrC-coated titanium bipolar plates were reduced by 1-2 orders of magnitude compared with that of the bare titanium bipolar plates, as shown in Figure 2. (a-b). Under the compressive force of 140 $N\cdot CM^{-2}$, the interfacial contact resistance was reduced from 0.11 $\Omega\cdot cm^2$ to 0.0077 $\Omega\cdot cm^2$ in Figure 2. (c-d). And the ZrC coating significantly improved the corrosion resistance, electrical conductivity, and hydrophobicity of the titanium bipolar plates. Mani et al. [9] deposited dense, smooth and high contact angle TiN/TiAlN multilayer coatings on the surface of 316L stainless steel bipolar plates using physical vapor deposition (PVD) technique for better inhibition of water contact. The anodic and cathodic corrosion current densities obtained from constant potential polarization tests were approximately 0.40 $\mu A\cdot cm^{-2}$ and 0.73 $\mu A\cdot cm^{-2}$, respectively, as shown in Figure 3. (a-b). The interfacial contact resistance has also been significantly reduced to 0.006 $\Omega\cdot cm^2$, successfully meeting the DOE 2025 performance specification. Chen et al. [10] firstly used polydopamine (PDA) to surface functionalize the carbon powder to obtain C-PDA powders, and then introduced PPY/C-PDA coatings on the surface of 304 stainless steel bipolar plates. PPY/C-PDA coatings provide excellent physical barrier properties, anodic protection and adhesion strength. The bipolar plates with PPY/C-PDA coatings showed a long-term corrosion resistance of 720 h in a simulated PEMFC environment. After the 720 h long term corrosion test, the PPY/C-PDA coated bipolar plates still showed a corrosion resistance of 0.017 $\Omega\cdot cm^2$. Interfacial contact resistance of the bare 304 stainless steel bipolar plate was 0.118 $\Omega\cdot cm^2$. Like metal coatings, multilayer coatings can be applied for improving the performance of metal bipolar plates.

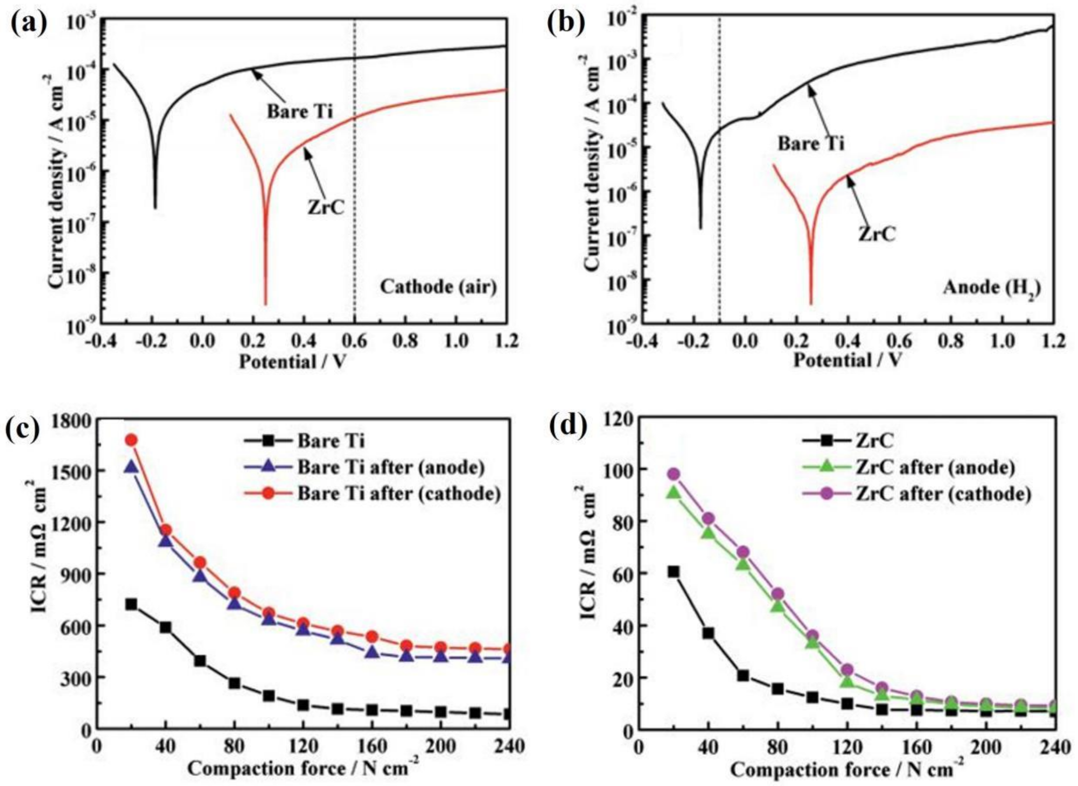

Figure 2. (a) Potentiodynamic polarization curves of ZrC-coated Ti and bare Ti bipolar plates; (b) Potentiodynamic polarization curves of ZrC-coated Ti and bare Ti bipolar plates; (c) ICR of bare Ti plates before and after simulated PEMFC potentiodynamic polarization; (d) ICR of ZrC-coated Ti plates before and after simulated PEMFC potentiodynamic polarization [8]

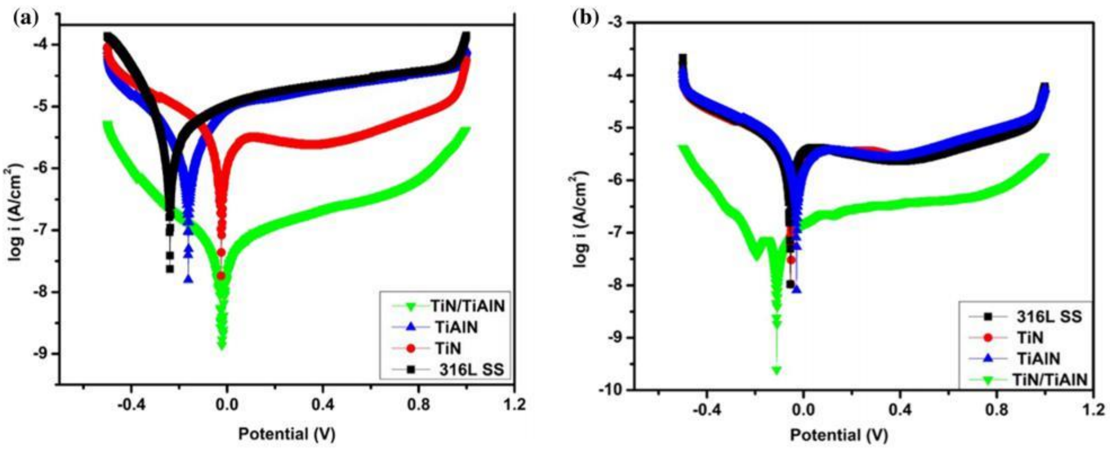

Figure 3. (a) Anode potential polarization diagram of TiN/TiAlN coating materials; (b) Cathodic Potential Polarization Diagram of TiN/TiAlN coating materials [9]

Carbon-based coatings can provide effective, long-term protection for metal electrode plates and can effectively improve the performance of bipolar plates. Carbon-based coatings are easy to prepare and come from a wide variety of sources. This can effectively reduce production costs. Then, Metal nitrides and metal carbides are chemically stable and good conductors of thermoelectricity, exhibiting good electrical conductivity, good corrosion resistance and strong film-based bonding with the metal plate. This has led to a wide range of metal nitride and metal carbide coatings being extensively studied and used for surface modification of polar plates.

3. Welding technique

The battery bipolar plates can usually be welded by laser welding process. But the laser welding process also suffers from deformation and lack of weld quality. Therefore, improving the welding process of battery bipolar plates is important for the stability and duration of the battery system.

Hailaing Xua et al. [11] welded ultra-thin 316 stainless steel plate by pulsed laser welding. Ultra-thin metal structures are prone to large welding deformation after welding, and power density, heat source parameters, welding speed and constraints are the main factors affecting welding deformation. The 3D finite element model, heat source modeling, z-direction of the deformations in experimental results are shown in Figure 4. (a-c), respectively. The relationship between weld and performance was obtained to be nonlinear and the parameters of the molten pool were optimized at welding power 0.84, molten pool parameters a, b and c were 0.15,0.35,0.02 (mm) respectively. The simulated temperature profile of the weld seam cross-section, the melt pool geometry of the weld head and the temperature history during the thermal cycle of the welding process are in good agreement with the experimental results. Experiments on laser welding with shielding gas by Lu Bingbing, Dong Liang et al. [12] in Figure 4. (d). As the laser welding power increases and the amount of defocus decreases, the weld melt width and melt depth show an increasing trend, and the weld strength increases by more than 20%. The shielding gas improves the quality of the weld in the welding process and increases the weld life. S.Y. Wang,H. Yang,Y. Wang et al. [13] added tooling to laser welding in simulation.

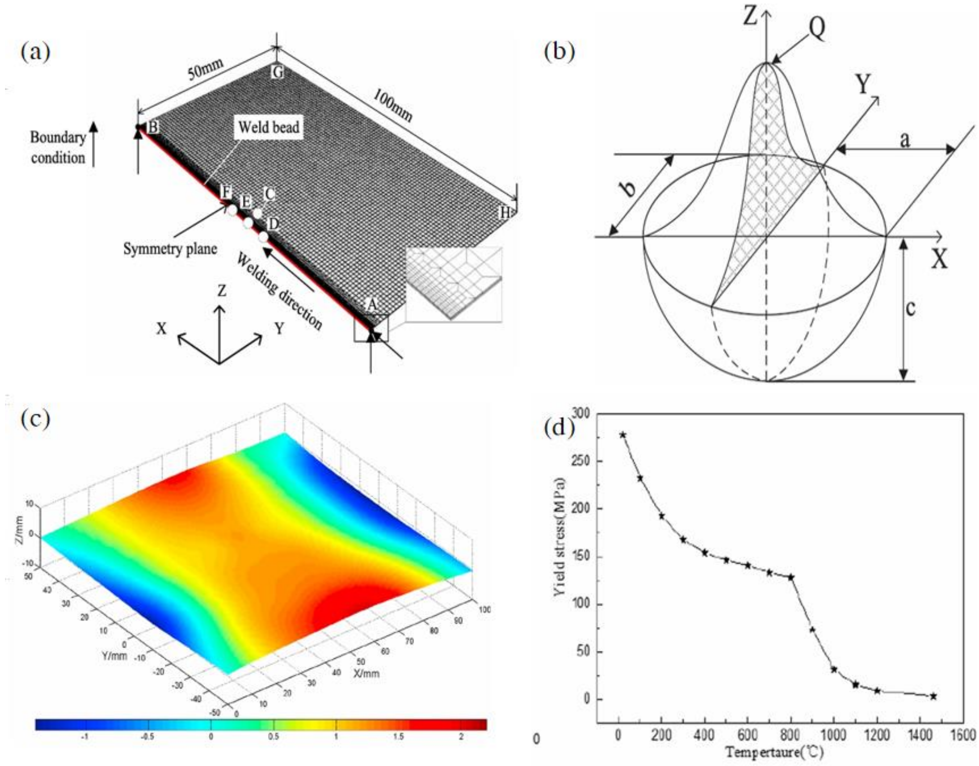

Figure 4. (a)Finite element model; (b)Heat source model; (c) Deformations in the z-direction; (d) Temperature dependent properties of the 316 stainless steels [11]

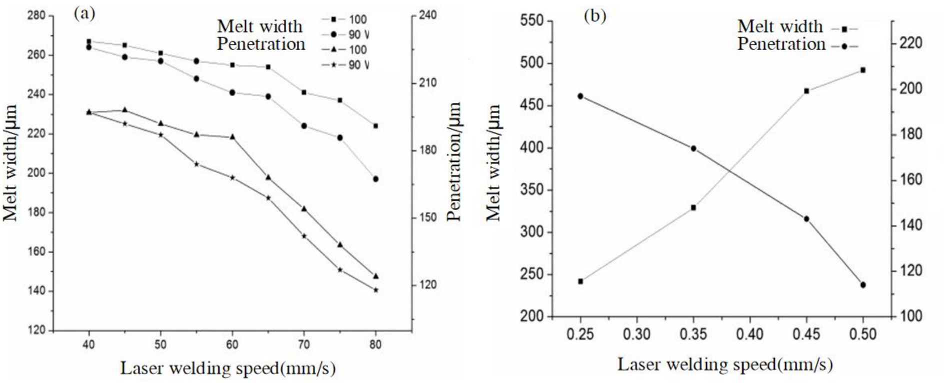

Figure 5. (a) Penetration depth and width with welding speed of 316L stainless steel plate; (b) Penetration depth and width with welding element of 316L stainless steel plate [13]

The problems in laser welding of bipolar plates, false welds and heat accumulation at the arc, were effectively solved. The sealing of the bipolar plate after welding is good. The weld yield increased from 40% to 90%, compared with the original direct contact and arc welding methods in Figure 5. (a). With the increase of laser welding speed, the melt depth and melt width produced by both 90 W and 100 W welding power showed a decreasing trend. In particular, the decrease in depth and width of melt is significantly accelerated at welding speeds of 60 mm/s or more. This is mainly because the residence time of laser on the plate is reduced and fails to fully melt the material. At the same welding speed, because the heat input of 100 W is greater than that of 90 W, the depth and width of melt are correspondingly greater. In addition, on keeping the welding speed and power constant. With the increase in the diameter of the welding pattern element, the melt width of the plate increases and the depth of melt decreases. This is due to the decrease in laser energy per unit area and the difficulty in completely penetrating the sheet metal. Based on the analysis in Figure 5. (b), the quality of the weld decreases, burrs and divergence appear, and the overall weld becomes less smooth, as the welding pixel increases. In short, the laser welding speed, power, and element size have a marked effect on the depth of fusion, width of fusion, and quality of the weld. The welding of stainless-steel materials using a high beam quality quasi-continuous wave (QCW) green laser source was investigated by E. Haddad1 et al. [14]. And in addition, the effect of wavelength and spot diameter on the welding process was specifically investigated. Halving the laser wavelength from 1064 nm to 532 nm increased the weld depth and reduced the weld width and 50% of the spot diameter. The trend of bipolar plate flow channel design is getting narrower and narrower, and E. Haddad1 et al. obtained four parameter sets suitable for welding in a narrow channel with a width of less than 75μm through a lot of experiments: " f200-300 W-1400 mm/s; f200-300 W-1600 mm/s; f200-300 W-1800 mm/s and f200-400 W-2000 mm/s", and concluded a welding speed of more than 600 mm/s will appear hump phenomenon.

Therefore, the pulsed laser welding process can improve the ability of bipolar plates to resist deformation. In addition, the laser beam QCW welding process can effectively improve the deformation resistance and penetration depth of the weld seam. Moreover, the application of shielding gas to weld can effectively increase the weld life, and adding fixtures can efficiently solve the problem of heat accumulation in the weld and increase the weld yield, just increasing costs.

4. Conclusions

In summarize, PEMFC are seen as a potential alternative energy technology, and they can reduce reliance on fossil fuels, decrease greenhouse gas emissions, and improve environmental quality. Amorphous carbon (a-C) films and ZrC coatings improve conductivity, corrosion resistance, and interfacial contact. Pulsed laser welding and shielding gas integration address deformation and weld quality issues. Parameters optimization minimizes deformation in stainless steel plates. Shielding gas enhances weld strength and quality. By addressing key challenges such as corrosion and weldingrelated deformations, these strategies contribute to the advancement of PEMFC technology, fostering its broader adoption for sustainable electricity generation.

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