Original Research Article

Review of Proton Exchange Membrane Fuel Cell (PEMFC) Bipolar Plate Forming Methods: Comparison of Performance, Scalability and Cost

Abstract

Bipolar plates are pivotal components in proton exchange membrane fuel cells (PEMFCs), performing current collection, reactant distribution, heat management, and stack structural support. Their material choice and manufacturing route strongly influence cell efficiency, durability, and cost. Traditional stamping of metallic plates has dominated high-volume production due to speed and low unit cost but struggles with complex microchannel geometries, springback, and surface integrity. Emerging techniques—hydroforming, incremental and hot forming, and additive manufacturing—promise improved geometric freedom, reduced tooling needs, and integration of functions, yet each introduces trade-offs in material thinning, electrical and corrosion performance, cycle time, and scalability. Coating and surface treatments further complicate process chains but are essential to meet conductivity and corrosion resistance targets. As PEMFCs transition from niche applications to automotive and stationary power markets, optimizing forming methods to balance manufacturability, performance, and lifecycle cost is critical. This study situates comparative analysis of forming methods within that imperative, aiming to guide material-process selections that advance commercial viability and long-term durability of PEMFC bipolar plates.

Proton Exchange Membrane Fuel Cells (PEMFCs) rely critically on the performance and manufacturability of bipolar plates, which serve multiple functions including current collection, gas distribution, thermal management, and mechanical Support. This paper presents a comprehensive comparative study of multiple forming methods for manufacturing bipolar plates, synthesizing current knowledge on stamping, hydroforming, and additive as well as hybrid manufacturing approaches. Each method is examined through the lenses of formability, dimensional accuracy, surface quality, mechanical robustness, electrical conductivity, corrosion resistance, and production cost. Stamping remains the industrial benchmark due to its high throughput and established toolsets; however, it faces limitations in achieving complex three-dimensional flow field geometries without compromising precision or inducing springback.

Hydroforming offers superior capability for producing intricate, smooth internal channels and reducing tooling complexity for certain geometries, but it introduces challenges in process control, material thinning, and cycle time that affect scalability. Additive manufacturing enables unprecedented geometric freedom and rapid design iteration, facilitating integrated features and lightweighting, yet it presently encounters hurdles in achieving the electrical and surface properties required for long-term PEMFC operation and in meeting mass-production speed and cost targets. Hybrid strategies—combining forming, machining, and surface-treatment steps—emerge as promising compromises that leverage the strengths of each approach to tailor bipolar plates for specific application regimes, from automotive-scale high-volume production to bespoke research devices.

The comparative assessment integrates technical performance metrics with economic and environmental considerations, highlighting trade-offs between manufacturing complexity, material utilization, and lifecycle impacts. Critical factors such as material selection (graphite, coated metals, composite materials), coating strategies to mitigate corrosion and contact resistance, and post-processing treatments (e.g., plating, heat treatment, machining) are woven into the evaluation of forming routes. The analysis identifies gaps in current knowledge—most notably the need for standardized test protocols to evaluate formed plate performance under realistic operating conditions, and further development of surface treatments compatible with additive and hydroformed substrates. The paper concludes by outlining future research directions: advancing high-rate additive processes with improved material properties, optimizing hydroforming process windows for minimal thinning and maximal repeatability, and developing economically viable hybrid production chains. Collectively, these advances can lower costs, improve durability, and accelerate adoption of PEMFC technologies across transportation and stationary power sectors.

Keywords: PEMFC, bipolar plates, stamping, hydroforming, additive manufacturing, hybrid manufacturing, formability, corrosion resistance, contact resistance, production cost.

1 Introduction

Proton exchange membrane fuel cells (PEMFCs) have emerged as a promising clean energy technology over the past decades, driven by their high power density, low operating temperature, and rapid start-up characteristics. Xu investigated advanced forming techniques for metallic plates, emphasizing the demand for precise microchannel fabrication to enhance mass transport and overall cell performance, which reflects broader trends in improving component-level manufacturability for PEMFC systems . Aklima examined the corrosion behavior of pure aluminum in PEMFC environments and highlighted the critical importance of material compatibility and surface protection to ensure long-term durability, underscoring that materials selection is as pivotal as design in enabling reliable operation . Yu studied the corrosion response of stainless steel 316L under varying test conditions, demonstrating how environmental factors and testing protocols influence perceived material performance and calling for standardized evaluation methods to compare candidate bipolar plate materials reliably. Complementing these material-focused studies, Xi explored novel flow field geometries, showing that thoughtful channel design can improve reactant distribution and electrochemical performance, thereby motivating forming methods capable of producing complex three-dimensional features. Together, these works illustrate the intertwined challenges of materials, manufacturing, and design that define the current landscape of PEMFC technology development.

1.1 Role of Bipolar Plates in PEMFC Systems

Bipolar plates perform several indispensable functions within PEMFC systems, acting as the structural backbone that supports membrane-electrode assemblies while providing pathways for reactant gases and cooled heat removal; Ho-Seong and Seong-Jong emphasize that surface treatments such as plasma ion nitriding can substantially influence the plates' electrochemical behavior and interfacial contact resistance, directly affecting overall cell performance and durability. Effective bipolar plate design must therefore balance electrical conductivity, mechanical strength, and corrosion resistance so that current collection is efficient and parasitic losses are minimized; Xiaoming highlight how mechanical sealing and stress relaxation in metal bipolar plate assemblies can drive leakage mechanisms, underlining the importance of robust structural and sealing strategies in maintaining long-term system integrity. Surface modification and material selection are also critical to controlling electrochemical degradation and maintaining surface conductivity under operating conditions; Shi report that carbide-based surface modifications on titanium can improve both electrochemical stability and surface conductivity, suggesting pathways to extend plate lifetime while preserving electrical performance. Additionally, ion implantation and other advanced surface treatments can tailor near-surface properties to reduce corrosion and contact resistance without compromising bulk mechanical properties, as demonstrated by Kim in studies of N+ implantation on 316L stainless steel, which show notable changes in surface characteristics relevant to PEMFC bipolar plate applications. Together, these findings indicate that the role of bipolar plates extends beyond simple gas distribution and current conduction to encompass engineered surface and structural solutions that are central to fuel cell efficiency, durability, and manufacturability.Proton exchange membrane fuel cell structure diagram as shown in Fig.1.

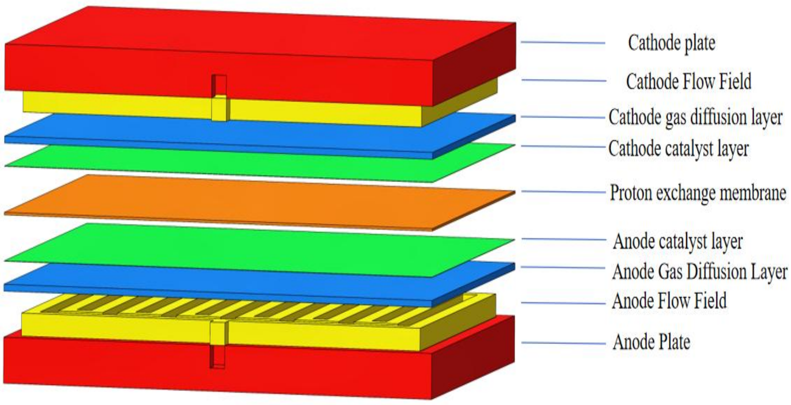

Fig.1 Proton exchange membrane fuel cell structure diagram

1.2 Research Objectives and Scope

This paper aims to provide a focused and actionable comparison of prominent forming methods for PEMFC bipolar plates, synthesizing recent advances in coating, design, and process optimization to inform both researchers and industry practitioners. The objectives are threefold: first, to summarize material and coating developments that influence bipolar plate performance and longevity, drawing on recent studies of electrodeposited composite coatings and plasma-based surface treatments that demonstrate routes to lower contact resistance and enhance corrosion protection; second, to evaluate forming process innovations—such as multistage forming with intermediate annealing and process parameter modeling—that have been proposed to produce fine flow-channel geometries in difficult-to-form materials like titanium while controlling defects and dimensional accuracy; and third, to articulate practical scope boundaries by identifying which performance metrics (electrochemical stability, mechanical integrity, manufacturability, and cost scalability) are compared and which application sectors (automotive high-volume production versus specialized stationary systems) are emphasized. Through this scope, the paper concentrates on process–material–surface interactions that dictate real-world bipolar plate behavior, highlights where empirical evidence currently supports specific forming choices, and identifies gaps where further experimental validation or standardized testing protocols are needed.

2 Materials and Design Requirements for Bipolar Plates

2.1 Material Selection Criteria

Material selection for bipolar plates is a critical determinant of PEMFC performance, durability, and manufacturability. Gongjin and Kai emphasize that material choice must reconcile competing demands: electrical conductivity for efficient current collection, chemical and electrochemical stability in the aggressive fuel cell environment, mechanical strength to withstand assembly pressures and deformation during forming, and compatibility with mass-production processes and coatings. Their work highlights how flow field design interacts with material properties, noting that softer or more ductile materials may facilitate complex channel forming but risk damage or increased contact resistance unless properly treated, whereas harder substrates offer dimensional stability at the expense of forming difficulty and potential brittleness . Additionally, the authors point out that cost and supply-chain considerations cannot be divorced from technical performance; economically viable materials that permit high-throughput forming and reliable surface treatment strategies are more likely to enable commercialization at scale .

2.2 Structural and Functional Design Requirements

Structural and functional design requirements for bipolar plates must reconcile competing demands of performance, manufacturability, and durability. Designers need to define gas flow field geometries that ensure uniform reactant distribution and effective water and heat management while minimizing pressure drop and parasitic losses; Gongjin and Kai emphasize that channel topology and dimensions strongly influence cell performance and that systematic optimization can yield measurable improvements in fuel utilization and power density. Material and structural choices also determine mechanical integrity under clamping loads and thermal cycling, as well as electrical conductivity and contact resistance at interfaces; Jie, Ruichuan, and Ningpan report that forming-induced residual stresses and geometric deviations from stamping processes can degrade sealing performance and increase the likelihood of failure, underscoring the need to control forming processes and incorporate allowances for springback and thickness variation in the plate design. Together, these perspectives imply that functional requirements—electrochemical compatibility, low interfacial resistance, effective thermal and water management, and sufficient mechanical robustness—must be integrated early with the selected forming process, so that channel designs, material selection, and tolerances are mutually compatible and achievable at the target production scale.

2.3 Performance Evaluation Standards

Performance evaluation standards for bipolar plates encompass a range of mechanical, electrical, and chemical metrics that collectively determine suitability for PEMFC applications. Nazasrenko emphasizes the necessity of rigorous and standardized measurement procedures to ensure consistency across comparative studies, arguing that without common processing and reporting protocols, drawing reliable conclusions about manufacturing methods is problematic. Bincontribute an application-focused perspective by demonstrating how composite formulations can be benchmarked through electrical conductivity and contact resistance tests aligned with operational humidity and temperature conditions, highlighting that material-level metrics must be correlated to in-cell performance to be meaningful. Jian extend this view to topologically complex plates produced by advanced forming techniques, showing that heat and mass transfer characterization under representative flow field geometries is essential for evaluating real-world performance beyond isolated property measurements . I. S. N. and colleagues illustrate the importance of testing bipolar plates within stack-like configurations to capture self-humidification and interaction effects that single-cell tests may miss, thereby advocating for multi-scale evaluation protocols that include transient and steady-state operation. Finally, Sharma argue for the inclusion of reproducibility and scalability indicators in performance standards, proposing that assessment frameworks should report not only peak properties but also statistical measures of variability and process throughput implications to inform manufacturing decisions. Together, these works support a comprehensive, standardized evaluation approach that integrates material characterization, in-cell testing, and manufacturing-relevant metrics to provide a robust basis for comparing bipolar plate forming methods.

3 **Overview of Bipolar Plate Forming Methods**

3.1 **Stamping Forming Methods**

Stamping remains the dominant industrial route for producing metallic bipolar plates due to its proven high throughput and compatibility with established sheet-metal production lines. Haodi investigated the robust design of stamping process parameters for metallic bipolar plates and demonstrated that careful optimization of blank-holder force, punch speed, and lubrication can substantially reduce defects such as wrinkling and tearing while improving dimensional repeatability, highlighting stamping's suitability for large-volume automotive applications . ÖZVAN and BOSTAN emphasized that surface quality and visual aesthetics, which are closely tied to die condition and forming strategy, play a critical role in downstream coating adhesion and sealing performance; their comparative assessment underscores the sensitivity of formed surfaces to process control and tooling maintenance in stamping operations. Ayu examined corrosion inhibition approaches for aluminum alloys and pointed out that the base material's response to chemical environments must be considered early in the forming-selection process because stamping-induced surface alterations can influence corrosion behavior and the effectiveness of subsequent protective treatments. Shadi and Ali discussed validation methodologies for predictive models and suggested that accurate, experimentally validated forming simulations are essential for transferring stamping process windows from lab to production without excessive trial-and-error, thereby reducing cost and time-to-market for bipolar plate designs formed by stamping .

3.2 **Hydroforming Techniques**

Hydroforming techniques offer a distinct pathway for producing bipolar plates with smooth, continuous channel geometries and reduced part count compared with traditional multi-piece assemblies. Kargar-Pishbijari demonstrated a hot metal gas forming variant tailored for metallic bipolar plates, highlighting the method's ability to generate fine microchannel features while maintaining acceptable wall integrity through careful control of temperature and gas pressure; their work underscores hydroforming's potential to realize complex flow fields without resorting to extensive machining. Complementing this process-focused perspective, Chen and Fei examined how variations in bipolar plate geometry influence overall PEMFC thermal and mass transport performance, implying that hydroforming's freedom to produce optimized, smooth channels can translate into measurable gains in cell cooling and reactant distribution when design and process parameters are jointly considered]. From a manufacturing methodology standpoint, Meilinda compared multiple synthesis and fabrication approaches in a different materials context but emphasized a broader lesson relevant to hydroforming: that process selection must weigh not only achievable geometries but also repeatability, parameter sensitivity, and scalability to ensure consistent product properties across production batches. While not directly addressing hydroforming, Riyaz provided a cautionary reminder about the importance of robust and standardized evaluation methods when introducing novel fabrication routes; their analysis of diagnostic techniques reinforces the need for standardized test protocols to validate hydroformed plates' functional properties such as channel fidelity, mechanical strength, and corrosion resistance under realistic operating conditions.Hydraulic forming diagram as shown in Fig.2.

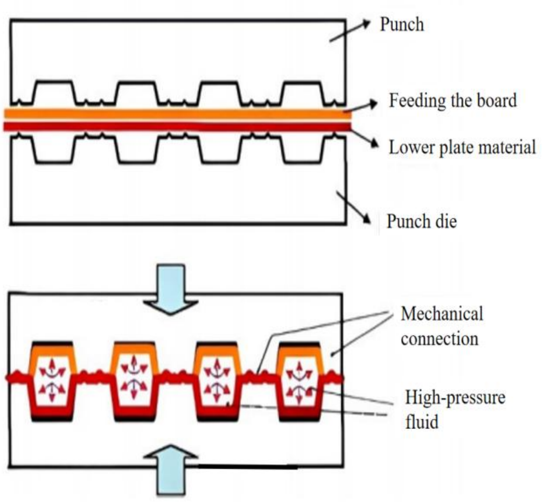

Fig.2 Hydraulic forming diagram

3.3 **Additive and Hybrid Manufacturing Approaches**

Additive manufacturing (AM) has emerged as a transformative option for bipolar plate production by enabling complex internal channel geometries, integrated features, and rapid design iteration that are difficult or impossible with traditional forming methods. Hassan discuss how advanced manufacturing techniques can exploit varied geometries and material distributions to optimize thermal and mass transport performance, suggesting that shape control at small scales—informed by computational design—can yield significant improvements in component-level heat and fluid management. Similarly, recent studies in image-driven and data-rich process optimization highlight how AM workflows benefit from machine learning–based defect detection and process control, enabling higher yields and consistent part quality as designers push toward finer, functionally graded structures. The capability of AM to address flow maldistribution through tailored channel topologies is echoed by Paweł , who compares methods for quantifying flow uniformity and underscores the potential for geometry-driven solutions to mitigate maldistribution in compact devices, an insight directly applicable to the design freedom offered by AM for bipolar plates. From a materials and functional-integration perspective, medical and bioengineering literature exemplifies the careful attention required when introducing new fabrication routes: studies on delivery methods and material distribution warn that changing manufacturing approaches can alter functional performance and biological compatibility, implying that AM-produced bipolar plates will likewise need rigorous validation to ensure stable electrochemical and mechanical behavior under operating conditions. Finally, sensors and condition-monitoring research emphasize the value of combining novel detection and control strategies with new manufacturing techniques; such hybrid approaches—where AM is combined with secondary machining, coatings, or embedded sensing—can address current AM limitations in surface finish, conductivity, and corrosion resistance while enabling smart, application-specific bipolar plate solution. Together, these perspectives support a view of additive and hybrid manufacturing as promising but still evolving strategies that require integrated design, process control, and post-processing to meet the stringent functional and durability demands of PEMFC bipolar plates.

4 **Comparative Analysis of Forming Methods**

4.1 **Formability and Dimensional Accuracy**

Formability and dimensional accuracy are fundamental considerations when selecting a manufacturing route for bipolar plates, as they directly influence the fidelity of flow field geometries, sealing interfaces, and overall stack performance. Recent studies have highlighted that the choice of material and forming process must balance the ability to produce intricate channel patterns with the need to maintain tight tolerances; for instance, Li emphasize that metallic bipolar plates designed for air-cooled PEMFC stacks demand precise channel geometries to ensure uniform cooling and effective stack integration, underscoring the importance of processes that deliver high dimensional control. Investigations into surface treatments and coatings reveal that deposition parameters can affect not only electrochemical properties but also the dimensional outcomes of formed plates, where variations in coating stress and thickness may alter surface profiles and mating surfaces after processing. Beyond electrochemical considerations, mechanical impact studies demonstrate that plate thickness and material behavior under load influence the susceptibility to local deformation and perforation during manufacturing and service; Turgut shows that penetrator-target interactions depend strongly on plate properties, implying that forming methods must mitigate risks of local damage while preserving dimensional integrity. Finally, thermal management analyses point out that the thermal resistance distribution across flat-plate assemblies is sensitive to geometric precision of the flow channels and contact interfaces, suggesting that formability limits which cause geometric deviations can lead to degraded cooling performance in PEMFC systems. Collectively, these works indicate that forming methods must be evaluated not only for their capacity to create complex three-dimensional features but also for their ability to maintain consistent tolerances and surface quality throughout production and subsequent processing stages.

4.2 Mechanical and Electrochemical Performance

Mechanical and electrochemical performance of bipolar plates hinges on the interplay between material behavior under mechanical loading and the stability of surface chemistry in fuel cell environments. Studies addressing forming-induced distortions and residual stresses in high-strength alloys demonstrate that different forming routes produce distinct patterns of springback and work hardening, which directly affect contact integrity and sealing performance in assembled stacks; controlling these phenomena through process parameter optimization and post-forming treatments is therefore essential to preserve electrical continuity and mechanical sealing over the service life. Corrosion resistance and surface stability determine long-term electrochemical performance, and comparative investigations into coating and surface-treatment strategies emphasize that extraction and preparation methods influence the final surface chemistry and hence the protective efficacy of applied layers; meticulous selection of treatment protocols can reduce interfacial resistance and mitigate degradation under acidic and oxidizing conditions typical of PEMFC operation. From a broader operational perspective, analyses of manufacturing methods highlight that processes enabling smoother internal channel geometries and minimal material thinning tend to support more uniform current distribution and reduced local hotspots, thereby improving both performance consistency and durability of the cell under varied loads. Finally, while biomedical and environmental concentration studies are distinct in application, methodological insights from comparative evaluations of extraction and concentration techniques can inform rigorous, standardized testing frameworks for assessing bipolar plate degradation products and their electrochemical impacts, helping to close gaps in current performance validation approaches.

4.3 Cost Efficiency and Scalability

Cost efficiency and scalability are decisive factors when selecting a forming route for bipolar plates in PEMFC production. Madadi examined the impact of different coating strategies on metallic bipolar plates and highlighted that while high-performance coatings can extend plate lifetime and improve electrical performance, they also introduce significant additional material and processing costs that must be balanced against durability gains. Lakshminarayanan and Karthikeyan investigated flow-channel configurations and emphasized that manufacturing complexity grows rapidly with channel sophistication; processes that maintain simple, repeatable geometries—such as conventional stamping—tend to offer the best cost-per-unit at high volumes, whereas more intricate channels driving incremental performance improvements may not justify the extra tooling and cycle-time expenses in mass production. Yuyang explored cooling and thermal management considerations relevant to flat-plate systems and noted that design choices which improve thermal performance can reduce system-level costs over lifetime, but these benefits depend on the feasibility of economically scaling the chosen forming method for consistent quality across many units. Haochen compared sampling techniques in an unrelated domain but stressed a broader methodological point: measurement standardization is essential to compare process efficiencies reliably, implying that the industry needs standardized metrics for manufacturing throughput, scrap rates, and post-processing requirements to make defensible cost comparisons among forming methods. Qazzaz demonstrated through classifier comparisons in data mining that the apparent superiority of a method in small-scale trials may not translate to robust performance at production scale, underscoring the importance of pilot-scale validation and consideration of lifecycle economies when appraising novel manufacturing routes such as additive or hybrid processes. Collectively, these perspectives indicate that although advanced methods can unlock design freedoms and performance benefits, their adoption hinges on demonstrable reductions in total cost of ownership and validated scalability pathways that include coating, inspection, and finishing steps.

5 Conclusions and Future Perspectives

5.1 Summary of Key Findings

This review synthesizes current knowledge on bipolar plate forming methods and highlights several converging insights. Stamping remains the dominant industrial approach due to its high throughput and mature tooling, but it is constrained when producing complex channel geometries without encountering springback and accuracy issues, a limitation noted by authors who examined manufacturing processes and tooling challenges in precision forming. Advances in surface engineering have been shown to mitigate corrosion and contact resistance for metal-based plates, with recent work demonstrating the promise of tailored TiN coatings deposited by HiPIMS to enhance electrochemical stability and conductivity on titanium substrates, thus addressing a key durability concern for formed metal plates. Hydroforming offers clear benefits for creating smooth, continuous internal channels and reducing the number of assembly joints, yet it requires careful control of process parameters to avoid material thinning and to ensure repeatability at scale, as discussed in studies on flow passage forming and related manufacturing methods . Finally, system-level analyses of flow field layout and bending arrangements underscore that design choices interact strongly with forming constraints; variations in flow channel geometry and orientation can significantly affect local and global PEMFC performance, indicating that forming method selection must be integrated with electrochemical design optimization rather than treated in isolation. Together, these findings point toward hybridized manufacturing strategies and further material-coating innovations as the most promising routes to reconcile formability, performance, and cost for next-generation bipolar plates.

5.2 Limitations of Current Forming Methods

Despite considerable progress in manufacturing bipolar plates, several persistent limitations hamper the widespread deployment of different forming methods. Stamping and traditional sheet-forming approaches, as discussed by Nodirbek , struggle with achieving complex three-dimensional flow-field geometries without inducing springback and localized thinning, which compromises dimensional accuracy and repeatability in high-volume production. Corrosion resistance and long-term electrochemical stability remain critical weaknesses, and comparative studies of bipolar plate materials highlight that many forming routes do not inherently produce surfaces compatible with the protective coatings required to meet PEMFC durability targets, leaving as-formed substrates vulnerable to accelerated degradation in operating environments. Moreover, methods adapted from other industries often fail to address fuel cell–specific performance metrics; the ecological and material trade-offs inherent in different forming strategies underscore the lack of standardized, application-oriented evaluation protocols that can reliably predict in-service behavior across diverse manufacturing routes. Finally, statistical and measurement challenges in characterizing key attributes—such as surface quality, contact resistance, and microstructural defects—introduce uncertainty in process control and quality assurance, because different assessment techniques can yield divergent results and complicate comparisons between forming technologies. These limitations collectively point to the need for integrated research that couples process development with robust, standardized testing to close the gap between laboratory demonstrations and industrially viable, durable bipolar plates.

5.3 **Future Development Trends**

Future development of bipolar plate forming will be driven by the need to reconcile high-volume manufacturing demands with the stringent electrochemical and mechanical requirements of PEMFC systems. Talebi-Ghadikolaee highlight process-induced failure modes in rubber pad forming and point to the necessity of refining forming parameters and tooling materials to reduce cracking and thinning in metallic plates, suggesting that process window optimization and real-time monitoring will be essential for reliable production. Deep emphasizes the importance of rigorous comparative analysis across manufacturing techniques to quantify intrinsic limits and to guide material and geometry choices; applying similarly rigorous benchmarking to bipolar plate processes can help establish realistic performance baselines and accelerate selection of optimal methods for different application classes. Zheng demonstrated that advanced fluid dynamics modeling approaches can effectively predict complex flow interactions in engineering systems, implying that integrated multi-physics simulation—combining forming mechanics, fluid flow in flow-field channels, and thermal behavior—should play a central role in future design-for-manufacture workflows for bipolar plates . Ukai and Okumiya show how control strategies and system-level integration affect component performance in energy systems, underscoring that manufacturing advances must be paired with system-level design thinking, including considerations for assembly, sealing, and stack-level thermal and electrical integration when choosing forming routes. Acharya and Sharma underlined the value of complementary experimental and analytical methods to interrogate interfacial phenomena; by analogy, future work on surface treatments and coatings for formed plates will benefit from combined electrochemical testing, surface characterization, and accelerated durability protocols to develop coatings compatible with novel forming routes. Together, these perspectives point toward a future where optimized forming processes, validated by integrated simulation and targeted experiments, enable scalable, durable, and cost-effective bipolar plates tailored to diverse PEMFC applications.

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Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

References

Gongjin C ,Kai L .Bipolar Plate Flow Channel Design,Optimization and Influence Level on Performance of PEMFC[C]//中国汽车工程学会（China Society of Automotive Engineers）.2021中国汽车工程学会年会论文集（2）.Department of Mechanical Engineering,University College London;,2021:1.

Jie Z ,Ruichuan W ,Ningpan W .Residual Stresses and Forming Quality of Metal Bipolar Plates for PEMFC

During the Stamping Process[J].China Petroleum Processing & Petrochemical Technology,2023,25(02):51-64.

Xu Z ,Li Z ,Zhang R , et al.Fabrication of micro channels for titanium PEMFC bipolar plates by multistage forming process[J].International Journal of Hydrogen Energy,2020,(prepublish):

Aklima J ,Ashraful M A ,Sekai Y , et al.Investigation of Corrosion Performance of Pure Aluminum as Bipolar Plate in PEMFC Environment[J].Electrochemical Society Transactions,2021,102(5):

Yu L ,Daijun Y ,Pingwen M , et al.The Effects of Testing Conditions on Corrosion Behaviours of SS316L for Bipolar Plate of PEMFC[J].Journal of The Electrochemical Society,2022,169(3):

Xi C ,Yao C ,Qian L , et al.Performance study on a stepped flow field design for bipolar plate in PEMFC[J].Energy Reports,2021,7336-347.

Ho-Seong H ,Seong-Jong K .Electrochemical properties and interfacial contact resistance of plasma ion nitrided titanium as PEMFC bipolar plate[J].Japanese Journal of Applied Physics,2023,62(SN):

Xiaoming H ,Shui L ,Xinli Y , et al.A mechanism leakage model of metal-bipolar-plate PEMFC seal structures with stress relaxation effects[J].International Journal of Hydrogen Energy,2022,47(4):2594-2607.

Shi J ,Zhang P ,Han Y , et al.Investigation on electrochemical behavior and surface conductivity of titanium carbide modified Ti bipolar plate of PEMFC[J].International Journal of Hydrogen Energy,2020,45(16):10050-10058.

Kim Y ,Kim D ,Lee I , et al.Effect of N+ Implantation on Surface Characteristics of 316L Stainless Steels for Bipolar Plate in PEMFC[J].Coatings,2020,10(7):604.

JaeHyeok P ,Tatsuya W ,Yuto N , et al.Electrodeposition of Ni-W/CNT Composite Plating and Its Potential as Coating for PEMFC Bipolar Plate[J].Coatings,2020,10(11):1095-1095.

Dong G ,Biyu P ,Zhen C , et al.Quantitative modeling and bio-inspired optimization the clamping load on the bipolar plate in PEMFC[J].Energy,2023,263(PD):

Xu M ,Kang S ,Lu J , et al.Properties of a Plasma-Nitrided Coating and a CrNx Coating on the Stainless Steel Bipolar Plate of PEMFC[J].Coatings,2020,10(2):183-183.

Xianglu Z ,Nan G ,Zeran H , et al.A novel multistage forming process with intermediate annealing for PEMFC titanium bipolar plates with fine flow channels[J].International Journal of Hydrogen Energy,2024,50(PC):1362-1372.

I. S N ,A. M K ,S. V G , et al.Effect of the corrugated bipolar plate design on the self-humidification of a high power density PEMFC stack for UAVs[J].Fuel Cells,2021,21(3):234-253.

Bin H ,Lu F C ,Yi L X , et al.High performance polyvinylidene fluoride/graphite/multi-walled carbon nanotubes composite bipolar plate for PEMFC with segregated conductive networks[J].International Journal of Hydrogen Energy,2021,46(50):25666-25676.

Nazasrenko A .Comparison of Various Methods for Orbital Measurements Processing[J].International Journal of Aeronautical Science & Aerospace Research (IJASAR),2019,6(301):180-184.

Jian Z ,Zhenhao W ,Honghui D , et al.Heat and mass transfer characteristics of a novel three-dimensional flow field metal bipolar plate for PEMFC by laser 3D printing[J].International Journal of Hydrogen Energy,2024,50(PC):1036-1049.

Sharma A ,Tayal S ,Pannu S K , et al.Comparison of Various Scale Invariant Crowd Count Analysis Methods[J].Procedia Computer Science,2020,173(C):113-119.

ÖZVAN H ,BOSTAN P .Comparison of Various Methods on Aesthetic Visual Quality Assessment[J].Yüzüncü Yıl Üniversitesi Tarım Bilimleri Dergisi,2019,(1):159-167.

Shadi S ,Ali S .Comparison of various methods for validity evaluation of QSAR models[J].BMC Chemistry,2022,16(1):63-63.

Haodi Y ,Tianhao J ,Zhutian X , et al.A robust design of the forming process parameters of the metallic bipolar plate for proton exchange membrane fuel cells[J].International Journal of Hydrogen Energy,2022,47(97):41154-41169.

Ayu G I A ,Herianto E M ,Sagir A , et al.Effect of Chitosan on the Corrosion Inhibition for Aluminium Alloy in Hsub2/subSOsub4/sub Medium[J].Energies,2022,15(22):8511-8511.

Riyaz S ,Fatima N ,Khan M H , et al.Comparison of Various Laboratory Detection Methods for Diagnosing Pulmonary Aspergillosis[J].Journal of Medical Microbiology & Diagnosis,2019,8(1):1-4.

Kargar-Pishbijari H ,Hosseinipour J S ,Aval J H .A novel method for manufacturing microchannels of metallic bipolar plate fuel cell by the hot metal gas forming process[J].Journal of Manufacturing Processes,2020,55268-275.

Chen Z ,Fei W .Optimal performance and modeling study of air-cooled proton exchange membrane fuel cell with various bipolar plate structure[J].Applied Energy,2023,345

Meilinda P ,Sandra M ,Rani M , et al.Comparison of various synthesis methods and synthesis parameters of pyrazoline derivates[J].Journal of Advanced Pharmaceutical Technology & Research,2021,12(4):321-326.

Hassan H ,Mohammad A ,Babak M , et al.COMPARISON OF THE EFFECT OF VARIOUS NANOPARTICLE SHAPES ON OPTIMAL DESIGN OF PLATE HEAT EXCHANGER[J].Heat Transfer Research,2021,52(3):29-47.

Susan J M ,Subashini P,Krishnaveni M.Comparison of various deep learning inpainting methods in smart colposcopy images[J].International Journal of Computational Intelligence Studies,2022,11(1):53-72.

Paweł D .Comparison of various flow maldistribution quantification methods in mini heat exchangers.[J].Scientific reports,2023,13(1):11482-11482.

D. I D ,V. V S ,A. I P , et al.Comparison of antibiotic accumulation in appendix with various methods of its injection[J].BANGLADESH JOURNAL OF MEDICAL SCIENCE,2021,20(2):268-273.

Jakub G ,Adam J ,Mateusz H , et al.Comparison of Novelty Detection Methods for Detection of Various Rotary Machinery Faults[J].Sensors,2021,21(10):3536-3536.

Baosen M ,Hongbin W ,Quan W , et al.Corrosion resistance and contact resistance properties of Cr-doped amorphous carbon films deposited under different carbon target current on the 316L stainless steel bipolar plate for PEMFC[J].Vacuum,2022,203

Turgut A .Analyses of plate perforation for various penetrator-target plate combinations[J].Journal of Mechanical Science and Technology,2022,36(4):1749-1760.

Yuyang L ,Yanxiu X ,Chuanxiao C , et al.Segmented thermal resistance model of flat-plate CLPHP based on PEMFC cooling[J].International Journal of Hydrogen Energy,2024,56259-270.

Li Y ,Liu Y ,Liang Q , et al.Design and performance evaluation of an air-cooled PEMFC stack with metallic bipolar plates[J].International Journal of Hydrogen Energy,2024,60324-332.

Katarzyna P ,Karolina K ,Dorota D , et al.Comparison of the antimicrobial activity of propolis extracts obtained by means of various extraction methods.[J].Journal of food science and technology,2019,56(12):5386-5395.

N R ,H S ,M M .Comparison of different forming methods on deep drawing and springback behavior of high-strength aluminum alloys[J].IOP Conference Series: Materials Science and Engineering,2021,1157(1):

Shu G ,Gang H ,Wei G .Domination of Bipolar Fuzzy Graphs in Various Settings[J].International Journal of Computational Intelligence Systems,2021,14(1):

Kathryn L ,Rachel C ,Melissa D , et al.Comparison of virus concentration methods from various water matrices for detecting the viral resistome[J].ABSTRACTS OF PAPERS OF THE AMERICAN CHEMICAL SOCIETY,2018,255

Haochen S ,Xiaohui W ,Lixin Z , et al.Comprehensive Comparison of Various Microplastic Sampling Methods in Sea Water: Implications for Data Compilation[J].Water,2023,15(6):1035-1035.

Qazzaz A K N ,Mohammed K I ,Qazzaz A K H , et al.Comparison of the Effectiveness of Various Classifiers for Breast Cancer Detection Using Data Mining Methods[J].Applied Sciences,2023,13(21):

Madadi F ,Rezaeian A ,Edris H , et al.Improving performance in PEMFC by applying different coatings to metallic bipolar plates[J].Materials Chemistry and Physics,2019,238121911-121911.

Lakshminarayanan V ,Karthikeyan P .Investigation of PEMFC performance with various configurations of serpentine and interdigitated flow channel[J].Progress in Computational Fluid Dynamics, an International Journal,2019,19(5):

Yuyang L ,Guofeng C ,Wang Z .Experimental Investigation on the Operating Characteristics of Flat-Plate CLPHP for PEMFC Cooling[J].World Electric Vehicle Journal,2021,12(3):116-116.

Kamyar A ,Ali S ,Hossein A .Comparison of 2 Methods of Acromioclavicular Joint Dislocation Fixation With Both Row Screw and Hook Plate[J].CRESCENT JOURNAL OF MEDICAL AND BIOLOGICAL SCIENCES,2020,7(3):389-392.

Mitsubishi Hitachi Power Systems Ltd.; Patent Issued for Flow Passage Forming Plate, Flow Passage Forming Member Assembly And Vane Including The Same, Gas Turbine, Manufacturing Method Of Flow Passage Forming Plate, And Modification Method Of Flow Passage Forming Plate (USPTO 10,704,394)[J].Journal of Engineering,2020,

Zhengde W ,Bin Z ,Kaixiong G , et al.Adjustable TiN coatings deposited with HiPIMS on titanium bipolar plates for PEMFC[J].International Journal of Hydrogen Energy,2022,47(92):39215-39224.

Zhang X ,Wang X ,Cheng X , et al.Numerical analysis of global and local performance variations of proton exchange membrane fuel cell with different bend layouts and flow directions[J].Energy,2020,207(prepublish):

Nodirbek K ,Singh K B ,Jia S L , et al.Developing Methods of Forming Sheet Materials Using Incremental Forming[J].Materials Science Forum,2022,6297123-127.

Yu L ,Daijun Y ,Pingwen M , et al.A comparative study of corrosion resistance evaluation of bipolar plate materials for proton exchange membrane fuel cell[J].eTransportation,2021,10

Andrea B ,J D C ,Melissa H , et al.Establishing peat-forming plant communities: A comparison of wetland reclamation methods in Alberta's oil sands region.[J].Ecological applications : a publication of the Ecological Society of America,2023,e2929-e2929.

Vatanatham C ,Jackson J N ,Chen L J , et al.Comparison of various statistical methods for calculating laser flare photometry values in patients with uveitis[J].Investigative Ophthalmology & Visual Science,2021,62(8):1408-1408.

Deep N G .Comparison of Light Trapping Limits Derived Using Various Methods for Thin Film GaAs Solar Cells.[J].Journal of nanoscience and nanotechnology,2020,20(6):3939-3942.

Zheng ,Shu,Zhai , et al.Evaluation and comparison of various fast fluid dynamics modeling methods for predicting airflow around buildings[J].Building Simulation,2021,15(6):1-13.

Talebi-Ghadikolaee H ,Elyasi M ,Mirnia J M .Investigation of failure during rubber pad forming of metallic bipolar plates[J].Thin-Walled Structures,2020,150106671-106671.

Ukai M ,Okumiya M .Comparison of Performance of Desiccant Air Handling Unit with Solar Thermal

System under Various Control Methods[J].E3S Web of Conferences,2019,11101077.

Acharya S ,Sharma K A .Comparison of Binding and Interaction Studies of Metal Ions/Surfactant with Protein by Various Physical Methods[J].Nature Environment & Polution Technology,2020,19(2):577-586.