Review Article

Current Status of Laser Welding for Bipolar Plates in Proton Exchange Membrane Fuel Cells

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ABSTRACT

Hydrogen fuel cells have become a hot research topic in recent years. Bipolar plates are the core components of fuel cells, and laser welding is considered one of the most suitable technologies for fuel cell bipolar plate welding. This article summarizes the current research status in the field of fuel cell bipolar plate laser welding, which can clearly represent the latest achievements in the field of fuel cell bipolar plate welding.

Keywords: hydrogen energy; Hydrogen fuel cell; Energy transition; Carbon neutrality; New energy technology; Fuel cell vehicles; Domestication; energy policy

1.Background

.In the research of hydrogen fuel cell vehicles, the study of proton exchange membrane fuel cell bipolar plates plays a crucial role. A hydrogen fuel cell consists of a membrane electrode, a bipolar plate, and a diffusion layer. The bipolar plate plays an important role in distributing reaction gases and supporting the membrane electrode. At the same time, the bipolar plate accounts for 60% of the mass and nearly 40% of the cost of the fuel cell, making it an indispensable and important component of the hydrogen fuel electric vehicle. In terms of material selection for bipolar plates, stainless steel has good conductivity, excellent plasticity, and low cost, making it extremely suitable for stamping and welding processing methods. It is very suitable as a raw material for processing bipolar plates. The general method for welding and processing stainless steel bipolar plates is laser welding. Laser welding, as a popular welding method in recent years, has the advantages of high precision, fast speed, and small heat affected zone, which is very suitable for the welding requirements of metal bipolar plates. Meanwhile, laser welding can be applied in large-scale production, making it favored by industry companies.

2 Empirical Review

Ahmad Aminzadeh et al.[1] experimentally studied the effects of important process factors such as welding speed, billet clamping force (BHF), base material properties, drying/lubrication conditions, and laser spot size on the motion of weld lines and deep drawing. The conclusion was drawn that using LBW with optimal parameters to produce heterogeneous TWB can control the failure of weaker base materials.

Malaya Prasad Behera et al.[2] proposed a typical point by point consolidation mechanism for additive manufacturing as a possible means of enhancing control over the composition of metal matrix composites. The selective laser melting composite material 3N4 with stainless steel 316L as the base material and Si as the filling stage was evaluated in the current study, and it was concluded that under appropriate process conditions, the tensile strength of the composite material was better than that of pure 316L when laser melted.

Yu Qiu et al.[3]re evaluated the fatigue reliability of thin plate welded joints using the JC method and concluded that the reliability index of thin plate welded joints is closely related to the plate thickness, and the tolerances recommended by traditional specifications should be corrected for the plate thickness.

Yongjian He et al.[4] studied the welding heat distribution state and its influence on welding deformation by adjusting the laser welding sequence. They used numerical simulation and experimental research to investigate the welding deformation of 1mm 6061 aluminum alloy thin plate by laser welding. The results show that the transverse shrinkage of segmented skip welding with a single weld is smaller, the longitudinal shrinkage is better controlled, and the out of plane deformation is lower than that of continuous welding with a single weld.

Sukanta Das, R et al.[5] studied and designed a friction stir spot welding method using consumable sheet metal (FSSW-C), which can be used to connect different sheets.

Sami Lininalampi et al.[6]studied the fatigue strength of 3mm thick laser hybrid welded butt joints using measured microscale weld geometry and notch stress methods. The notch stress is defined using Neuber's stress averaging method, which allows for the determination of effective fatigue stress without the need for fictitious geometric modifications.

Vanessa Bawden de Paula Macanhan et al.[7] studied the natural frequency variation of welded thin plates. Experimental analysis was conducted on 8 AISI316LSS plates with a thickness of 6.30mm, including beads on board (BOP) and butt welding. The results indicate that the variation of the first torsional mode is significant, while the variation of the longitudinal bending mode is around zero.

Pengfei Zhao et al.[8] used an AC-300 W pulse laser welding machine to weld 1 mm magnesium alloy at preheating temperatures of 25 □, 100 □, 150 □, 200 □, 250 □, 300 □, and 350 □, respectively. They studied the effects of different preheating temperatures on solidification cracks, porosity, and undercutting. The results showed that preheating increased the peak temperature of the molten pool, reduced the cooling rate of the molten pool, and thus reduced the sensitivity of welding defects.

Tobias Valentino et al.[9] investigated a new method of reducing bending angle dispersion by modifying the residual stress state of thin plates before the forming process. It has been proven that the thermal mechanism plays a dominant role in the deflection of the sheet metal, and laser pretreatment increases the robustness of subsequent bending operations.

Jayanta Ghosh Roy et al.[10] applied cold metal transfer technology to welding AISI 304 stainless steel and selected various welding process parameters, such as welding current, welding speed, and contact working distance, to study the welding strength characteristics. Conclusion: There is no fracture at the weld seam; The residual tensile stress levels of all samples are in a controlled state; Welding speed is the most important welding process parameter, followed by the influence of welding current and contact working distance on the tensile strength of welded joints.

Jae et al. [11]conducted thermal elastoplastic simulation on the laser welding process of I-core sandwich panels. In the welding simulation, an improved conical heat source model was first proposed, and the reliability of the heat source model was verified through welding experiments. Then, the improved heat source model was used to study the effects of welding power, welding speed, and other post weld deformations. The results showed that welding power was positively correlated with post weld deformation, while welding speed was negatively correlated with post weld deformation.

Harald Schlag from the United States used vacuum clamping to clamp bipolar plates and conducted laser welding tests on metal bipolar plates. Through experiments, it was found that using vacuum clamping bipolar plates for laser welding results in higher weld strength and stronger corrosion resistance of bipolar plates. However, due to the need for vacuum pumping in this clamping method, the welding cost of the metal bipolar plate increases.

Mato Peri ć et al.[12] proposed an effective thermoplastic method for predicting welding induced deformation in large panel structures. Two numerical examples were analyzed to evaluate the accuracy and effectiveness of the method. The results indicate that shell/3D modeling technology significantly reduces the computation time required for simulating welding processes, enabling effective thermal elastoplastic analysis of large structures.

Ninshu Ma et al.[13] conducted a quantitative study on the influence of fixture constraints on welding deformation. The welding deformation of square bead welding plates under unconstrained and fixture constrained conditions was studied through experiments. The results show that fixture constraints greatly reduce welding angle deformation, and simulation and experiment have good consistency.

Nikhil Kumar [14]conducted welding tests on 304 stainless steel and 316L stainless steel separately, and compared the mechanical strength of their welds. The results showed that compared with 316, 304 requires higher linear energy to achieve maximum ultimate tensile strength and minimum weld width. The pulse width is the most important factor affecting the ultimate tensile strength of 304 and 316, followed by laser power and scanning speed. Laser power is the most important factor affecting the width of 304 weld seam, followed by scanning speed and pulse width. The laser power is the only important parameter that affects the width of the 316 weld seam.

Morgan Dal et al. [15]briefly explained the methods of numerical simulation for welding, dividing the simulation into thermodynamic simulation and multiphysics simulation, and proposed the problems and improvement methods of these two simulations.

Lijun Han et al. [16]determined laser beam indicators such as focusing index by studying the internal relationship between laser parameters and welding laser characteristics. Simplify it to a small number of laser parameters to facilitate the study of the influence of welding parameters on the forming coefficient. The results indicate that material, assembly clearance, laser power, and welding speed have a significant impact on weld penetration. When the laser power density reaches 106 J/cm2, the characteristic of deep penetration welding occurs. Under the condition of constant gap, the depth of the weld increases with the increase of t/b. The weld seam increases with the increase of laser power and tends to stabilize when the welding speed is 12mm/s.

Wojciech Suder[17] studied the formation law of laser welding weld pool through fluid dynamics simulation and high-precision camera observation. It was found that the main cause of Marangoni convection in conductive laser welding or laser wire melting process can be controlled separately through beam forming; And a new concept of dynamic beam forming was proposed, and its ability to freely adjust the melt flow was demonstrated.

ZunYue Huang et al.[18] measured the welding bending distortion of 1mm thick AA5052 aluminum using digital image correlation technology after laser welding. Two mathematical response models for predicting laser welding bending deformation were established based on the rotatable design method of central composite materials. The conclusion was obtained that the minimum welding bending deformation was achieved within the working range at a laser power of 900 W, a welding speed of 9 mm/s, a defocusing distance of 2 mm, and a gas flow rate of 25 L/min.

Shichun Li et al.[19] used laser hot wire welding technology to weld 7075 high-strength aluminum alloy. Analyzed the influence of parameters on weld formation during laser hot wire welding process, and analyzed the microstructure characteristics and mechanical properties of the weld. The results indicate that the parameters that affect the formation of welds from high to low include laser power, current, gap width, welding speed, and wire supply rate. As the temperature of the welding wire increases, the quality of the weld seam formation decreases successively.

Salman Nisar et al.[20] conducted transient thermal analysis on AA5083 aluminum alloy and studied the parameterized effects of laser power and welding speed on the peak temperature, aspect ratio of weld width and depth, and width of heat affected zone of samples with different thicknesses. The results indicate that laser power has a significant impact on weld width, and welding speed has a significant impact on peak temperature.

Danny et al. [21] used a YAG laser beam to weld 60 μ m AISI 304 (a type of austenitic stainless steel) stainless steel sheet. The results show that compared with resistance welding, laser welding requires nearly three times less heat input, produces a 50% narrower weld seam, reduces porosity by 15%, and increases strength by 25%. It overcomes obstacles such as excessive deformation, formation of discontinuities (pores, voids, and thermal cracks), uncontrolled melting, and poor aesthetics.

Brady et al. [22] also used laser welding in the design of advanced metal bipolar plate connections. In this design, 0.1 mm thin foils of Fe-20Cr-4V and Fe-23Cr-4V are processed through stamping technology and then laser welded under argon protection to produce metal bipolar plate components for the anode and cathode, including cooling channels. Then, the laser welded plate is subjected to surface treatment through pre oxidation and nitriding.

The process parameters of laser welding have a significant impact on the welding quality. In order to improve the quality of laser welding, Pakmanesh et al. [23] studied the effect of Nd: YAG pulse laser welding process parameters on the corrosion resistance of metal bipolar plates after welding. The results indicate that reducing the peak power, duration, and frequency of the pulse will decrease the corrosion current density of the sample, with the pulse duration having the greatest impact.

Nawi et al. [24] used an ultra short pulse Nd: YAG laser with a wavelength of 1064 nm to perform spot welding on 304 stainless steel. We studied the effects of laser welding parameters, including peak power of the laser beam, pulse duration, incident angle, focal position, and number of shots, on the size of the weld seam (penetration depth and weld width). The results show that the penetration depth and width increase with the increase of welding power, pulse duration, and number of shots. However, as the laser defocusing amount and incident angle increase, the penetration depth and width decrease.

Liao et al. [25]used pulsed Nd: YAG laser to weld stainless steel samples. The laser energy range is 0.6-1.2J, and the incident angle (the angle at which the laser beam is incident on the surface of the plate) is 30-75 °. Research has found that with the increase of laser energy, the penetration depth, weld bead length, and weld bead width of the molten pool all increase. As the laser incidence angle increases, the melting depth and width also increase.

Venturella et al. [26] used a YAG laser to weld 100 μ m AISI 316L stainless steel plates. The laser pulse energy ranges from 1.0 J to 2.25 J, with increments of 0.25 J, and the pulse duration is 4 ms. The results indicate that pulse energy control is of great significance for the welding quality of thin plates, as it can generate good mechanical properties and reduce the discontinuity of welded joints. As the pulse energy increases, the maximum tensile strength of the welded joint first increases and then decreases.

Liu et al. [27]proposed a new method of synchronous heat dissipation and ultrasonic hybrid laser welding (SHS+UHLW). We established simulation models for synchronous heat sink assisted laser welding (SHSLW), ultrasonic assisted laser welding (UALW), and SHS+UHLW for comparison, and studied the distribution of stress and deformation under different welding processes. The results showed that compared with conventional laser welding, SHSLW, UALW, and SHS+UHLW all reduced the residual stress and post weld deformation of the weld seam. Among them, SHS+UHLW has a more significant reduction effect, with stress and deformation reduced by 8% and 40% respectively. In the SHS+UHLW process, the ultrasonic cavitation effect and cooling are used to refine the grain size of the weld seam to the maximum extent, thereby improving the mechanical properties of the weld seam. Compared with LW, the hardness and tensile mechanical properties of SHS+UHLW joint have increased by 11.8% and 13.62%, respectively. Therefore, this method not only reduces the deformation of thin plates, but also improves the mechanical properties of welds, achieving coordinated control of welding deformation and weld performance.

Deng et al.[28] optimized the welding deformation of stainless steel plates by changing the welding process parameters. The results indicate that different heat inputs have a significant impact on both lateral and longitudinal deformation, and bending deformation increases with increasing heat input.

Adak [29] placed a cooling system (water circulation) under the welding plate to regulate the temperature of the welded thin plate. Experimental results showed that placing a cooling system under the lower plate can significantly reduce welding deformation by about 41%. However, the cooling system accelerates the cooling rate of the molten pool, greatly reducing the forming quality of the weld and thus lowering the performance of the weld.

Zhan[30] placed the specimen at a certain angle in the opposite direction of deformation before welding, which is called the reverse deformation method. The key to implementing this method is to design specific fixtures. The influence of welding sequence on deformation was analyzed using ANSYS, and a new welding sequence was proposed to reduce welding deformation.

Guirao [31] studied the effect of heat input on the deformation and stress of a thin plate with a thickness of 0.5 mm during micro arc welding. In the experiment, copper fixtures were used to constrain the sample, resulting in faster cooling in the thickness direction, smaller temperature gradients, and reduced angular deformation. The laser magnetic welding of L steel plate shows that the magnetic field is beneficial for reducing the transverse direction

Rong et al.[32] studied hybrid laser magnetic welding of 316L stainless steel. A new simplified heat source model was developed to simulate temperature distribution, taking into account the influence of magnetic field on the geometry of magnetic beads. Combining steady-state magnetic field with laser welding reduced angular deformation by 26.56%, longitudinal residual stress decreased, and transverse tensile stress decreased from 199.1 MPa to 167.3 MPa. Laser magnetic welding helps to improve the quality of the weld bead, reduce angular deformation, residual stress, and plastic strain.

Zhang [33] proposed a multi beam preheating method to reduce distortion. Yi et al. successfully utilized transient thermal tension technology to reduce buckling deformation during thin plate welding. There are also some control techniques based on mechanical methods, such as the prestressing method.

Casalino et al. [34] used laser offset welding to connect AZ31B magnesium alloy and 316 stainless steel into a butt joint structure. The results indicate that the use of adhesive welding method can effectively avoid many drawbacks of laser welding between magnesium and stainless steel. It can produce good metal welds, with good tensile strength and effective connections.

Tao et al. [35] enhanced the performance of laser welded joints between AZ31B magnesium alloy and DP590 duplex steel using pre fabricated groove structures with external and added Sn powder. The results indicate that plasma has a shielding effect on laser energy, thereby improving the absorption rate of laser energy. This promotes the "bidirectional" metallurgical bonding of the magnesium/steel interface, thereby improving the mechanical properties of the magnesium/steel joint.

Suman et al.[36] performed nanosecond laser welding on Al Cu and Cu Al joints. The results showed that by changing the laser power, Al Cu welds exhibited better microstructure, with fewer voids and cracks compared to Cu Al welds.

Shu et al.[37] conducted welding experiments on 316L stainless steel and 6063 alloy thin plates with different line distances. The results indicate that when the line spacing is 0.02 mm, an oxide free joint is obtained, and thermal conductivity decreases with increasing line spacing.

Abderrazak et al. [38] established a three-dimensional transient heat source model using the Goldak volume method and studied the thermal fluid flow in laser welding of magnesium alloys. This study reveals the influence of surface tension temperature coefficient and Marangoni convection on the formation of molten pools.

Artinov et al. [39] established an equivalent volume heat source model for predicting the temperature and weld bead profile of alloy steel laser welding, and the numerical results showed good correlation with experimental results. In one of the studies, the authors demonstrated that by changing or modifying the heat source parameters, the heat source model used for numerical simulation of laser welding can be adjusted to produce better results similar to experiments.

Wu et al. [40] established a three-dimensional conical heat source model and conducted thermal and static analysis on 304 stainless steel using ANSYS. The welding process, molten pool morphology, and post weld deformation were observed and verified through experiments. The final experiment showed that the simulation results matched well with the experimental results.

Theoretical review

Aghaee Attar et al. [41] studied six different thermal distribution models for thermal and mechanical analysis of 304 stainless steel and copper dissimilar laser welding. Rahman Chukkan et al.[42]compared the prediction of temperature, residual stress, and deformation in laser welding of 316L stainless steel using different heat source models, including 3D cone, 3D cone and double ellipsoid composite heat sources, and combined 3D cone and cylindrical composite heat sources. The numerical results indicate that the 3D conical and cylindrical composite heat source can accurately predict the residual stress and deformation of thin plates after welding.

Ahmad et al. [43] successfully welded the super alloy Inconel 625 and duplex stainless steel 2205 (DSS 2205) using a fiber laser with different heat inputs. As the energy input decreases, the width of the weld seam narrows and the mechanical properties of the joint improve. Characterization of welded joints using scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction (XRD), and microhardness testing. No solidification cracks or porosity were observed in the microstructure of the weld metal (WM). Honeycomb shaped dendritic and columnar dendritic grains are the main grain types observed in welded metals. At a heat input of 43 J/mm, there was more molybdenum and niobium segregation in the interdendritic arms of the weld metal compared to the sample welded at a heat input of 21.5 J/mm. Research on tensile strength shows that when the provided heat is low (i.e. 21.5 J/mm), the maximum strength is 890 MPa. This strength value is greater than the strength value of the base material (DSS 2205). The results obtained from the comprehensive correlation between structure and characteristics recommend the effectiveness of laser beam welding for the joining of the dissimilar alloys.

MIS Ismail et al.[44] established a three-dimensional finite element model to simulate the temperature, stress, and deformation fields in continuous wave (CW) laser micro welding of stainless steel thin plates. Welding deformation was evaluated experimentally using a single-mode fiber laser with a high-speed scanning system. The application of the developed thermal model shows that laser parameters (such as laser power, scanning speed, and spot diameter) have a significant impact on the temperature field and weld pool. Numerical simulations were conducted using a non coupled thermodynamic model in the case of welding deformation. During heating and cooling, plastic deformation can generate welding stress and deformation. It can be confirmed that residual stress is higher than the yield strength and has the greatest impact on welding deformation. The numerical simulation results demonstrate that the developed finite element model can effectively predict the thermal cycling, thermal stress, and welding deformation of thin materials.

P Pankaj et al. [45] conducted experiments and numerical analysis on CO2 laser welding of AISI 304 stainless steel plate with a thickness of 1 mm. Predicting transient thermal history is crucial when designing welded joints. A 3D finite element model was developed using ANSYS to determine the influence of welding process parameters (i.e. laser power and welding speed) on the thermal history of laser welded joints. The influence of weld geometry obtained from experiments was considered in this 3D finite element model to simulate a moving volumetric heat source. The element birth and death technique is used in finite element thermal analysis to simulate the progress of laser welding zones. It is observed that the cooling rate is greatly affected by changes in laser power and welding speed. It was also observed that increasing laser power and decreasing welding speed would lead to an increase in the size of the fusion zone and heat affected zone. The transient thermal analysis results obtained from the finite element model and experimental results have been well validated, with a maximum percentage error of 6.47% for peak temperature.

Kim et al.[46] studied a hybrid welding process that combines TIG arc welding with YAG laser. Especially, the welding conditions suitable for thin steel plate welding were studied, and welding results with beautiful surface and back weld beads but no welding defects were obtained. During the research process, it was confirmed that the emission position of the laser beam is crucial for achieving good welding in hybrid welding. Therefore, a new intelligent system using visual sensors to monitor the welding area has been constructed. In addition, a control system was constructed to emit the laser beam to a selected position in the molten pool, which is formed by TIG arc. The results of welding experiments using these systems indicate that the hybrid welding process and control system are effective for stable welding of thin stainless steel plates.

Farid [47] studied the precise seam welding ability of a photolytic iodine laser (PIL) on a 0.1mm thick AISI 316 stainless steel sheet in a lap structure. The welding performance data of PIL laser was compared with Nd: YAG and CO2 lasers. The advantages of PIL welds include narrow seams, extremely fine solidification unit structure, complete austenitic structure, and smaller heat affected zone (HAZ). In contrast, the welds produced by Nd: YAG and CO2 lasers exhibit wider seams, coarser solidification structures, dual phase microstructures of austenite and ferrite, and larger heat affected zones due to slow cooling and transverse thermal diffusion of the melt.

M. Zain Ul Abdein et al.[48] studied the thermal mechanical response of thin plates made of aluminum alloy 6056T4 used for manufacturing fuselage panels under complex industrial boundary and load conditions to laser beam welding. Single pass fusion welding with laser beam was performed on several test boards. Use thermocouples to record temperature history. By macroscopic inspection of the geometric shape of the weld seam and observation of the displacement field through 3D image correlation technology. Then use Abaqus 6.6-1 for decoupling thermodynamic analysis and compare the simulation results with experimental results. Good consistency was found between the simulation results and experimental results.

Nikhil Kumar et al.[49] used an empirical model developed by RSM to investigate the effects of laser power, scanning speed, and pulse width on ultimate tensile strength and welding width. The results of the analysis of variance indicate that the developed model can fully predict the response within the range of input parameters. In addition, microstructure analysis and hardness and tensile performance tests were conducted on the welds of 304 stainless steel and 316 stainless steel. The results indicate that compared to high heat input, low heat input typically results in fine grain structure and improved mechanical properties, regardless of the substrate composition. Compared with 316 stainless steel, 304 stainless steel has better microstructure and mechanical properties.

Suman Chatterjee et al.[50]conducted experimental research on laser butt welding using pulsed Nd: YAG laser. The influence of laser parameters such as laser current, pulse width, and welding speed on the welding quality of 0.45mm thin plates was studied. Research has shown that laser current is the most important parameter in thin plate welding, as it helps to achieve good mechanical and metallurgical quality of the welded joint. The welding strength increases to a certain level with the increase of scanning speed, and then decreases. Overlapping solder joints can seriously affect the surface integrity (surface roughness) and welding strength of the welded joint. The microhardness of the melt zone (FZ) is higher than that of the heat affected zone (HAZ), due to differences in grain structure (coarseness) caused by cooling rate. Laser pulse energy has a significant impact on the generation of residual stresses in welded joints. The study was extended using nonlinear regression analysis to develop an empirical relationship between laser parameters and welding strength. The adequacy of the empirical model was verified by comparing the results obtained from the empirical model and experimental values.

3CONCLUSION

The research on welding formation of bipolar plates in proton exchange membrane fuel cells is important for environmental protection; Optimization of energy structure; The development of the economy has significant implications. In terms of environmental protection, the research on the welding of proton exchange membrane bipolar plates has accelerated the development and production of hydrogen energy vehicles, gradually replacing traditional fuel vehicles. This can effectively reduce the emissions of greenhouse gases such as carbon dioxide and sulfur dioxide, thereby reducing the occurrence of adverse weather conditions such as acid rain, and providing great help in achieving the goal of carbon peak and carbon neutrality. In terms of optimizing the energy structure, the research on welding and forming of bipolar plates for proton exchange membrane fuel cells can effectively promote the popularization of hydrogen energy vehicles and hydrogen energy, thereby reducing the proportion of traditional fossil fuels such as oil, and achieving the goal of protecting energy security. At the same time, it can also change the long-standing shortage of fossil fuels. In terms of economic development, the research on the welding of bipolar plates in proton exchange membrane fuel cells has increased the utilization rate of hydrogen energy vehicles, injected a shot in the arm into the automotive industry, promoted the optimization and upgrading of the automotive industry and its related industrial chain, and provided tremendous assistance for economic development.

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