Commentary

A Study on the Current status of Metal Bipolar Plate Materials and Stamping and Forming for Fuel Cells

ABSTRACT

Bipolar plates are one of the most important components in fuel cell stacks and have multiple functions. Compared with composite materials, bipolar plates of metallic materials have superior electrical and thermal conductivity, good mechanical strength, high chemical stability, very wide choice of alloys, and [1]coating techniques are employed to improve their corrosion resistance and reduce their bottom contact resistance. This paper investigates the selection of materials and stamping and forming of metal bipolar plates in the hope that this research can promote the development of metal bipolar plates for fuel cells. On this basis, we expect to innovate the material and fabrication process of metal bipolar plates, reduce their cost, and promote their commercialization.

Keywords: metal bipolar plates; metal materials; coating technology; stamping and forming; review

1.INTRODUCTION

Electrochemical devices such as fuel cells, capacitors, batteries , sensors [Refs: A-D] , etc , are the technologies belonging to electrochemistry which they use chemical energy to produce electrical energy in conversion energy aspect. It has been used in the automotive and power generation industries due to its reaction process that is not limited by the Carnot cycle and its high energy density[1]. Fuel cells can be classified according to the different electrolytes：Proton Exchange Membrane Fuel Cell(PEMFC）、Phosphoric Acid Fuel Cell(PAFC)、Alkaline Fuel cell(AFC）、Solid Oxide Fuel Cell(SOFC) and Molten Carbonate Fuel Cell(MCFC）.The performance and applications of different fuel cells are shown in Table 1. Proton Exchange Membrane Fuel Cell (PEMFC), one of the most promising mobile energy sources evaluated by research results in recent years[2].

Table 1. **Comparison of performance and applications of different types of fuel cells**

Fuel Cell	Operating temperature	Reaction fuels	Applications	Advantages	Disadvantages
PEMFC	60~80℃	Hydrogen Gas Methanol	Automotive	High start-up speed	Toxic catalyst Higher cost

PAFC	150~220℃	Reorganization Natural Gas	Decentralized power generation	Low noise and vibration	Low start-up speed
AFC	100~200℃	Pure hydrogen	Spacecraft	High start-up speed	Short working period
SOFC	800~1000℃	Natural Gas Coal purification gas	Large-scale decentralized Power Generation	Materials, electrohydraulics Corrosion problems	High cost Material limitations
MCFC	600~700℃	Coal purification gas	Large-scale decentralized Power Generation	High power generation efficiency Waste heat utilization value High value	Low start-up speed Electrolyte corrosion Short working period

Compared with the movable energy devices developed at this stage, the proton exchange membrane fuel cell, because of its high starting efficiency、high current density、high operational reliability、 and low operating temperature, Used as a preferred power generator for energy supply such as electric vehicles [3].he energy conversion efficiency of proton exchange membrane fuel cells can reach about 50-60%, which is about twice that of traditional internal combustion engines, in which the key role is played by the bipolar plate[4]. Bipolar plates have important functions such as cell reaction fuel distribution, single cell separation, current collection, and heat dispersion, Its manufacturing cost is about 40% of the total battery manufacturing cost[5]. Membrane electrodes and bipolar plates are the key components of fuel cells, which determine the performance of fuel cells. The structure is schematically shown in Figure 1. Currently, bipolar plates are mostly prepared by CNC machining and forming with high conductivity graphite material as the substrate, time-consuming and costly to prepare, The graphite bipolar plate is basically replaced by the corrosion-resistant metal bipolar plate due to its high manufacturing and usage costs and processing difficulties. Metal bipolar plates are cheap to manufacture and can be used to develop small size bipolar plates, it can reduce the mass of the electric stack. However, metal bipolar plates lack efficient, low-cost and high-precision processes in manufacturing and forming [6].

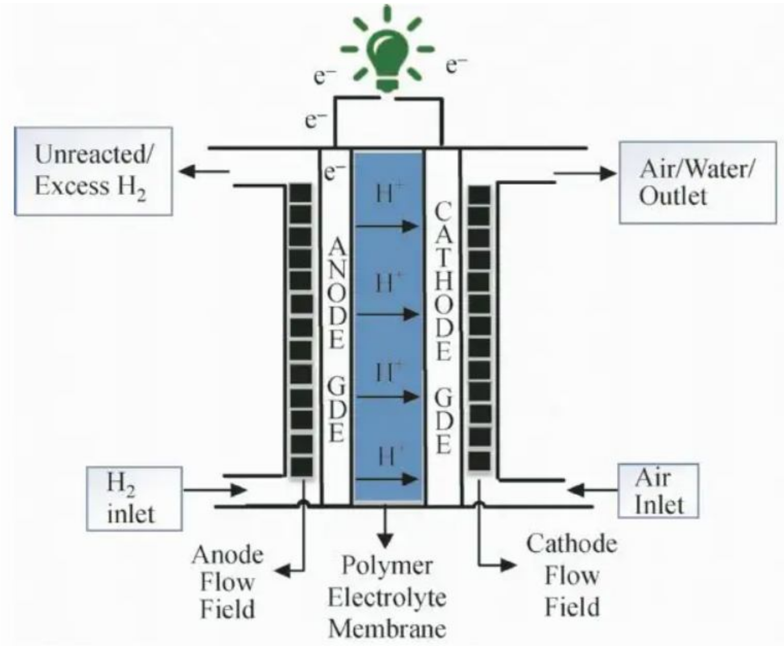

Figure .1. Basic components of fuel cell

2. BIPOLAR PLATE METAL SUBSTRATE MATERIAL

The bipolar plate material must be chemically stable, highly conductive and thermally conductive; With the advantages of low contact resistance with the substrate, good mechanical strength, low permeability, and low cost for mass production; Make the reactant gas distribution and product discharge uniform. It also needs to be light weight and small in size [7]. Graphite dominated the early applications, its large size, its permeability, the high cost of processing air channels and its brittleness were the biggest obstacles for this material, In view of the limitations of graphite substrate materials, many scholars have turned to metals as substrate materials for fuel cell bipolar plates. Bipolar plates of metallic materials, especially stainless steel, are gaining more and more attention due to their excellent electrical conductivity, high strength, high chemical stability, wide range of options, mass production and low cost.

2.1 Bare alloy material

A bare alloy is a metal material that has no coating on the surface of the metal. The most studied metal material for bipolar plates is stainless steel, because of its high chemical stability, good mechanical strength, wide choice of alloys, mass production and low cost. The relative high density of the material can be compensated by the application of thin plates.Won Tae Park et al[8] In the use of stamping process parameters to improve the channel depth of stainless steel bipolar plates for fuel cells, it is mentioned that type 304 and 316 stainless steel are the most widely studied materials for bipolar plate applications, In its experiments on the effect of stainless steel materials on its channel depth found that 304 contains a small amount of carbon has excellent corrosion resistance, 316 contains molybdenum, This gives it better resistance to corrosion, acid and high temperatures. Yu Leng et al[9] In the study of stainless steel bipolar plates for proton exchange membrane fuel cells, it was found that stainless steel can provide desira ble properties such as high electrical and thermal conductivity, good gas impermeability, excellent mechanical properties, and excellent formability. In addition, stainless steel bipolar plates have higher strength, impact toughness and better gas impermeability than graphite bipolar plates, and have higher electrical conductivity than composite plates.M.P. Brady et al[10] A Fe-20Cr-4V ferritic stainless steel was developed with lower Cr and V content compared to the conventional Fe-27Cr-6V. It can reduce the cost of Fe-20Cr-4V and improve its ductility at the same time. By pre-oxidation and nitriding, the corrosion resistance and ICR of Fe-20Cr-4V are better adapted to the fuel cell use environment. Wang XianZong et al[11] When studying the effects of hydrogen and stress on the electrochemical and passivation behavior of 304 stainless steel in a simulated PEMFC environment, it was found that a highly synergistic effect of hydrogen and stress on current density was observed for stainless steel in the moderate hydrogen-filled current density range. The stainless steel pole plate is shown in Figure 2.

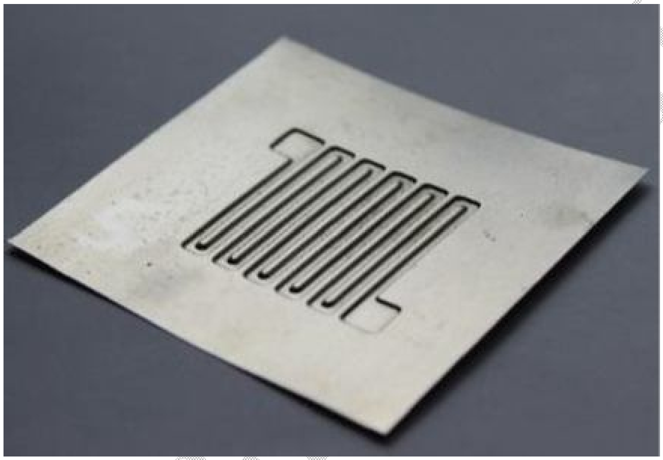

Fig.2 . Stainless steel pole plate

Titanium and titanium alloys have excellent characteristics such as low density, high specific strength, good electrical conductivity and corrosion resistance, and are widely used in chemical industry, aerospace, shipping, metallurgy, electric power and other fields. Pure titanium is also an ideal material for metal bipolar plate substrates.Zhipeng Li et al[12] In the study of titanium bipolar plates for fuel cells, it was found that the corrosion rate of Ti is comparable to that of graphite under the same conditions and has similar corrosion resistance as graphite, which is a better choice for metal-based bipolar plates.Zhutian Xu et al[13] In the study of titanium-based proton exchange membrane fuel cell bipolar plates, it was found that bipolar plates made of ultrathin titanium metal plates have high corrosion resistance, electrical conductivity and strength-to-weight ratio. They are considered to be satisfactory candidates for proton exchange membrane fuel cells (PEMFC) for vehicles.

Lim et al[14]the comparison in the preparation of aluminum 1050 type bipolar plates revealed that it has a low density and shows more formability in the manufacturing process compared to stainless steel. In addition, it has excellent corrosion resistance, high bulk conductivity and excellent thermal conductivity. Aluminum and aluminum-based alloys offer greater cost advantages than titanium alloys. Bare Al has a high corrosion rate, while carbon-coated Al can reduce the corrosion rate by more than two orders of magnitude, and the initial performance of fuel cell stacks with treated Al bipolar plates is superior to that of graphite plates, but the output of the former is slightly reduced.

2.2 Coated alloy materials

Feng et al[15] In a study on the surface modification of metal bipolar plates for proton exchange membrane fuel cells, experiments have shown that pure metal bipolar plates are susceptible to corrosion in a proton exchange membrane fuel cell environment. Corrosion of metal plates releases metal ions that may poison the catalyst or form dense oxide films that can increase the interfacial contact resistance (ICR), thus affecting the output power and service life of the fuel cell. Coating the surface of metal-based materials improves their corrosion resistance and contact properties [16]. The coating should be electrically conductive, with good adhesion to the base material and a coefficient of thermal expansion compatible with that of the base material [17]. Coatings are usually of two types: carbon-based coatings and metal-based coatings. The former includes graphite, conductive polymers, diamond-like and organic self-assembled monomers. The latter includes precious metals, metal nitrides and metal carbides, etc.

Nur Fawwaz Asri et al[18] To improve the corrosion resistance and electrical conductivity of proton exchange membrane fuel cells, a corrosion-resistant coating of stainless steel was evaluated. In their research, it was found that coated modified stainless steel bipolar plates exhibit excellent performance in proton exchange membrane fuel cells by using niobium carbide (NbC) coating on the stainless steel material.Lee et al[19] Application of cathodic arc ion plating (CAIP) surface coating technique to deposit CrN on the surface of stainless steel 316L. To evaluate the potential of CrN-coated 316L stainless steel as a PEMFC bipolar plate material, its electrical conductivity and corrosion resistance were evaluated. The ICR values of CrN-coated 316L stainless steel were lower compared to uncoated 316L stainless steel, and the CrN coating provided a highly corrosive protective layer for the stainless steel in a cathodic environment. CrN coating deposited by CAIP is a potential coating material.M.A.Deyab et al[20] Study on the use of polyaniline/zinc porphyrin composite coating to enhance fuel cell performance and protect stainless steel bipolar plates from corrosion by adding 1.0% zinc porphyrin, a polyaniline/zinc porphyrin composite. This new composite clad 303 stainless steel has excellent corrosion resistance to corrosive fuel cell electrolytes, increasing the output power of the fuel cell.Zhang Dongming et al[21] Two surface coating techniques, pulsed bias arc ion plating (PBAIP) and magnetron sputtering (MS), were used to prepare tin-plated stainless steel. The corrosion resistance and electrical conductivity of the coated substrates were evaluated. Ti2N/TiN multilayer coating provides excellent corrosion protection and low contact resistance for stainless steel.

Xin Yang et al[22] Research on metal bipolar plate modified carbon-based coating technology, using a combination of theoretical calculations and experiments to prepare metal-doped carbon-based coatings, solving the problems of poor adhesion and high compressive stress between coatings and specific metal substrates.Wang et al[23] In studying the modification of metal surface coatings, it was found that conductive SnO2:F coatings could protect the metal substrate from corrosion,and provides better surface conductivity due to the coating being stable in most environments, which significantly reduces the contact resistance of the coated stainless steel. The metal surface coating equipment is shown in Figure 3.

Fig.3.Metal sheet surface coating equipment

3 .METAL BIPOLAR PLATE STAMPING AND FORMING

Liu Yanhong and Hua Lin[24] study the precision forming technology of metal bipolar plates for fuel cells, and to point out that sheet metal stamping is one of the most widely used methods for plastic forming of metal bipolar plates for fuel cells. It is a processing method that uses a mold to produce plastic deformation by applying pressure to the sheet under the action of a press to obtain parts that meet certain structural requirements. Metal bipolar plate stamping and forming is one of the most promising forming methods for future fuel cell metal bipolar plates because of its high production efficiency, good part strength and stiffness, high dimensional accuracy and high material utilization rate[25].

3.1 Single press forming

At present, the traditional stamping and forming process is mostly used for processing and manufacturing thin metal sheet microstructure parts. Put the cut sheet metal into the stamping die,Lan Jian and Wei Xi[26] designed a technical route for a single-pass stamping, As shown in the Figure4. A metal sheet with runner design features is formed in one press for the metal pole plate of fuel cells. This processing method using press forming has the advantages of being mature, stable and easy to process, and is a common method for processing and manufacturing
Metal pole plates.

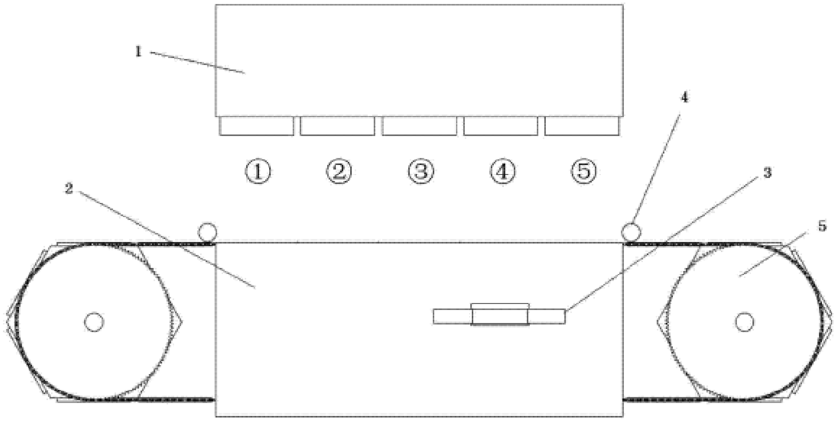

Fig. 4. Schematic diagram of single press forming

The second part of the figure is a fuel cell large area metal bipolar plate stamping and forming die, including a progressive die consisting of 5 stations：Station ① is to punch four pin holes and insert pins；Station ② is a parallel groove with compensated forming runners；Work station ③ is punching shaped holes；Work station ④ is cutting edge drop processing；Work station ⑤ is to pull the positioning pin；After passing through stations ①, ② and ③ in turn, the sheet will be cut and formed into bipolar plates at station ④, and the scrap after cutting will be taken out of the stamping and forming die at station ⑤. The said station ② convex die is a self-compensating runner parallel groove forming convex die, the transverse section and longitudinal section of the convex die are symmetrical structure with high center and lower sides in turn[27].

Zhai Hua and Li Yuan et al[28] in their study of thickness thinning in the corner region of stamped metal bipolar plates, noted that，Conventional single press forming is done instantly by press machine, and it is difficult to deform the metal sheet evenly due to short action time and difficulty in material replenishment. In local areas where large tensile deformation occurs, it is very easy to have serious thinning and rupture, which leads to sheet metal forming failure. Through several experiments it was found that as the degree of tensile deformation of the sheet metal increased significantly, the degree of local thinning and destabilization rupture became more serious.Xu et al[29] investigated the thickness distribution and residual stresses in stamped bipolar plates. The residual stresses after stamping are large and are influenced by the geometry.Jin et al[30] used dynamic loading during stamping to fabricate stainless steel bipolar plates for fuel cells and performance evaluation of individual cells, which was found during experiments to study the stamping process of stainless steel bipolar plates under different loading conditions. They found that dynamic loading during bipolar plate forming can improve the formability of metal plates [31]. The bipolar plate stamping machine is shown in Figure 5.

Fig.5.Metal bipolar plate stamping machine

Barzegari et al[32] studied the thickness distribution and dimensional accuracy of stamped metal bipolar plates. They found that the forming pressure could be optimized to improve the forming accuracy of SS316L bipolar plates.Chen et al[33] while studying the preparation of proton exchange membrane fuel cell microchannel arrays on thin stainless steel plates by microstamping technique, found that the depth of the flow channels on the prepared metal pole plates was usually shallow and it is difficult to process metal bipolar plates with high aspect ratio and fine-grained microfabrication structure. Not conducive to the distribution and flow of hydrogen and oxygen in the flow channel. It is concluded that increasing the depth to width ratio of the flow field of the metal electrode plate of the fuel cell can increase the homogeneity of gas transfer and heat dissipation performance and thus increase the cell power.

Therefore, the traditional single press forming method is prone to defects such as compression instability, rupture caused by tensile instability, and springback when the deformation force is released or disappears, and has certain limitations.

3.2 Roll press + press forming

In order to overcome the limitations of single-press forming, some researchers have proposed some new methods for forming metal bipolar plates.Li Xi-ang et al[34] proposed a processing device and method based on roll forming + stamping composite forming process to process and manufacture high depth to width ratio metal sheet microstructures in their study of metal-rubber roll forming process and mechanical property correlation analysis. The sheet metal is continuously and progressively formed into an initial micro-fine feature sheet with an initial micro-fine structure by roll forming prior to press forming. It is conducive to the uniform deformation of sheet metal and the reduction of stress concentration, so as to realize the continuous production of sheet metal microstructure parts with high depth to width ratio microstructure on one production line[35]. The schematic is shown in Figure 6.

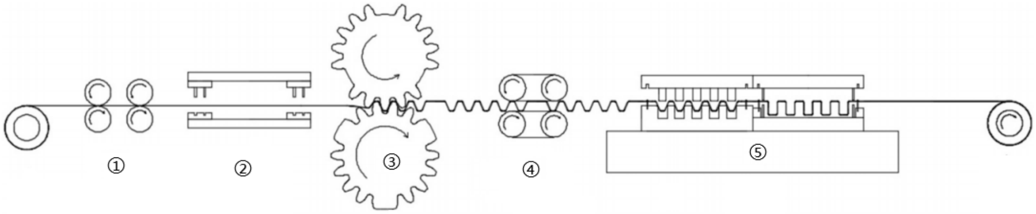

Fig. 6. Schematic diagram of roll pressing + stamping

In Fig. 6, station ① is the feeding roller, station ② is the positioning hole punching, station ③ is the initial microstructure roll forming, station ④ is the leveling mechanism, and station ⑤ is the microstructure press forming and edge cutting combination. The forming method includes the following steps:(1) Processing the stamping die by mapping the target microstructure by selecting the forming roll die with the corresponding characteristic structure according to the initial microstructure of the initial microfine characteristic thin plate.(2) The metal sheet to be processed is output from the uncoiler, sent to the positioning hole punching tool through the feeding roller to process the positioning hole, and then enters the forming roller die and rolls to form the initial micro-fine feature sheet with the initial micro-fine structure.(3) The resulting initial micro-featured sheet is fed into the leveling mechanism for leveling, and then the initial micro-featured sheet is cut and stamped using edge cutting tools and stamping dies in turn, or integrated stamping and edge cutting using a progressive die to obtain a thin metal micro-fabricated part with the target form of high depth to width ratio micro-fabricated structure.

Buddhika Abeyrathna et al[36] ,in their study of micro roll forming of stainless steel bipolar plates for fuel cells, used a roll forming process to form thin stainless steel plates into bipolar plates with the required micro-scale channel cross sections for experimental tests, The results show that the roll forming technique is feasible for manufacturing the modified bipolar plates and there is no failure of the formed bipolar plates.Bong Hyuk et al[37] performed experimental and numerical simulations of a two-stage forming method for bipolar plates of proton exchange membrane fuel cells. t is proposed that the micro-roller is first pressed into a micro-runner, and then the edge is cut by stamping, etc. The experimental results confirm that the proposed method has improved formability.Kivanc Karacan et al[38] in study of the press formability of metal bipolar plates for lightweight proton exchange membrane fuel cells. Through numerical simulations and experiments, it is concluded that both the depth and width of the runner have an effect on the processing and forming, and the appropriate depth and width have a positive effect on the forming performance of the roll-formed microfluidic bipolar plates.

3.3 Multi-step progressive stamping

Wang Kai et al [39] designed a multi-step stamping procedure for thin metal plates in a simulation and experimental study of multi-step stamping and forming of ultra-thin stainless steel plates. A fuel cell bipolar plate stamping die comprising a die holder and an upper die, as shown in Figure 7; Said mold holder is mounted on the horizontal base, the upper surface of the mold holder is provided with a recessed concave mold, and the upper mold is provided above the mold holder. The upper die is lifted by a press, and the lower surface of the upper die is set with 8 raised bosses, The first, second, third, fourth and fifth convex dies are profile stamping dies, and the sixth, seventh and eighth convex dies are pipe stretching and finishing dies.

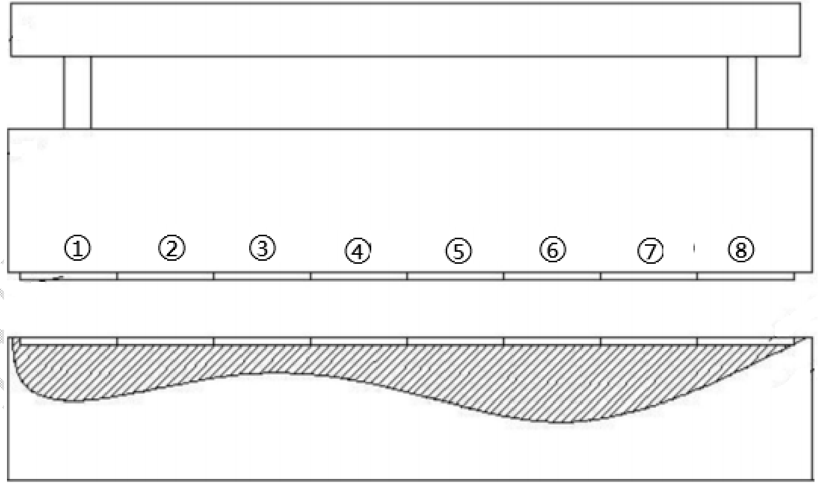

Fig.7. Schematic diagram of multi-step progressive stamping

A stretching die is provided in the middle of the sixth convex die, and the stretching die is used for the initial stretching of the fuel cell reaction pattern in the middle of the monopole plate[40]，tensile accuracy of 2-4mm；a finishing die is provided in the middle of the seventh convex die, and the finishing die is used for precise stamping of the fuel cell reaction pattern in the middle of the monopole plate, punching accuracy of 1-2mm；the eighth convex die is set in the middle of the finished die, and the finished die is used for forming and stamping the reaction pattern of the fuel cell in the middle of the monopole plate, stamping accuracy of 0.5-1mm. Stamping and forming of high aspect ratio microfluidic metal bipolar plates is accomplished through this three-step progressive stamping process[41].

Min-June Kim et al[42] used various frequencies of sine, square and ramp waves for dynamic load stamping and static load stamping tests in their study of the effect of static and dynamic loading on the stamping and forming properties of stainless steel 316L bipolar plates,the experimental results show that the bipolar plate bipolar plate channels with smaller runner depths cannot be formed correctly by static load stamping, the experimental results of dynamic load stamping and forming show that sine wave and square wave loads are more suitable for processing bipolar plates than oblique waves, and the forming effect is better than that of static load processing.Bong Hyuk et al[43] explored the improvement of unconventional forming properties of bipolar plates and investigated the increase in formability of unconventionally formed profiles programmed in a servo press using finite element analysis and performed forming tests. Four different forming profiles were considered to investigate the effect of forming profile on formability and shape accuracy, it was found that stress relaxation and variable contact conditions are the main mechanisms to improve formability during multi-step progressive forming hold and swing.Chen et al[44] investigated the effect of springback on the forming properties of multi-step stamping and forming of metal bipolar plates, in which it was found that the feeding speed and stamping speed and stamping load during multi-step stamping and forming can cause springback and affect the forming properties.Majid Elyasi et al[45] studied the dimensional accuracy of metal bipolar plate forming in serpentine flow fields, in diagonal, longitudinal and transverse directions (directional dimensional accuracy). The results show that the directional dimensional accuracy (uniformity of channel depth) improves with increasing force.

4.CONCLUSION

In summary, metal bipolar plates with metal-based materials are an important development direction for fuel cell bipolar plates with corrosion resistance and surface modification. Metal bipolar plate stamping and forming technology has been studied in depth and has made important progress, and has the potential to become the main manufacturing technology for metal bipolar plates. It is difficult for uniform deformation to occur in single press forming, and large tensile deformation occurs in local areas, which is highly susceptible to severe thinning and rupture, thus leading to sheet metal forming failure. Roll + press forming with multi-step progressive stamping can effectively overcome the limitations of single press forming, which places higher demands on metal bipolar plate materials and press forming under the demand of commercial fuel cell applications.

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