

Fuel Cell Development using Additive Manufacturing Technologies - A Review

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Abstract

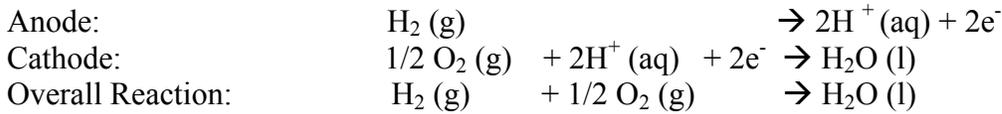
Fuel cells are being perceived as the future clean energy source by many developed countries in the world. The key today for clean power is the reliance of fuel cells not only to power automobiles but also for residential, small commercial, backup power etc. which calls for production on a large scale. Additive manufacturing is perceived as a way to develop cost effective fuel cells. It imparts flexibility to design different kinds of fuel cells along with reduction in material wastage. This paper deals with the review of additive manufacturing processes for research and development of fuel cell components, such as synthesizing and prototyping new materials for fuel cell components, fuel cell system design and prototyping, designing well sealed fuel cells, bridging from fuel cell design to manufacturing tooling, etc.

1. Introduction

Fuel cells are electrochemical devices similar to batteries which convert energy from chemical state to electricity. There is an anode side and a cathode side in it. Fuel enters the cell from the anode side and oxidant flows into it from the cathode side. The reactants react inside the cell and the reaction products or the waste products flow out of it. The basic difference between batteries and a fuel cell is that fuel cell is only an energy conversion device and not energy storage device. Fuel cells consume reactant (fuel) from an external source which must be replenished. Hence fuel cells represent a thermodynamically open system. However batteries are both energy storage and conversion devices and hence they represent a thermodynamically closed system. The advantage of separating the storage and conversion functions is that power and energy capacity can be sized independently of each other. Also, many different fuels can be used as the primary energy source of the fuel cell setup depending on the types of fuels compatible with the type of fuel cell being employed [Spiegel 2006].

This paper primarily discusses Proton Exchange Membrane (PEM) fuel cells because most of the research regarding fuel cells has been undertaken with regards to PEM fuel cells, due to its many advantages such as versatility. PEM fuel cells can be employed for various uses starting from portable power to automotive power to stationary residential power. The by-product of a PEM fuel cell is water, which is not only non-polluting but can be used as a potable water supply.

In the PEM fuel cell, hydrogen is the fuel which enters the fuel cell through the anode end and oxygen through the cathode end. The following reactions take place at the cathode and the anode



The components in a fuel cell are:

1. Bipolar Plates.
2. Membrane Electrolyte Assemblies (MEA's).
3. Gas diffusion electrode layers.

Apart from this there are various auxiliary components such as gas flow pipes, the gaskets(seals), the connectors, end plates and cooling plates(required in fuel cell stack). The cost of these auxiliary components is relatively insignificant as compared to the cost of the major components.

Cell Stack	Membrane	35~40 %
	Catalyst	15~20 %
	Bipolar plates	10~15 %
	MEA's	30~35 %

MEA is the heart of the fuel cell; rather it is the distinguishing criteria for different types of fuel cells. An MEA, as the name suggests, is the assembly of the membrane and two electrodes on either side of the membrane. An electrode is a carbon cloth which is fabricated in a particular pattern depending on the mesh size required. Also, it needs to have specific properties to facilitate proper water management throughout the cell.

As for the membrane, it is the electrolyte which is being employed for that particular fuel cell. The most common electrolyte used for a PEM fuel cell has been Nafion[®]. Nafion[®] is a generic brand name given by its developer DuPont. Its chemical name is sulfonated Polytetrafluoroethylene (PTFE). Although Nafion[®] is the most common polymer membrane employed in PEMFC, extensive research is being carried out to find a cost effective alternative which is as mechanically and chemically stable as Nafion[®] [Payne 2009].

The most common catalyst used for the PEMFC is Platinum due to its stability in highly corrosive atmospheres as well as its performance characteristics. The methods used for applying the catalyst are screen printing and hand painting. However, the uniformity of the catalyst deposited is not easily controlled. Also, these processes are time consuming, and require iterations of painting, drying and massing to achieve the

required loading of the catalyst. The reproducibility of these methods is poor. There is considerable amount of catalyst wasted in the feed lines due to clogging which results in an increase in the production cost [Taylor 2007].

The aforementioned commercial methods of producing major components of fuel cells are not in accordance with the economic threshold value as required by the US Department of Energy. These processes combine costly materials and processes that result in increased costs of fabrication of fuel cells.

To achieve the target of production cost of \$30/kw by 2015 as set by the US DOE [DOE 2005], there is a need to achieve low cost fabrication of fuel cells and use alternate cheaper materials in the manufacturing processes. Based on the Results of the Workshop on Manufacturing R&D for the Hydrogen Economy, several challenges confront the transformation of the U.S. manufacturing sector to support the hydrogen energy economy such as:

- Develop innovative, low-cost manufacturing technologies for new materials and material applications.
- Adapt laboratory fabrication methods to low-cost, high-volume production.

Rapid manufacturing is an innovative manufacturing technique which can be used for the fabrication of fuel cells which goes hand-in-hand with the aim of US DOE. Rapid prototyping is defined as a machine technology which is used to fabricate 3-dimensional models and prototype parts from a numerical description (typically a CAD model) using an additive approach to form physical models. That is why Rapid prototyping is also referred to as 'Additive Manufacturing'. Additive Manufacturing (AM), as the name suggests is the process of fabrication of physical models or prototypes by addition of materials. This addition takes place layer by layer incrementally. By this process, the problems of form generation and material composition are addressed. The smaller the incremental volume of material better is the accuracy of the form generated and also the control over system parameters. AM doesn't require any external tooling for the manufacturing of 3D freeform objects.

There are various kinds of widely used Additive Manufacturing techniques such as:

1. Selective Laser Sintering(SLS)
2. Fused Deposition Modeling (FDM)
3. Stereolithography (SLA)
4. 3D printing
5. Laminated object manufacturing (LOM)
6. Electron Beam Melting (EBM)

Variations of these processes also exist but it is not important to be listed above since a small variation of some system parameters might lead to an entirely different process. For the manufacturing of PEM fuel cells, more importance has been given to a few processes such as Fused Deposition Modeling (FDM), 3D Printing and Selective Laser Sintering (SLS) which are discussed in detail in this paper.

The advantages of AM itself make it an attractive way to build fuel cells. With additive manufacturing technologies, you have the flexibility to change the design of the fuel cells without the need to change the entire setup as would be required with regards to conventional manufacturing technologies. In this paper, there is an example of a planar array fuel cell with a mono polar plate design. It gives a good proof of the flexibility of additive manufacturing technology. This feature of AM enhances the prospects of further cost reduction. Inkjet printing aids the process of precision manufacturing since we can deposit materials with micrometer precision thereby again reducing material waste. Impressive results from the three processes as described in this paper maximize the scope of AM for building fuel cells. It might happen that, under a single roof, we see multiple AM techniques used to build an entire fuel cell.

2. FDM (Fused Deposition Modeling)

Fused Deposition Modeling is an additive fabrication technology which constructs superior rapid prototypes from 3D CAD data where in a thermo plastic material is extruded in the form of beads layer by layer using a temperature controlled head which is actually controlled by Computer Aided Manufacturing (CAM) software [Zhong 2000].

A plastic filament or wire supplies material to an extrusion nozzle which is heated so as to melt the material and deposit the required amount of material in horizontal and vertical directions(i.e., wherever it is necessary).The material hardens as soon as it is extruded from the nozzle.

The thermo plastic materials used in FDM process have good stability and durability of the mechanical properties over time; they have high heat resistance and also produce smooth parts with all the finest details intact. The commonly used materials with this process are Acrylonitrile Butadiene Styrene (ABS) polymer, elastomers, investment casting wax and some of the water soluble materials are used in this process which acts as support structures during the manufacturing process [Masood 2004].

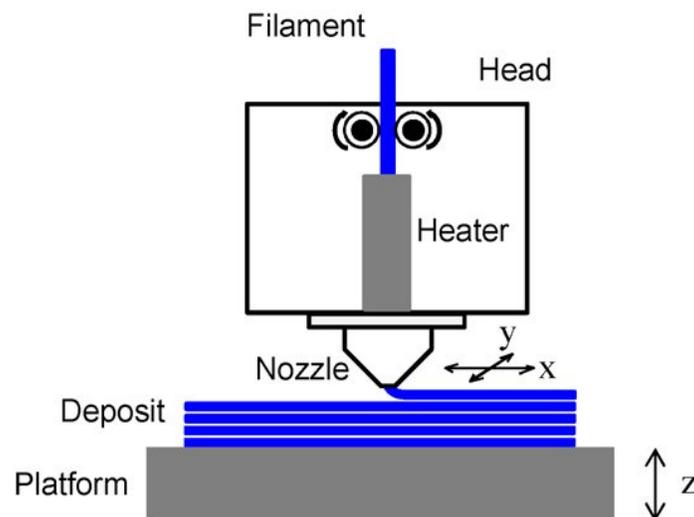


Fig. 1. Process of FDM

FDM has been used for the fabrication of miniature fuel cell stack in a planar array form [Chen 2008]. For the development of miniature fuel cells, it is required to have pin-point precision, since the aim of this type of fuel cell is to have high power density in a small stack. A study has been made to develop a 10 cell planar array air breathing fuel cell using FDM as the RP (Rapid Prototyping) process [Chen 2008].

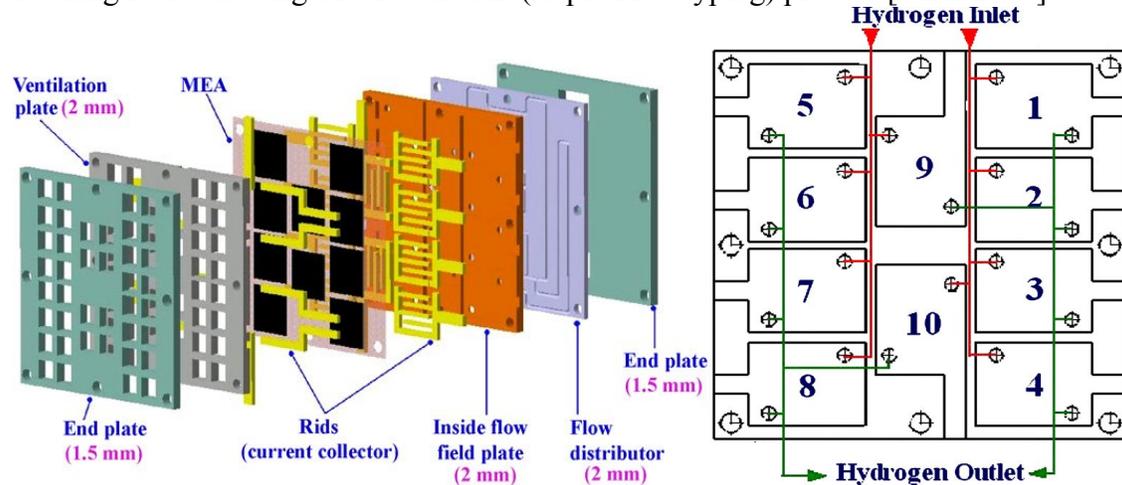


Fig.2. Construction and layout of the stack [Chen 2008].

The alternative processes for the development of such miniature fuel cell are the Micro-Electro-Mechanical processes (MEMS) and the conventional CNC machining processes. The flow field plates were the parts which were fabricated using RP, more specifically Fused Deposition Modeling (FDM). Acrylonitrile-butadiene-styrene (ABS) was the material used for the fabrication of flow field plates since it has high mechanical strength, low cost and easy to fabricate by RP.

The following table gives a comparison of the manufacturing time required for the geometry of flow field plates by different processes [Chen 2008].

Process	Time (approx)
Rapid Prototyping	1 hour
CNC	2hours
MEM's	12-36 hours

It is noted that RP is faster than the rest of the methods. Also, if the flow field plate is designed more and more complicated, CNC machining may not be possible at all. This kind of miniature PEM planar array FC stack is a first try in both academic as well as industrial world.

The FDM process used for planar array fuel cell fabrication is described next with respect to the design and performance of the PEMFC.

2.1 Design and characteristics of the planar array PEMFC

- There are 10-segments in the PEM. Hence the total reactive area is 17cm^2
- The cell operating temperature is 70°C internal and ambient temperature is 25°C .
- Two configurations have been tried: Parallel and series.
- These 2 configurations have been tested with natural convection and forced convection.
- The anode is on the same side of the membrane whereas the cathode is on the opposite end or the ventilated end.
- Hence, it is called as a mono-polar stack design.

2.2 Performance test in parallel connection [Chen 2008].

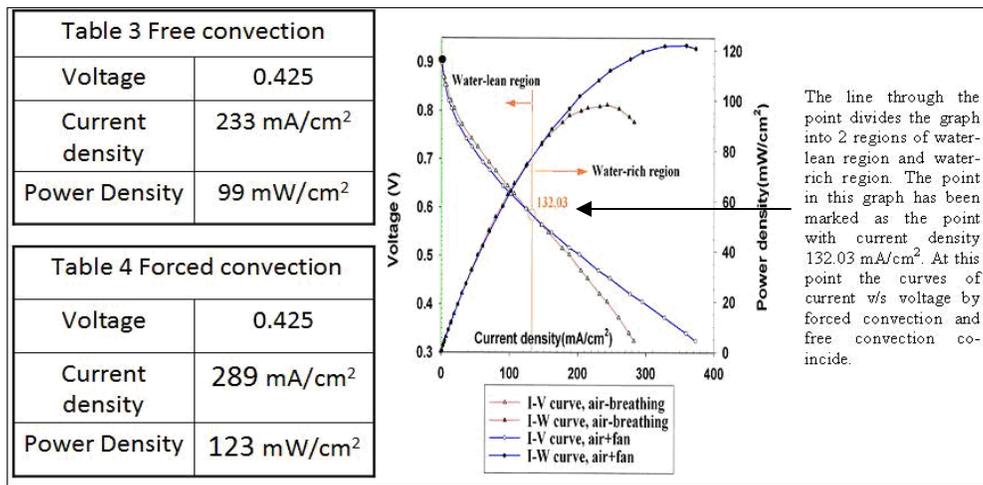


Fig.3. Comparison of forced and natural convection in a parallel connection. [Chen 2008]

2.3 Performance test in series connection [Chen 2008].

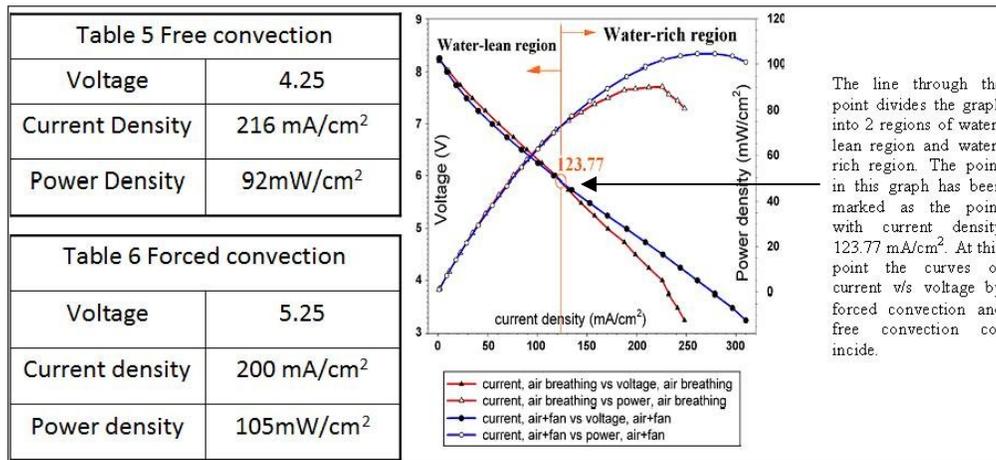


Fig.4. Comparison of forced and natural convection in a series connection. [Chen 2008]

Parallel connection stack has higher power density than serial connected stack since some cells performing badly will affect serial connection where parallel connection won't be affected a lot. [Chen 2008]. The performance of the stack reaches power density of the state of the art planar array fuel cells (100-120 mW/cm²) [Chen 2008]. Clearly, fuel cell components made by RP (FDM) instead of conventional CNC machining or more costly MEM processes do deliver performances as required which does speak about the reliability of the process. So, we infer that RP is a successful procedure in prototyping the components. In the future, we might even see RP being applied for larger scale production.

3. 3D Inkjet printing

3D Inkjet printing is yet another form of Additive Manufacturing. What differentiates 3D printing from other forms of additive manufacturing is that it is much more affordable than other processes existing till date. Inkjet printers are plug and play devices that require little setup, training or maintenance.

Inkjet printing utilizes drop-on-demand technology to deposit various materials in a colloidal ink form. Also, there is no contact between the printer head and the substrate on which it is going to be deposited. There are two types of inkjet printers- one which use piezoelectric transducers and one which use thermal resistors to expel droplets through the nozzles. Development of inkjet printers will result in smaller nozzle sizes and hence ink droplets, which will result in higher resolution (dots per inch) as well as in printing intricate features, patterns which is advantageous in the development of fuel cell components.

Inkjet printing can be employed in printing different MEA's since the composition is not very different from each other. Inkjet printing can be considered as an efficient method used for the deposition of catalyst layers because of the performance it gives in terms of controlled catalyst deposition for ultra loadings of Platinum which results in a better utilization of Pt as compared to conventional catalyst deposition methods like Screen Printing and Hand Painting. Inkjet printing will also help in optimizing the Pt loading which will result in reduction of costs. The reproducibility produced in the catalyst printing is incredible and this will in turn lead to lesser cell failure rates.

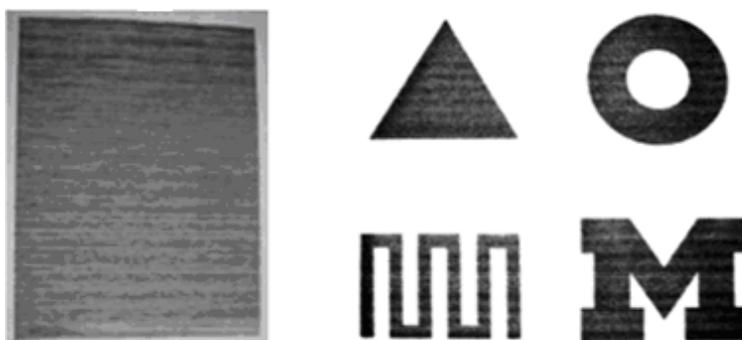


Fig.5. Sample catalyst layers printed using inkjet printing [Taylor 2007]

3.1 Inkjet printing as compared to other printing techniques [Taylor 2007].

IJP as compared to other printing techniques proves to be more advantageous as it allows for a uniform distribution of catalyst material onto the surface of GDL and provides picolitre precision and control of the deposition of each print and thus paves a way for ultra low loadings. IJP is also found to be reproducible due to the elimination of some of the intermediate steps of drying and massing which are two important steps in Hand painting and screen printing.

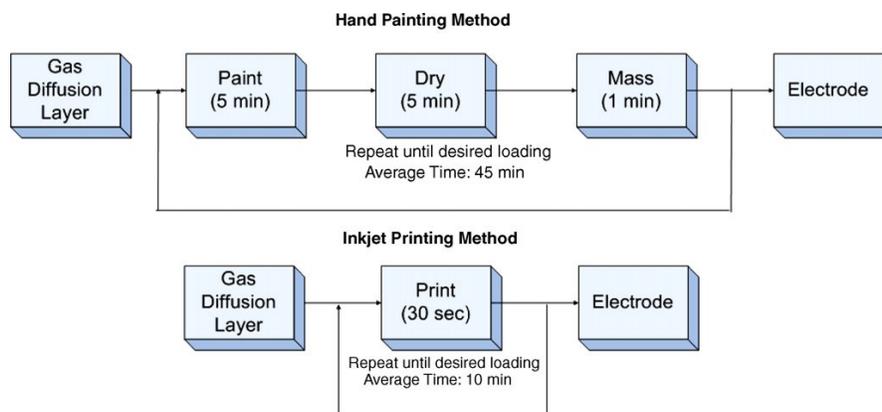


Fig.6. Time illustration of inkjet printing compared to hand painting [Taylor 2007].

Catalyst inks should be similar to the OEM inks as specified by the manufacturer so that the printing can be executed smoothly.

Viscosity (centipoises)	1-4
Surface tension (mN/m)	30-35
Average Particle size (µm)	0.2

3.2 Setup used for the experiment [Towne 2007].

Catalyst formation takes place by thoroughly mixing a carbon supported catalyst with Nafion[®] solution and de-ionized water. Water, ethylene glycol and isopropanol are added to achieve the required properties of surface tension and viscosity. The Nafion[®] membrane is prepared by washing in 3% wt H₂O₂ for 1 hour, rinsed and boiled in de-ionized water for 1 hour and stored in Milli-Q grade de-ionized water. The printers considered for this experiment were simply off the shelf printers whose cartridges were cleaned off the original ink and replaced with the catalyst ink with the help of a syringe. Illustrator software is used for making different size and shape electrodes and for different amounts of platinum loading by changing the hue, saturation and luminescence.

3.3 Results and discussion [Towne 2007].

Property	Result	Within range	Comments
Particle size	< 2 μ m	No	Not within range but the ink is maintaining colloidal stability.
Surface Tension	35.5 mN/m	No	Just a tad out of range.
Viscosity	3.35 cP	Yes	

There were two attempts to print the catalyst layers. One was on a cellulose acetate substrate and the other was on Nafion[®] substrate.

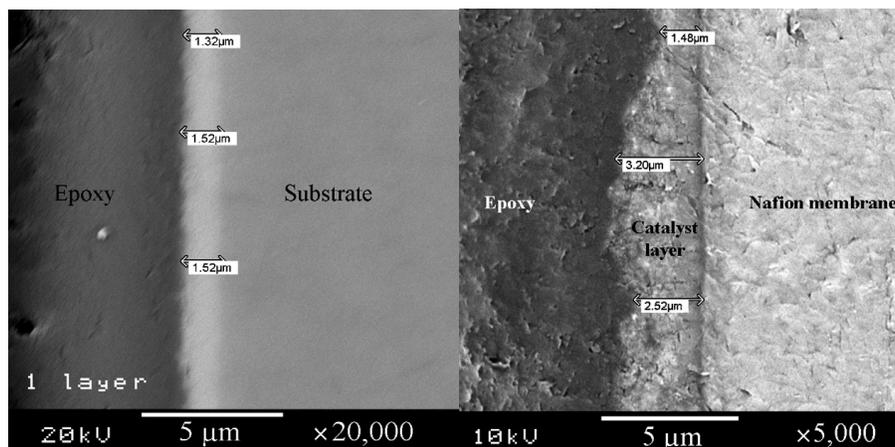


Fig.7. SEM cross section of a single catalyst layer on cellulose acetate substrate [Towne 2007].

In the above the catalyst layer is seen between the epoxy layer and the substrate and its thickness is 1.02 μ m thick since below the thickness of 580 nm, the resistivity of the catalyst increases tremendously which is detrimental to our interests.

Fig.8. SEM cross section of eight printed catalyst layers on Nafion[®] [Towne 2007].

In the above figure a layer thickness upto 3.2 μ m was measured. We can observe here that the thickness of the catalyst layer is not uniform and is very uneven. This happens due to swelling of the Nafion[®] membrane.

As expected, the Nafion[®] substrate swells due to the water and alcohol in the catalyst ink. Water alone can lead to swelling of the membrane by 32%. This results in uneven printing. The cross section of the single layer catalyst section as seen in figure b clearly shows the swelling of the membrane.

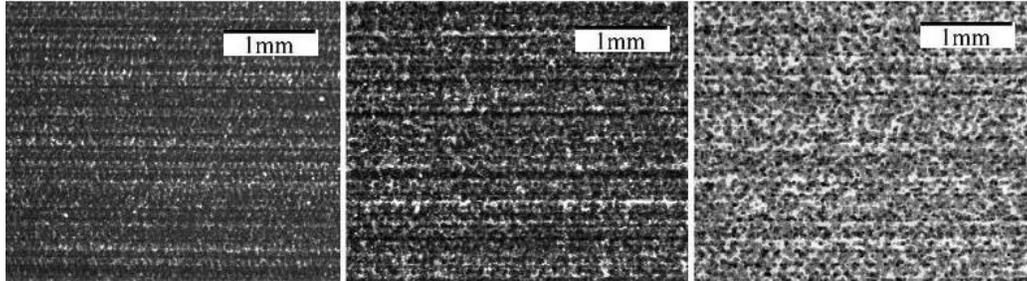


Fig.9. Optical micrographs taken at 15x magnification showing evidence of banding in three samples of different thickness [Towne 2007].

The three figures above show 3 single layer inkjet printed catalysts. They have different amounts of thicknesses (drop amounts). The darker the layer, the thicker it is and hence well connected. This leads to better conductivity.

Thus it is evident that inkjet printing allows excellent control over the individual layer thicknesses. Hence, many layers and ultimately thicker electrodes can be deposited.

The earlier images show that it is difficult to print the catalyst layer on a Nafion[®] membrane, however, with some post processing, the catalyst layer can be made uniform as well as well mechanically adhered to the membrane. The usual post processing steps are hot pressing and water extraction.

Hot pressing leads to removal of ethylene glycol and also it leads to more uniform catalyst formation on the membrane.

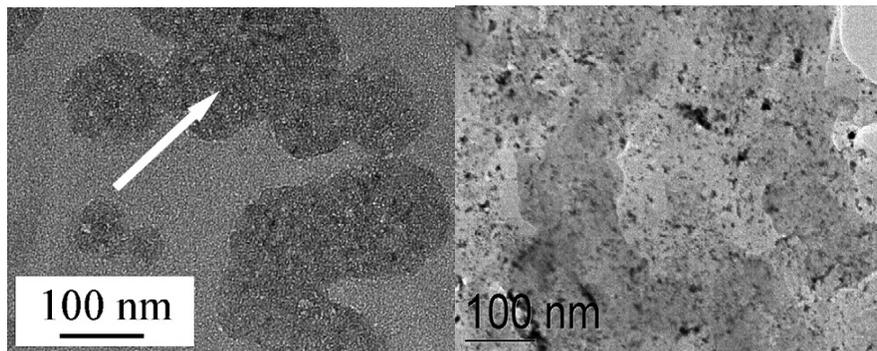


Fig.10. TEM image of printed catalyst layers on Nafion[®] before processing [Towne 2007].

The arrow represents carbon particles. This figure depicts the discrete nature of platinum and carbon particles. This definitely affects the interconnectivity and thus the conductivity.

Fig.11. TEM image of printed catalyst layers on Nafion[®] after hot pressing [Towne 2007].

You cannot make out the separate layers of carbon and platinum particles, thus showing the continuity. Hot pressing was done at 2045 psi, 125°C for 5 min

3.4 Performance of single cells [Towne 2007].

The testing of these catalyst printed membranes was carried out by making a single cell out of it. MEA's had printed layers on both anode and cathode.

Table 9. Specifications of the MEA [Towne 2007].	
Active area of the MEA	2.25 cm ²
Platinum loading	0.094 mg/cm ²
Drop size	3 pL

Only 2.75% H₂ was used for initial studies for comparison of different electrodes. The testing started by the comparison of the unprocessed MEA with hot pressed MEA's.

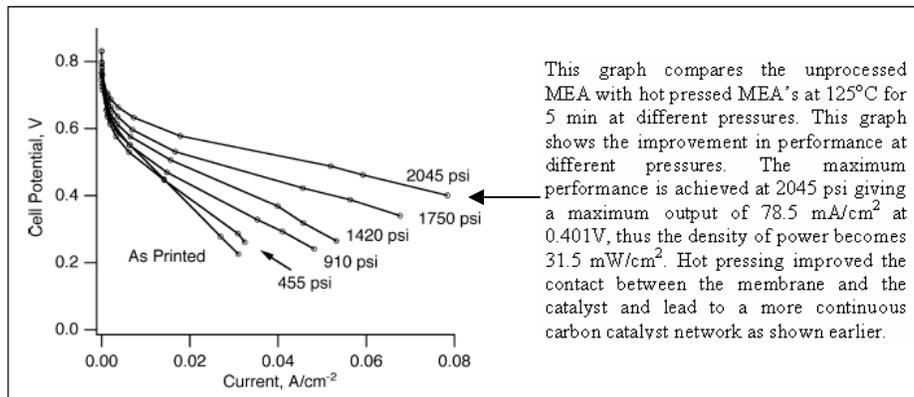


Fig.12. Graph comparing printed MEA with processed MEA's [Towne 2007].

It was presumed that hot pressing did not remove the ethylene glycol completely. Hence water soaking was carried out on the printed MEA to remove the rest of the ethylene glycol. Water soaking led to maximum current output of 106mA/cm² at 0.401V. Thus the density of power is 42.4mW/cm².

After this initial testing, 100% H₂ was used for better comparison with the commercial MEA's. The figure below describes the comparison of different MEA's with 100% H₂ and with different treatments after the printing.

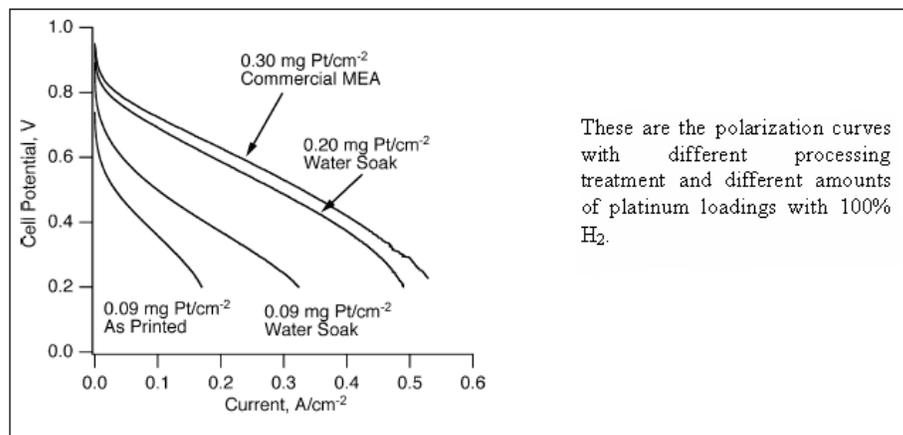


Fig.13. Power Curves comparing a commercial MEA with printed MEA's [Towne 2007].

In figure 13, it is clear the commercial MEA's outperformed those inkjet printed MEA's are having the catalyst loading of 0.094 mg Pt/cm^2 . However, when the catalyst loading was 0.2 mg Pt/cm^2 , it was a comparable performance as compared to commercial MEA's.

Type of MEA	Platinum loading (mg Pt cm^{-2})	Peak power density (mWcm^{-2})
Inkjet printed	0.2	155
Commercial	0.3	167

Hence, with a 33% lower catalyst loading, only 7% lower power density was obtained. This result proves that inkjet printed MEA's can compete with the commercial ones.

Thus, it is evident how efficient can inkjet printing method for fabricating MEA's is as compared to commercial MEA's. The efficiency of the catalyst usage or loading can be further enhanced by grading the amount of platinum loading in every layer. Previous literatures suggest that the graded catalysts were found to perform better than the uniformly loaded catalyst in every layer [Xie 2005, Wang 2004].

Paganin et al. clearly suggests that platinum is better utilized when it is more concentrated near either the GDE layer or the electrolyte membrane layer [Paganin 1996]. Inkjet printing makes it possible to grade the platinum loading print after print. Previous research carried out by Taylor et al. demonstrated that a graded catalyst of Pt wt% 10-50 on carbon black outperformed the uniform catalyst structure of 20 % wt Pt on carbon black at nearly the same amount of overall platinum loading [Taylor 2007].

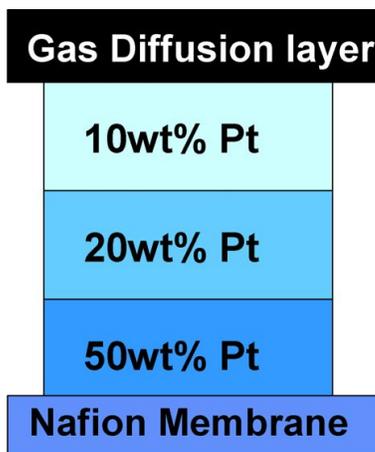


Fig.14. Graded Catalyst layer [Taylor 2007].

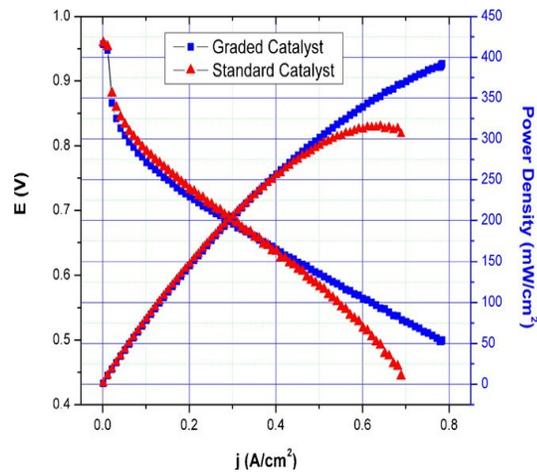


Fig.15. Performance comparison of a standard uniform catalyst to a graded catalyst [Taylor 07].

4. SELECTIVE LASER SINTERING

The functions of bipolar plate are:

- To provide electrical contact between two adjacent MEA's.
- Uniformly distribute hydrogen gas and oxygen gas/air to the anode and the cathode side of the MEA respectively.
- To serve as a platform to support the soft MEA.
- To act as an outlet medium for heat and water vapor generated from the net reaction.

Hence, the requirements for a bipolar plate accordingly are:

- High electrical conductivity
- Plate material electrically compatible with the electrode
- Very low gas permeability for reactant gases.
- High thermal conductivity to make use of the waste heat.
- Chemical stability i.e. corrosion resistant.
- Low density plate material to keep the stack volume and weight low.
- Inexpensive plate material.

4.1 Material selection for a fuel cell bipolar plate

There are three types of materials identified for the manufacture of fuel cell bipolar plates which are: pure graphite, metallic materials, and carbon-polymer composites.

Pure graphite

Pure graphite is a very good conductor of electricity with peak conductivity of 1.44×10^3 S/cm. Graphite is very difficult to machine when it comes to the machining of the flow field channels because of its flaky microstructure and irregular geometry. This also reduces its mechanical strength [Chen 2006].

Metallic materials

Metal powders such as stainless steel, titanium, gold, aluminum, have good machining characteristics as compared to graphite. However, gold and titanium are very costly. Aluminum can be used with a gold coating. However, there is large difference in co-efficient of thermal expansion which leads to micro-cracks in the coating. Stainless steel has corrosion issues [Maeda 2004, Chen 2006].

Composite materials

Composite materials suitable for the application of bipolar plates are a combination of porous graphite along with polycarbonate plastic. Graphite is an allotrope of carbon and a semimetal. The carbon based materials suitable are resins such as polyethylene, phenolic, Vinyl ester etc. with filler materials like carbon black and carbon/graphite powders. These composite systems provide electrical conductivity as well as corrosion resistance and mechanical strength [Chen 2006].

4.2 Set-up and procedure for the experiment.

There are two kinds of SLS procedures: Direct and Indirect

- Direct SLS means parts are produced by just laser sintering of the powder without any post processing measures
- Indirect SLS involved production of a porous green part held together by a certain polymer binder followed by some post processing measures.

According to the research conducted by Chen, indirect SLS of carbon based composite material accommodates the material and procedure selection criteria for the PEM fuel cell bipolar plate fabrication [Chen 2006]. This Indirect SLS proceeded in 3 stages to meet all the plate requirements:

1. SLS of bipolar plates
2. Carbonization of the binder
3. Epoxy infiltration

Powder constituents	Graphite (GrafTech GS150E) and Phenolic resin (Georgia Pacific GP5546)
Composition:	70w% graphite and 30 w% phenolic resin
Average particle size	Graphite: 80 μm Phenolic resin: 11 μm
Powder mixing	Roller mixed
SLS machine	DTM Sinterstation 2000
CO ₂ laser power	10~20 W
Laser scan speed	60 in/s
Laser scan spacing	0.003 in
Powder layer thickness	0.004 in
Powder bed preheating Temp	60°C
Purging gas	Nitrogen

After the SLS process, post processing of the bipolar plates was further carried out. The post processing basically consisted of two steps of binder carbonization and epoxy infiltration.

CARBONIZATION PROCESS [Chen 2006].

A vacuum furnace was used for this purpose. The maximum heating capacity of the vacuum furnace being 2000°C. Argon gas was filled into the chamber to prevent oxidation of carbonized phenolic resins which reduce the glassy carbon yields.

Table 12. Temperature rise and the ramp rates [Chen 2006].		
	TEMPERATURE	RAMP RATE
INITIAL PROFILE	Room Temp-200°C	60°C/hr
INTERMEDIATE PROFILE	200°C-600°C	30°C/hr
FINAL PROFILE	At 800°C	0

At 800°C, the dwelling time was 1 hour. During this process the phenolic binders are burned off and a part of it was converted into glassy carbon. This resulted in good interconnected pores which increased the electrical conductivity as well as the mechanical strength of the parts.

EPOXY INFILTRATION FOR FINAL SEALING [Chen 2006].

After the carbonization process, the structure was still found to be porous. Epoxy resin was chosen as the infiltrant to seal these pores because of its good mechanical strength, chemical stability and ability to wet most substrate materials. Clear coat resin which is a mixture of more than 70% diglycidyl ether of bisphenol A and less than 30% alkylglycidyl ether was used for this purpose. The resin was initially cured with the help of a hardener and then diluted with solvents like toluene, xylene etc., this was done in order to reduce the viscosity of the resin so that it can easily penetrate through the cured pore structure. The epoxy, hardener and the solvent should be mixed in proper ratios (2:1:1) to avoid the formation of un-reacted epoxy and hardener which affect the final part properties. So as to form a gas tight plate structure the brown part were immersed in the infiltrant at least twice. The parts were then oven dried at 60°C for several hours to remove residual moisture. The electrical conductivity of the infiltrated parts was found to be better than the brown parts.

4.3 Results and discussion

Table 13. Properties of the SLS bipolar plates [Chen 2006].		
PROPERTY	TEST METHOD	VALUE
Flexural strength	Two point bend test	1730psi
Electrical Conductivity	Four point probe test	80 S/cm
Specific weight	Archimedes principle of fluid displacement	Avg. density=1.27g/cm ³
Corrosion Rate	Tafel extrapolation method	6μA/Cm ²
Gas Permeability	Mass spectrometer leak detector	5x10 ⁻⁶ Cm ³ /Cm ² .s
Interfacial contact resistance		<200mΩ.cm ² / 1.6MPa

All the above properties were found to be satisfactory but the electrical conductivity of these bipolar plates could be improvised to meet the target set by the DOE [DOE 2005]. The following methods were followed to improve the electrical conductivity [Chen 2006]:

- Infiltration of brown parts with conductive polymer
- Addition of a liquid phenolic infiltration/re-curing step prior to final sealing
- Reduction of glassy carbon resistivity by curing process parameter control

These processes showed results which are quantified as below

Table 14. Enhancement in electrical conductivity.	
First Infiltration/Recurring step	~108 S/Cm (35% boost in the conductivity)
Second Infiltration/Recurring step	~117 S/Cm (8.3% further enhancement)

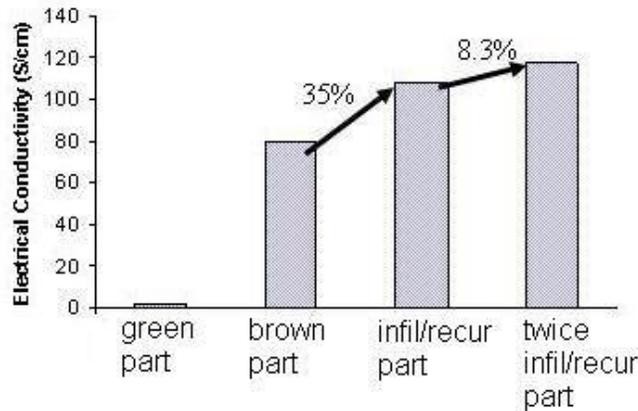


Fig.16. Graph showing the improvement in electrical conductivity with each process [Chen 2006].

5. Conclusions

The paper reviews three Additive Manufacturing (AM) processes. Each process is suitable for building specific fuel cell components. Performance characteristics of these components fabricated using AM processes prove that they give performance equal or better than the components fabricated by conventional techniques. Inkjet printing, amongst all AM processes is the process where most of the research has been undertaken with regards to building fuel cell components. The reason for that is it is easiest to commercialize as compared to rest of the methods since off the shelf printers have been demonstrated to produce components competitive with the commercial ones. FDM is convenient for planar array fuel cells as compared to MEMS and CNC manufacturing. Indirect SLS of graphite composite bipolar plate demonstrates fabrication of plates having superior characteristics which also meet DOE specifications. Development of these processes on a commercial basis is still under a lot of investigation.

6. ACKNOWLEDGEMENTS

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