International Seminar on Forming Technologies, BIEC Bangalore
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3D Printing of Bipolar Plates

Prof. P. P. Date

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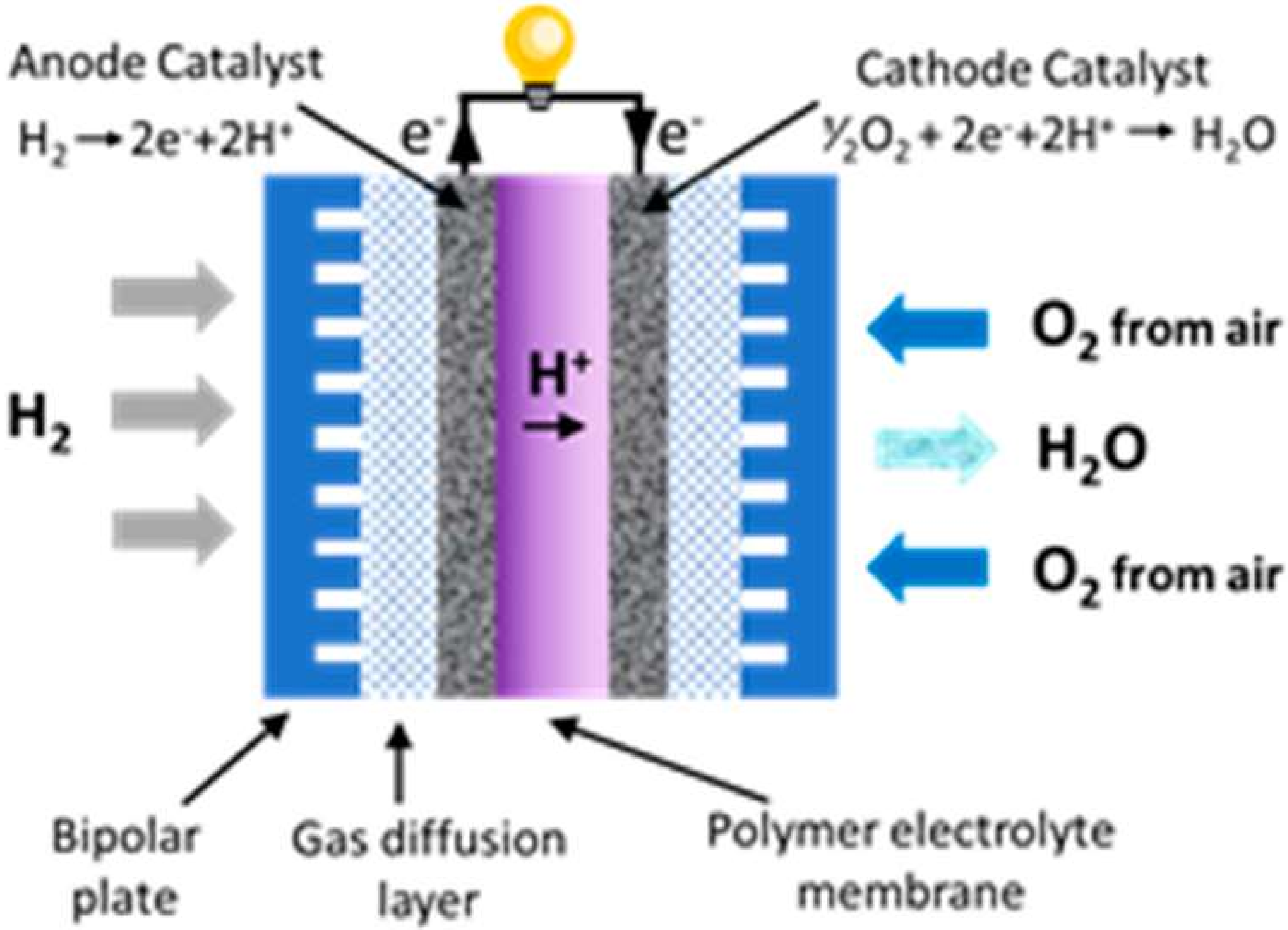
Disclaimer

- The material presented herein is largely taken from published literature as gratefully acknowledged on each slide. Few slides based on the work of the Authors are also included for completeness.

Fuel cell Components

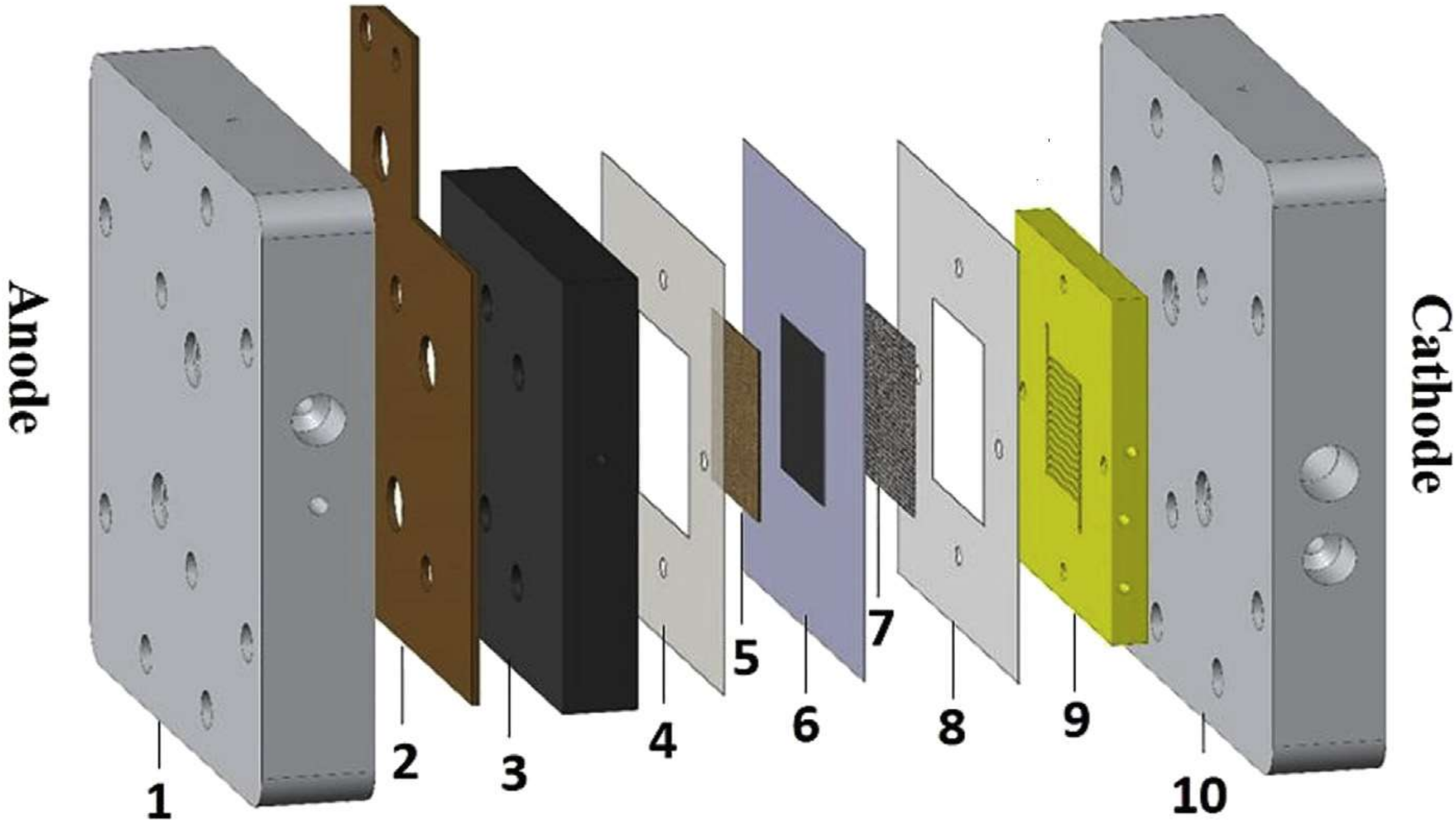
- Three essential components are anode (i.e. the component responsible for fuel oxidation and proton generation), electrolyte (i.e. the part responsible for ions (O^{2-} or H^{+}) transport), and cathode (i.e. the component responsible for catalytic oxygen reduction)
- Components with porous surface and highly flexible structures are conducive to electrochemical reactions
- Structural and mechanical properties of fuel cell components play vital roles during their operations
- Performance will also depend on properties of other components responsible for diffusion of gas and reactants (e.g. bipolar plates (BPPs))
- AM processes are useful for eliminating joints, welding and cracks (part integration)

Schematic of fuel cell



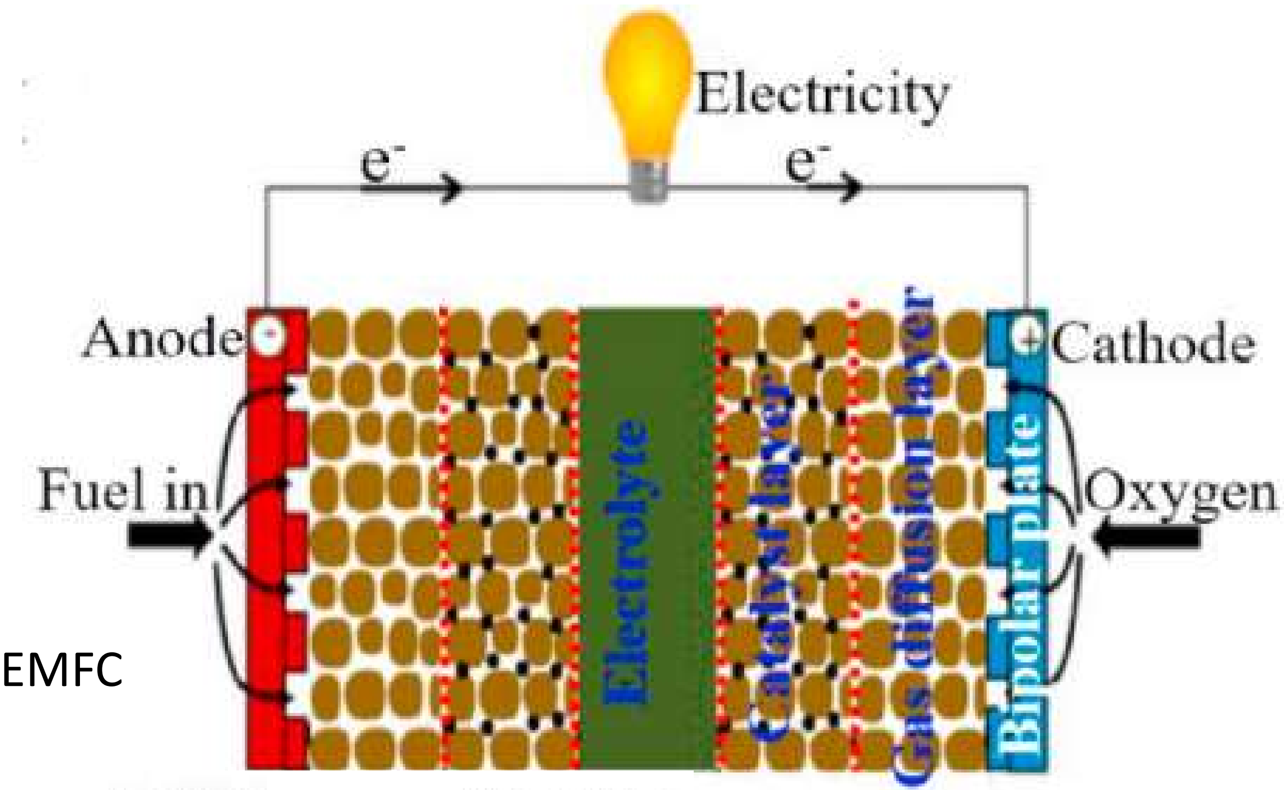
S. Golubkov, S. M. Morozova, Polymers 15(2023)4553

Fuel Cell : Opened up view

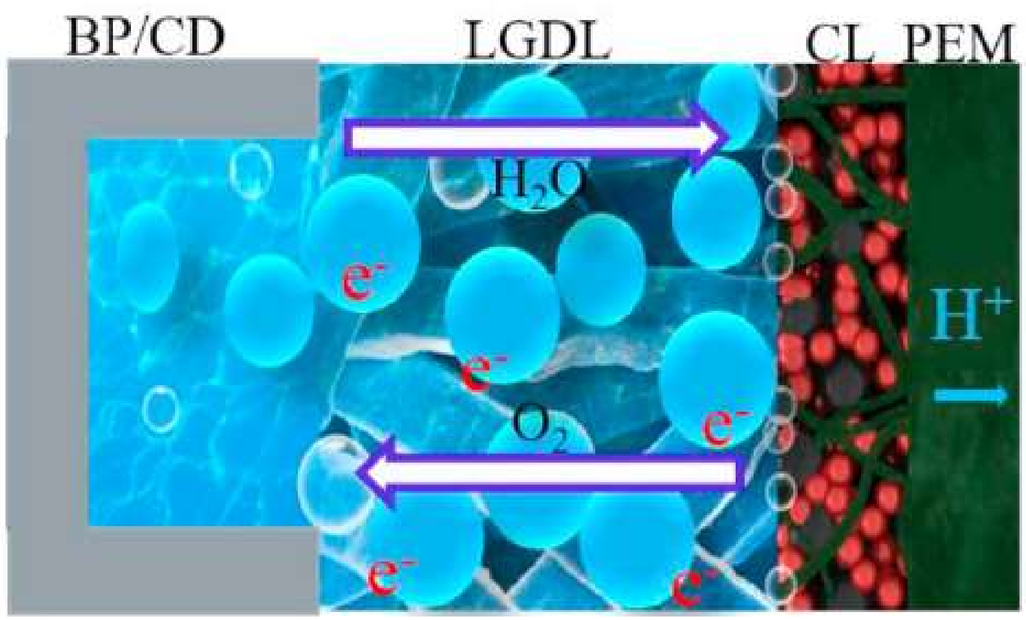


1 anode end plate, 2 anode current distributor,
3 graphite bipolar plate, 4 anode gasket, 5 Ti felt LGDL, 6 CCM, 7
e carbon paper LGDL, 8 cathode gasket, 9 AM SS
bipolar plate, 10- cathode end plate.

G. Yang et. Al., Int. J. Hydrogen Energy, 42 (2017) 14734-14740



Working principle of a PEMFC



Gas and reactant Transport through GDL of a PEMFC (Proton Exchange membrane Fuel Cell)

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Membrane Based Fuel Cells (MBFCs)

SLFCs types	Electrolyte	Electrode	T (°C)
Direct ethanol fuel cells	Polymer membrane (ionomer)	CS	≤100
Proton exchange membrane fuel cells	Polymer membrane (ionomer)	CS	≤100
Molten carbonate fuel cells	Molten alkaline carbonate	CS	600–650
Phosphoric acid fuel cells	Molten phosphoric acid	CS	150–200
Direct formic acid fuel cells	Polymer membrane (ionomer)	CS	<40
Direct carbon fuel cells	Polymer membrane (ionomer)	CS	≤800
Metal hydride fuel cells	Alkaline solution	CS	≤0
Direct borohydride fuel cells	Alkaline solution	CS	70

CS = Carbon Support

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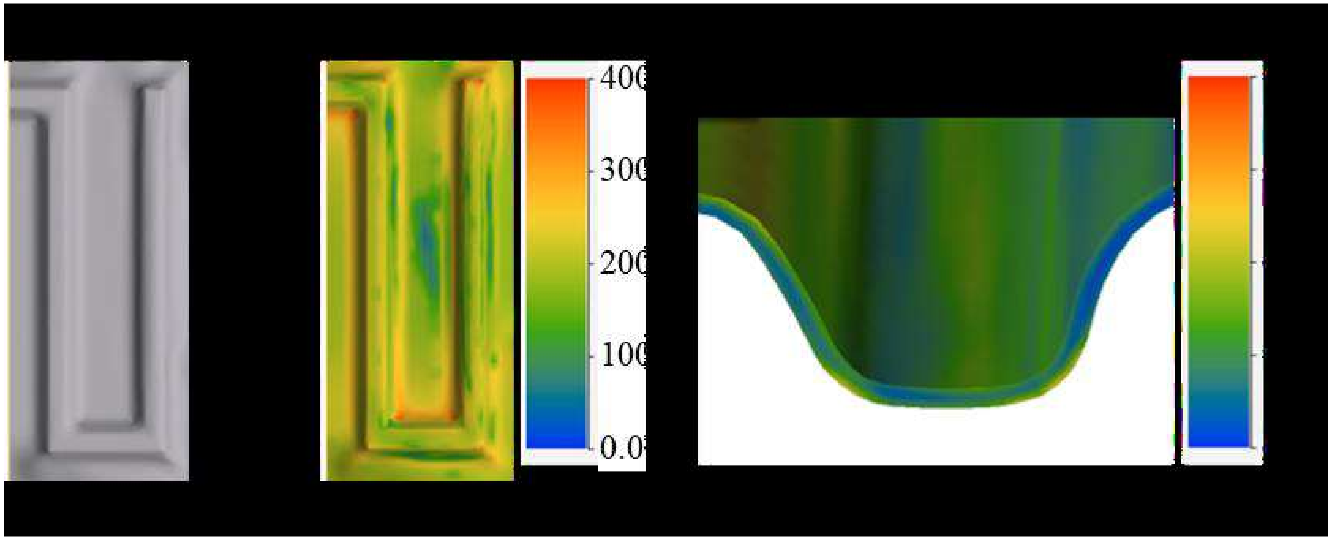
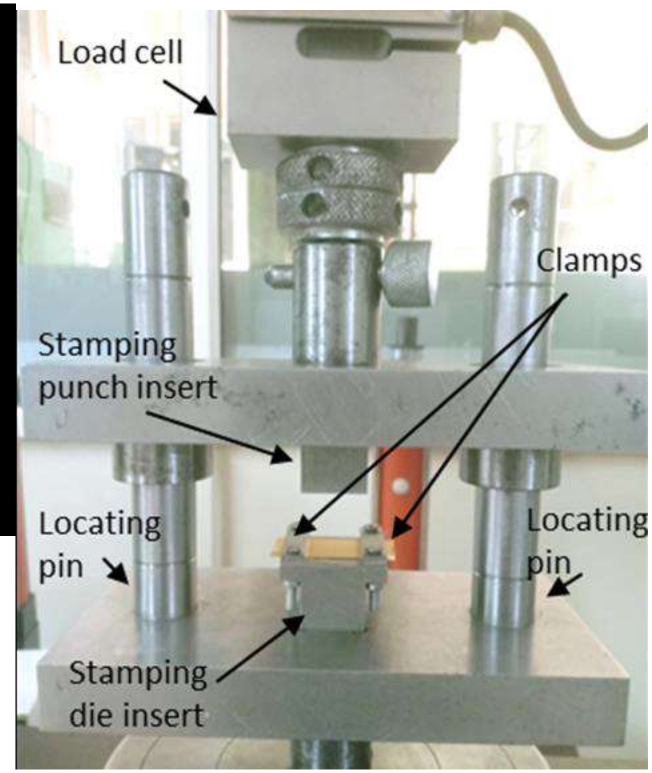
Bipolar plates (BPPs)

- Provide continuous current of Hydrogen, remove reaction products and heat through a complex system of channels
- The catalyst deposited to the electrode should have a complex microstructure, i.e., porosity for providing sufficient permeation of gases and help for water vapour to reach the Polymer electrolyte membrane membrane and enhance its ionic conductivity
- High level of uniformity of coating is needed for the catalyst coating

Bipolar Plates by Warm Stamping



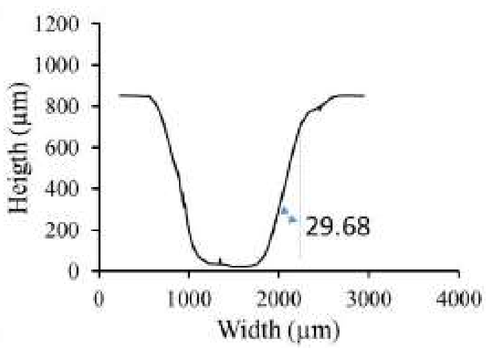
FEM Simulation of stamping process



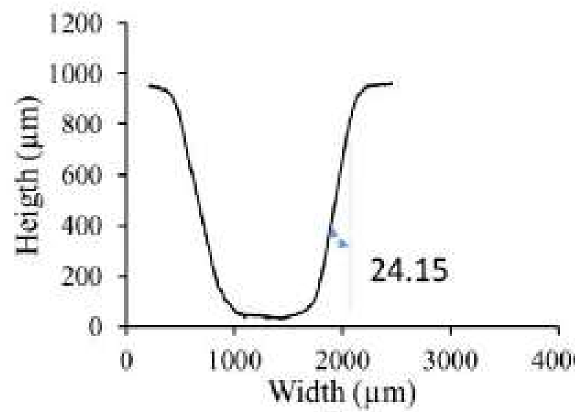
Bipolar plate

(b)

Dimensions



(c)



(f)

Bipolar plate

Dimensions

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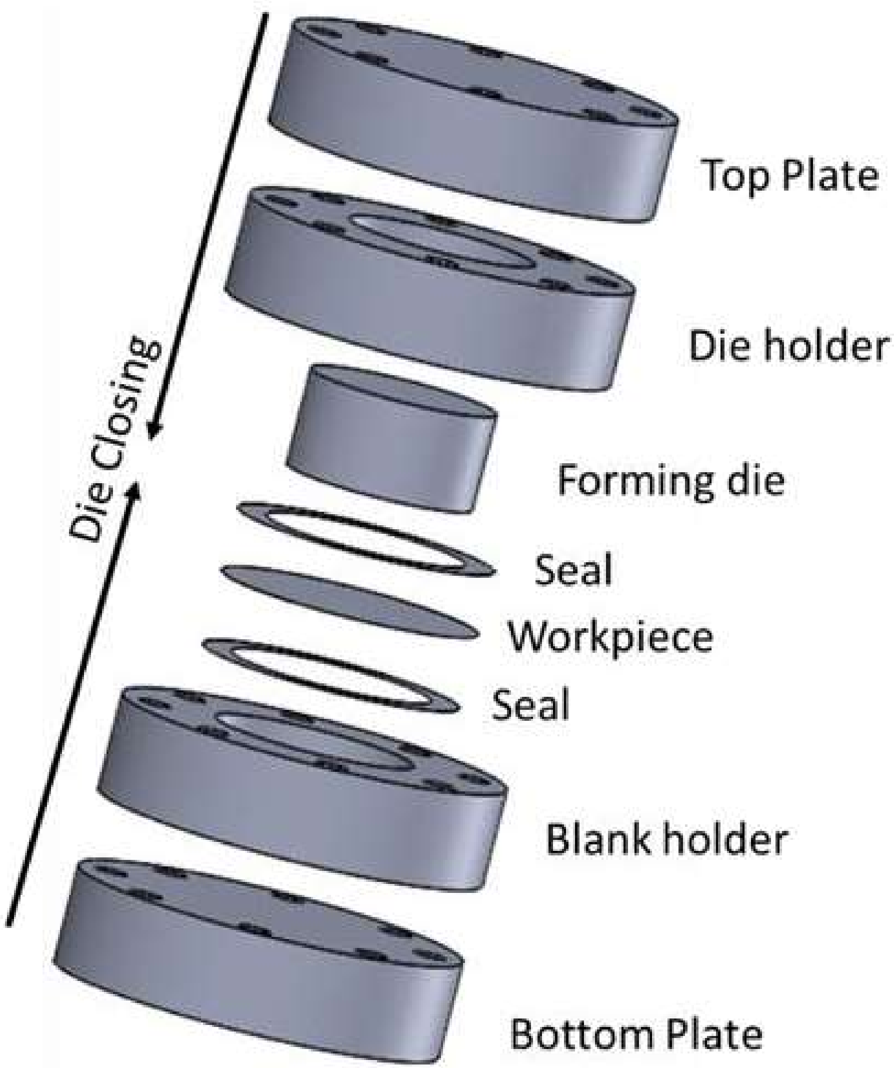
Bipolar Plates : Hot gas forming



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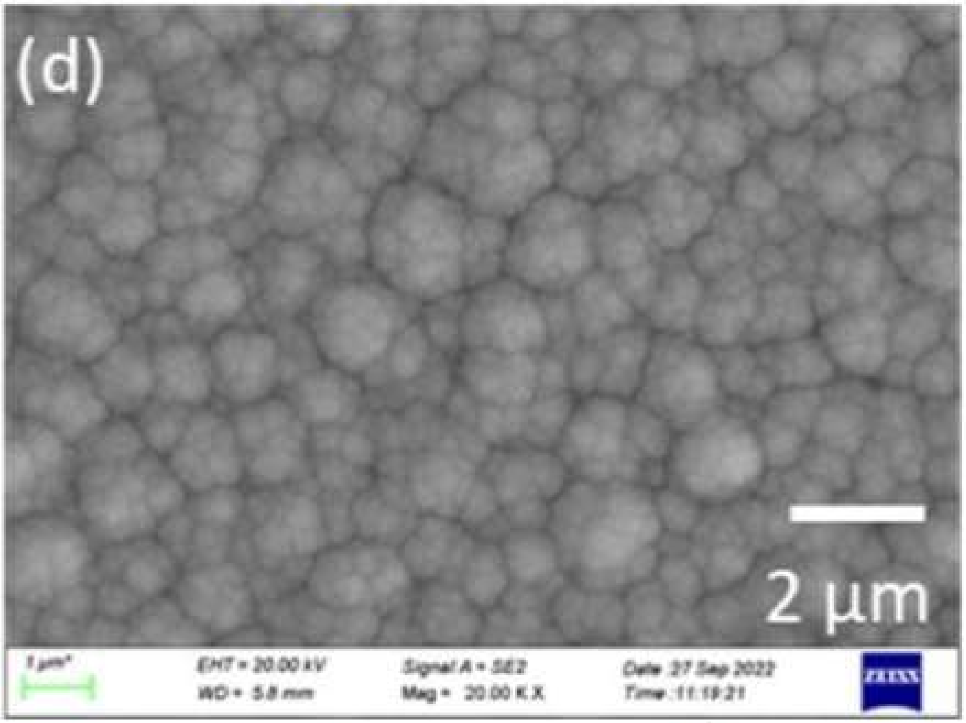
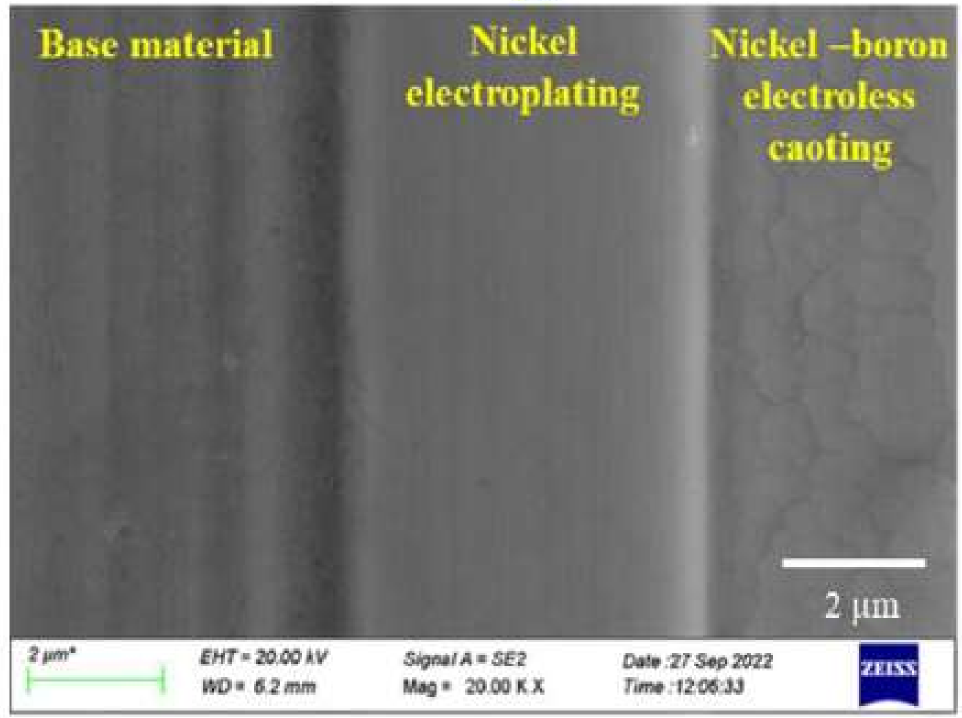
Corrosion & Wear resistant Ni-B coating



Coating growth



Developed coating

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Additive Manufacturing of Fuel Cell Parts

- Fuel Cells manufacturable by AM processes are
  - ceramic,
  - microbial,
  - polymer electrolyte membrane,
  - laminar flow fuel cells
- Ceramic fuel cells are electrochemical conversion devices using oxides as electrolytes.
- Steam reforming fuel cells
- Operating temperature >500 ◦C

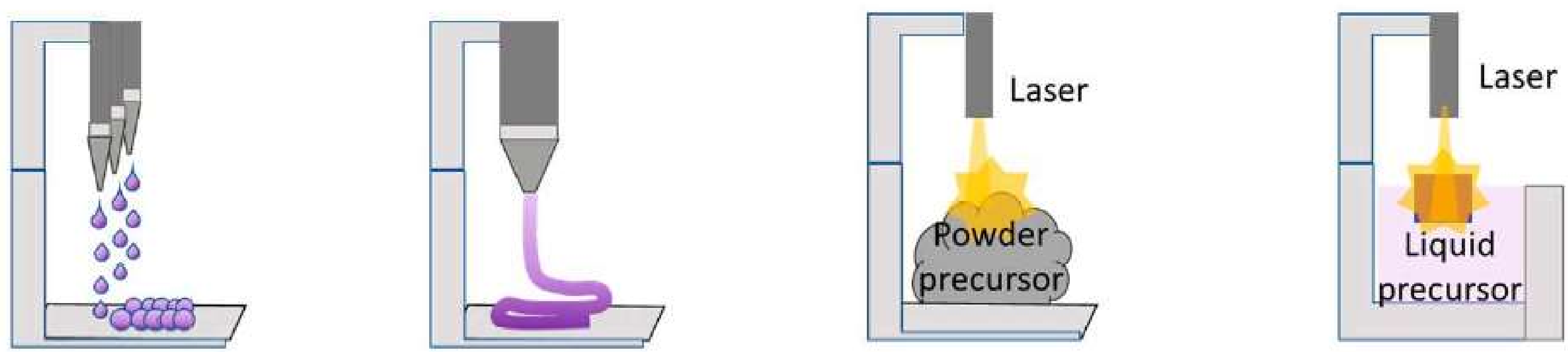
AM suits SOFC Electrolytes

- The two major factors needed to put into consideration are density and thickness when electrolyte is being engineered for improving the performance of SOFCs

Manufacture by 3D printing

Methods of 3D printing

(a) Inkjet printing **(b) FDM** **(c) SLS** **(d) Stereolithography**



(a) Inkjet printing

Highest resolution: 20 µm
Precursor state: liquids

Precursor rheology: Ohnezorge number 0.1-1

(b) FDM

Highest resolution: 100 µm
Precursor state: liquids, melts or gels

Precursor rheology: flow viscosity 10^2-10^9 Pa·s

(c) SLS

Highest resolution: 50 µm
Precursor state: solid powder

Precursor rheology: none

(d) Stereolithography

Highest resolution: 20 µm
Precursor state: liquids

Precursor rheology: flow viscosity <10^3 Pa·s

(a')

Catalyst deposition

Gas diffusion layer

(b')

Catalyst deposition

Gas diffusion layer

Bipolar plates

(c')

Gas diffusion layer

Bipolar plates

(d')

PEM patterning

Bipolar plates

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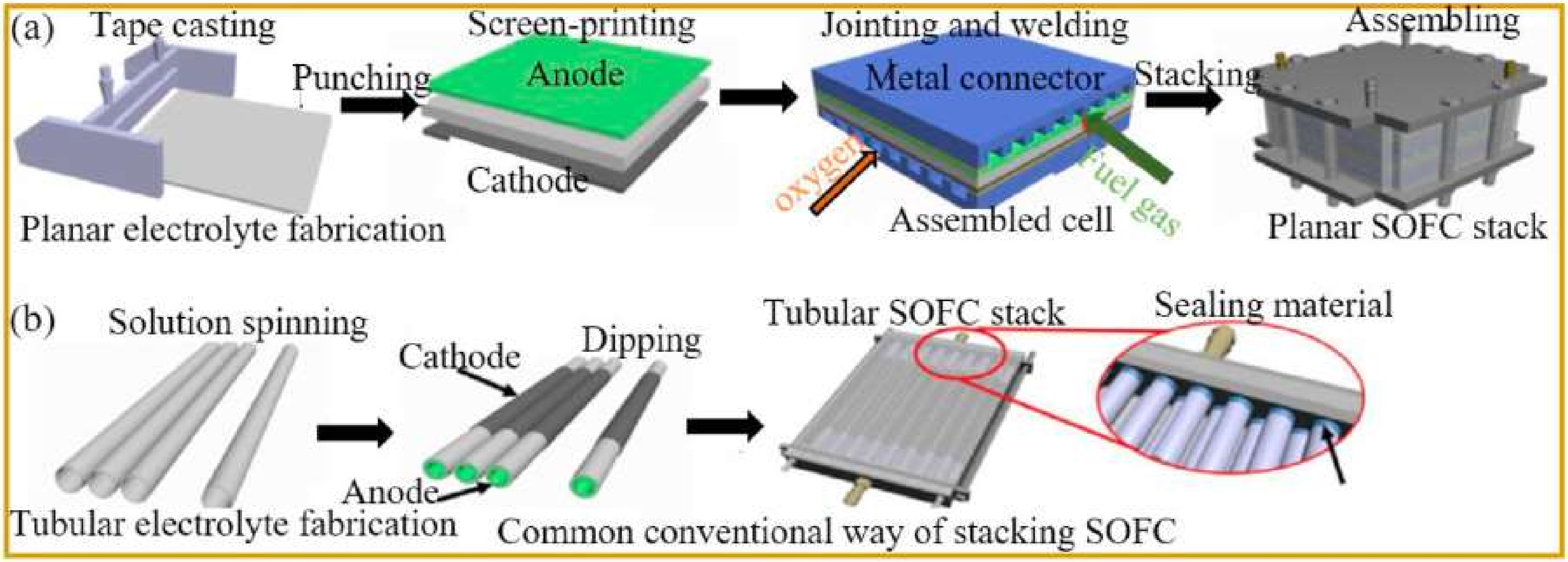
Conventional method of manufacture



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Demerits of Traditional Methods of manufacture

Techniques	Material requirement	Advantages	Disadvantages
Screen printing	slurry	simple, economical, and versatile	Limited resolution, wea mechanical properties, not suitable for complex structures design, high volume of ink requirement, and excessive material use and wastage
Dry pressing	Solid ceramics	Cost-viability, fast and easy to operate, and user-friendly	Poor resolution, low porosity, rigid structures with poor mechanical strength, poor flexibility, and not suitable for complex structure fabrication
Chemical vapor deposition	Thermally volatilized solid	Suitable for thin film electrode and electrolyte fabrication, and highly flexible for complex structure design	High cost, user-unfriendly, sophisticated apparatus, and not suitable for porous electrode fabrication
Spray painting	slurry	Cost effectiveness, suitable for thin film electrode and electrolyte fabrication	high material waste, excessive waste generation, poor resolution, low and weak mechanical strength
Physical vapor deposition (e.g. e-beam evaporation, sputtering, and pulse layer deposition etc.)	Volatile solid	It is flexible and suitable for thin film electrodes and electrolytes deposition	High cost, and poor material porosity

Cheap methods : Milling, Moulding and Dry Pressing

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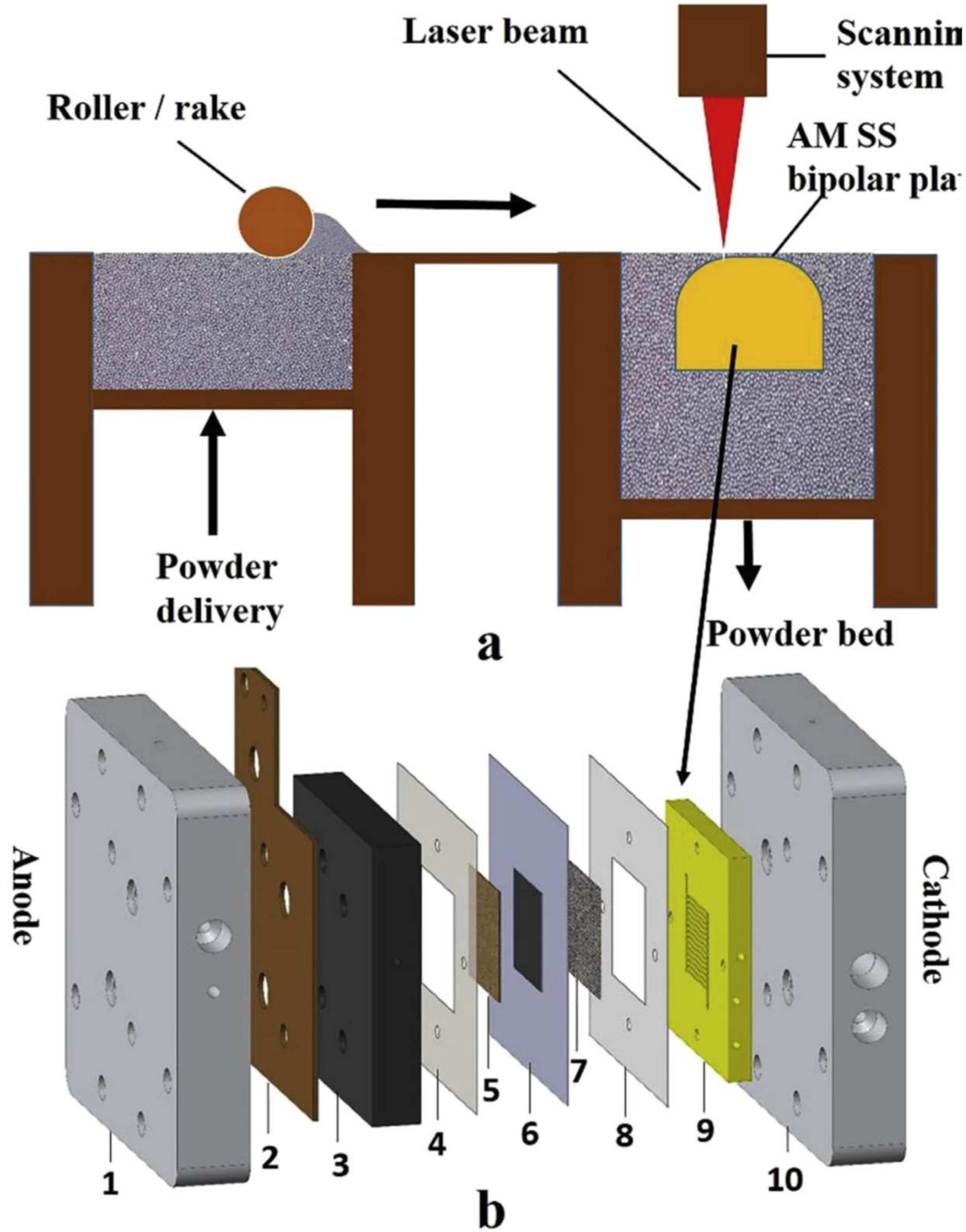

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Fuel Cell Components and Technologies

Fuel cells type	Major component	Applicable AM techniques
SOFC/ PCFC	(1) Porous electrodes (2) Dense electrolyte	(1) Slurry and powder based techniques (2) Slurry and powder based techniques
PEMFC	(1) Bipolar plate (2) Catalyst layer (3) Gas diffusion layer	(1) Powder based techniques (2) Slurry based techniques (3) Powder based techniques
MFC	(1) Electrode (2) Electrolyte (3) Casing	(1) Powder and slurry based techniques (2) Slurry based techniques (3) Powder based techniques
LFFC	(1) Microchannel electrode	(1) Powder based techniques

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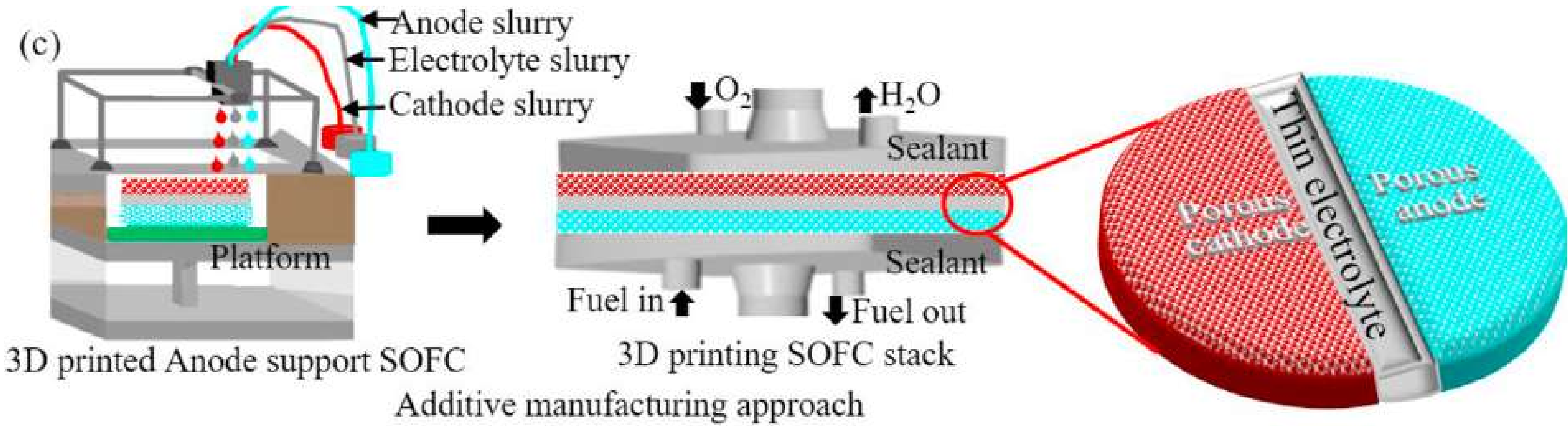
Additive Manufacturing



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AMT	Merit	Demerit
SL	(1) Suitable for complex structure design. (2) Suitable for the design of fuel cell components with high resolution. (3) It aids fabrication of fuel cell components with large size.	(1) Slow operation process. (2) Complex operation process. (3) Material requirement processing is complex due to the incorporation of photosensitive resins.
IJP	(1) Cheapest among AM techniques (2) Easy setup and operation, and maintenance (3) Suitable for microstructure design	(1) Not suitable for fuel cell components with large sizes (2) slow operation process
DLP	(1) Suitable for the fabrication of components with high resolution and precision (2) Fast operation	(1) Only suitable for the fabrication of small sized components (1) It is expensive (3) Material processing is difficult due to requirement for photosensitivity.
PBI	(2) Printing process is simple and fast. (1) Cheap	(1) It produces materials with low resolution. (2) Not suitable for complex structure design
SLS	(1) It is fast and cheap (2) Suitable for microstructure design	(1) Not suitable for the fabrication of components with high resolution
SLM	Same as SLS, but cheaper	Same as SLS

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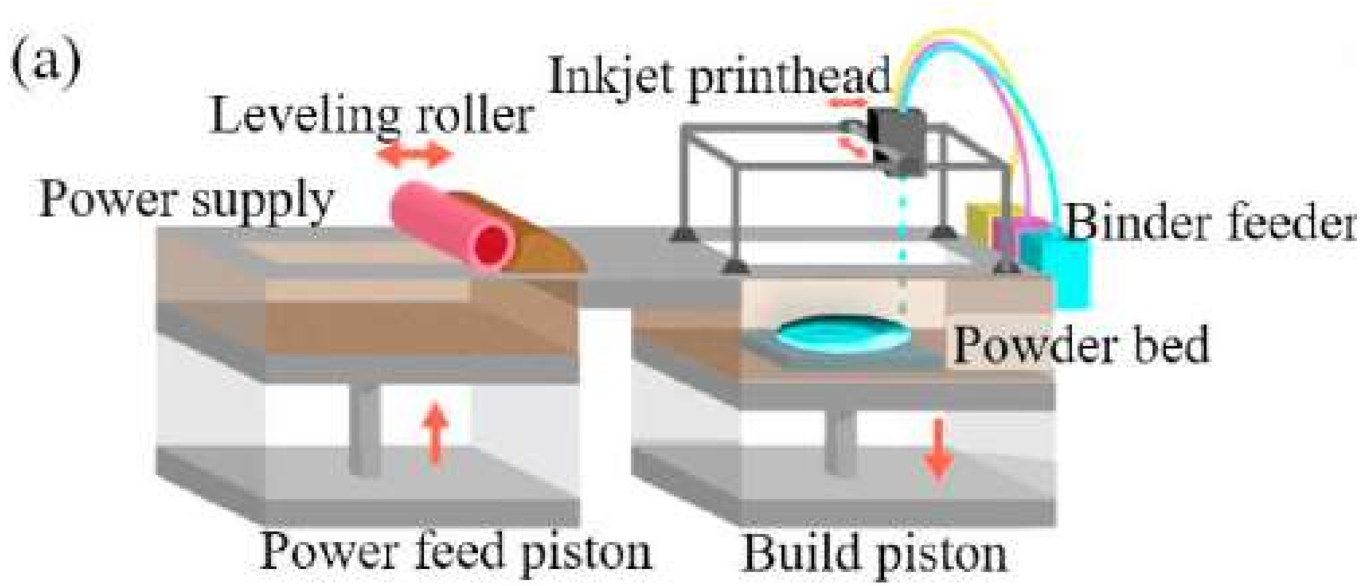
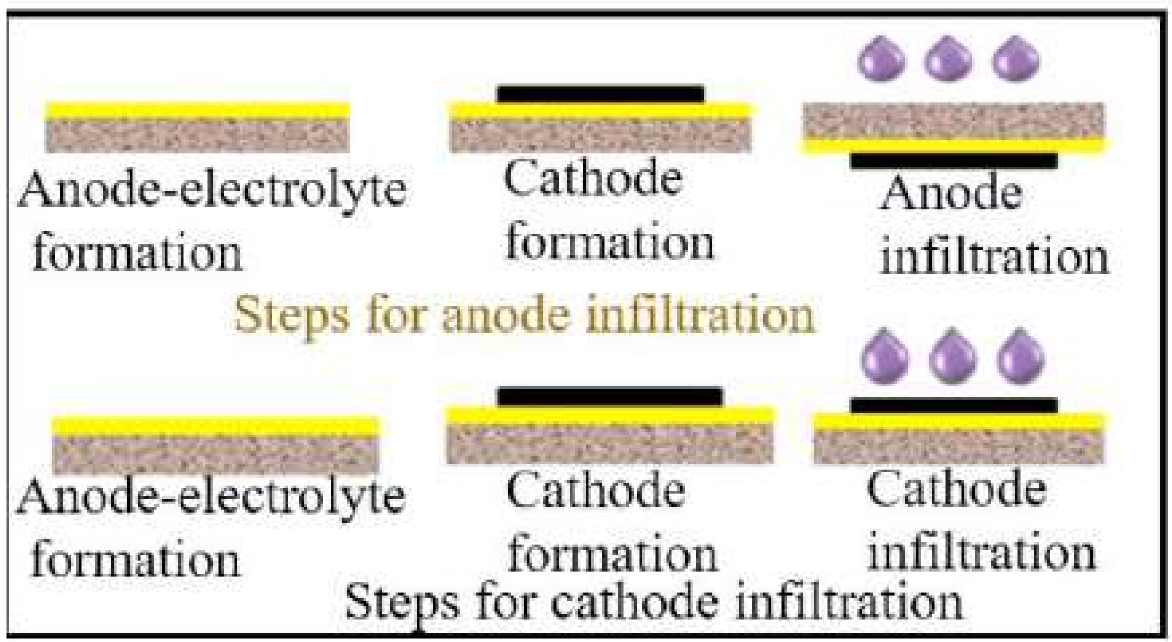
Inkjet Printing





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Thickness of 3D Printed Solid Electrolyte And SOFC Preformance

3D printed electrolyte	ET	AMT	SOFC-E	OT	PPD	OCV
YSZ-LSM	23.0	IJP	Ni-YSZ/YSZ/ YSZ-LSM/ LSM	80	–	0.84
YSZ	1.2	IJP	NiO-YSZ/ YSZ/YSZ/ LSM-YSZ	800	1.50	1.09
GDC	–	IJP	NiO-YSZ/ GDC + YSZ/ LSM-YSZ	–	–	–
YSZ	6.0	IJP	NiO-YSZ/ YSZ-SDC/ LSM	800	0.86	1.05
YSZ	6.0	IJP	NiO-YSZ/ YSZ + SDC/ BSCF	800	1.04	1.10
YSZ	6.0	IJP	NiO-YSZ/ YSZ/LSM + YSZ/LSM	800	0.17	1.01
YSZ	10	IJP	NiO-YSZ/ YSZ/LSM + YSZ	800	0.30	1.10
YSZ	6	IJP	NiO-YSZ/ YSZ/LSM	750	0.17	1.06
SDC	1200	DIW	NCAL/SDC-SC/NCAL	550	0.44	1.00
YSZ	<5.0	IJP	NiO-YSZ/ YSZ/SSC + SDC	750	0.94	1.10
YSZ	500	DLP-SL	Ag-GDC/ YSZ/Ag-GDC	850	0.17	1.04

ET* = Electrolyte thickness (μm), AMT* = Additive manufacturing techniques, SOFC-E* = SOFC component (anode/electrolyte/cathode), OT* = Operating temperature (°C), OCV* = Open circuit voltage (V), PPD* = Peak power density (W cm^{-2}), NCAL* = $Ni_{0.8}Co_{0.15}Al_{0.05}LiO_{2-\delta}$. SSC* = $Sm_{0.5}Sr_{0.5}CoO_3$, SDC* = $Sm_{0.2}Ce_{0.8}O_{1.9}$, GDC* = $Ce_{0.8}Gd_{0.2}O_{1.9}$, LSM* = $La_{0.9}Sr_{0.1}MnO_3$.

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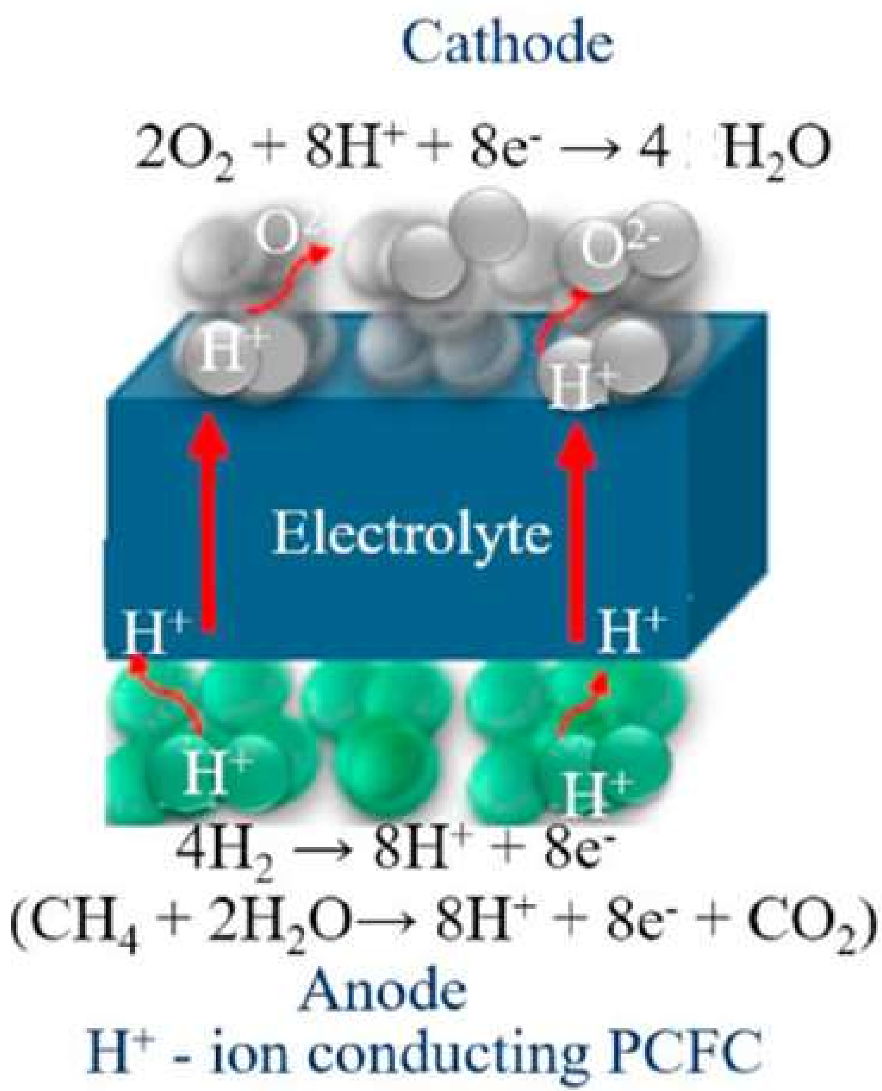
Protonic Ceramic Fuel Cells : Proton Transfer Mechanism



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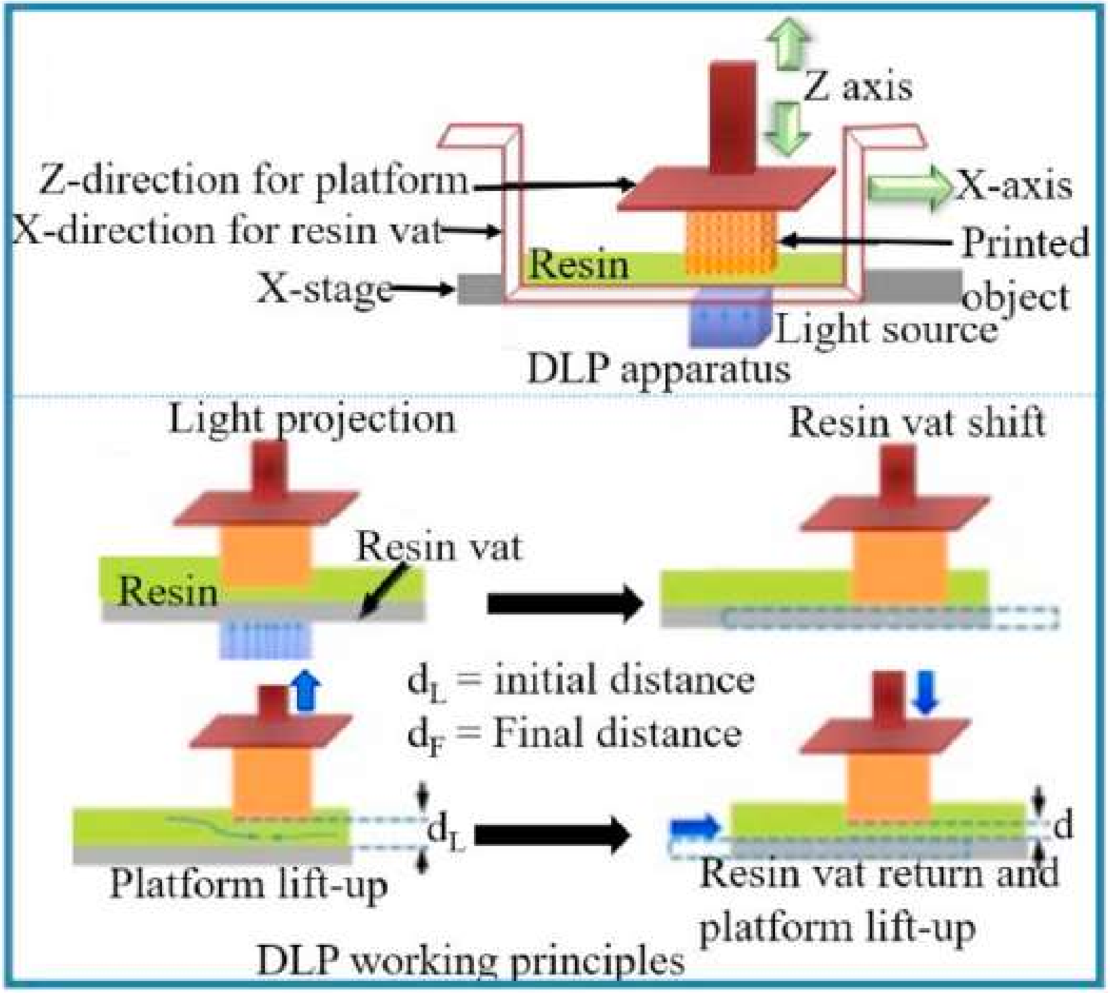
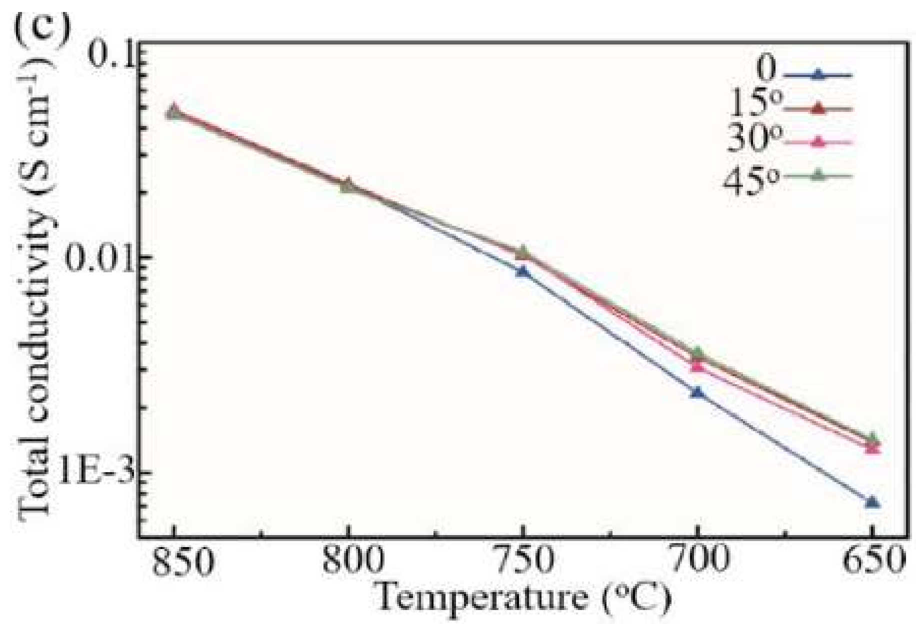
Digital Light processing





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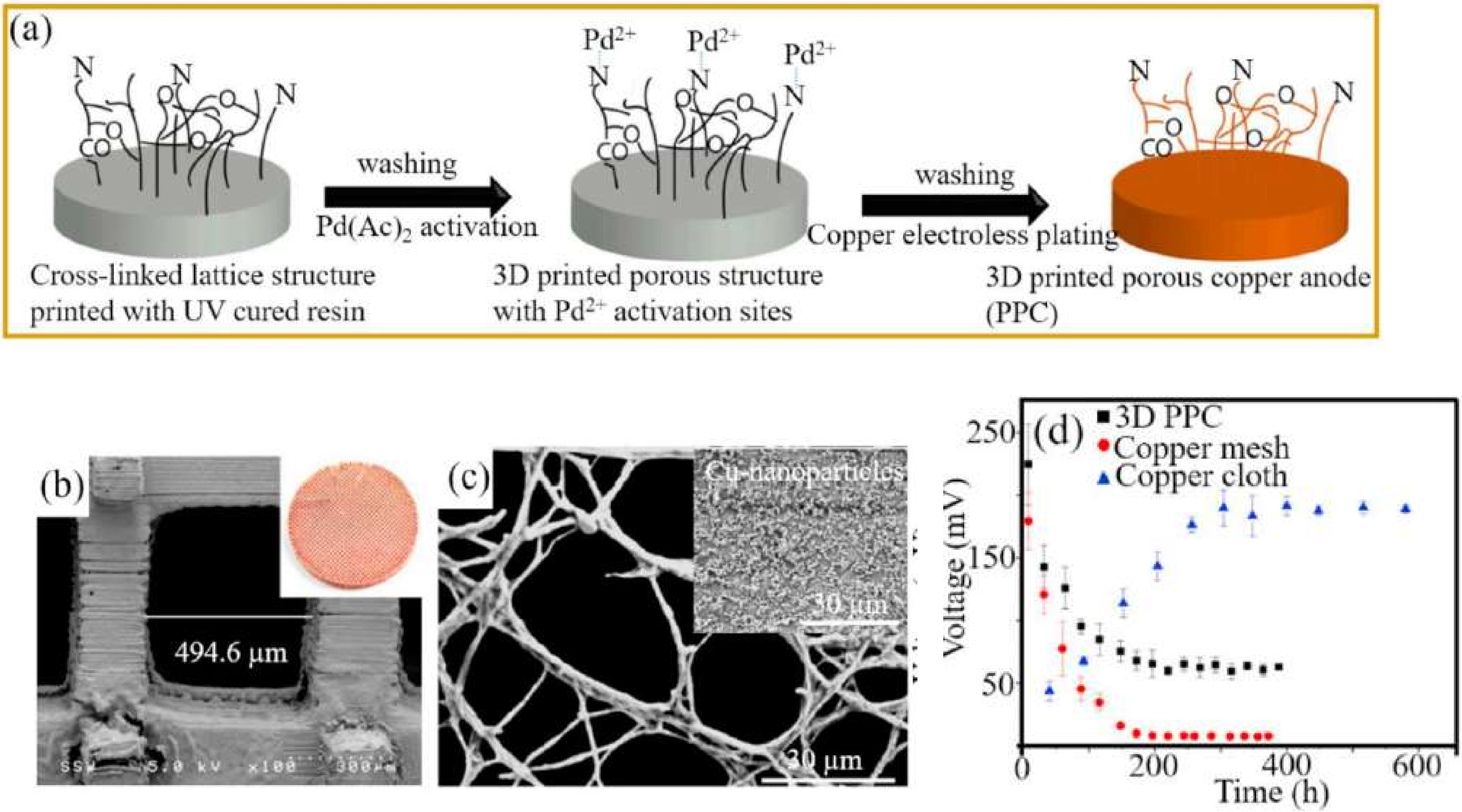
Application of Digital Light Processing



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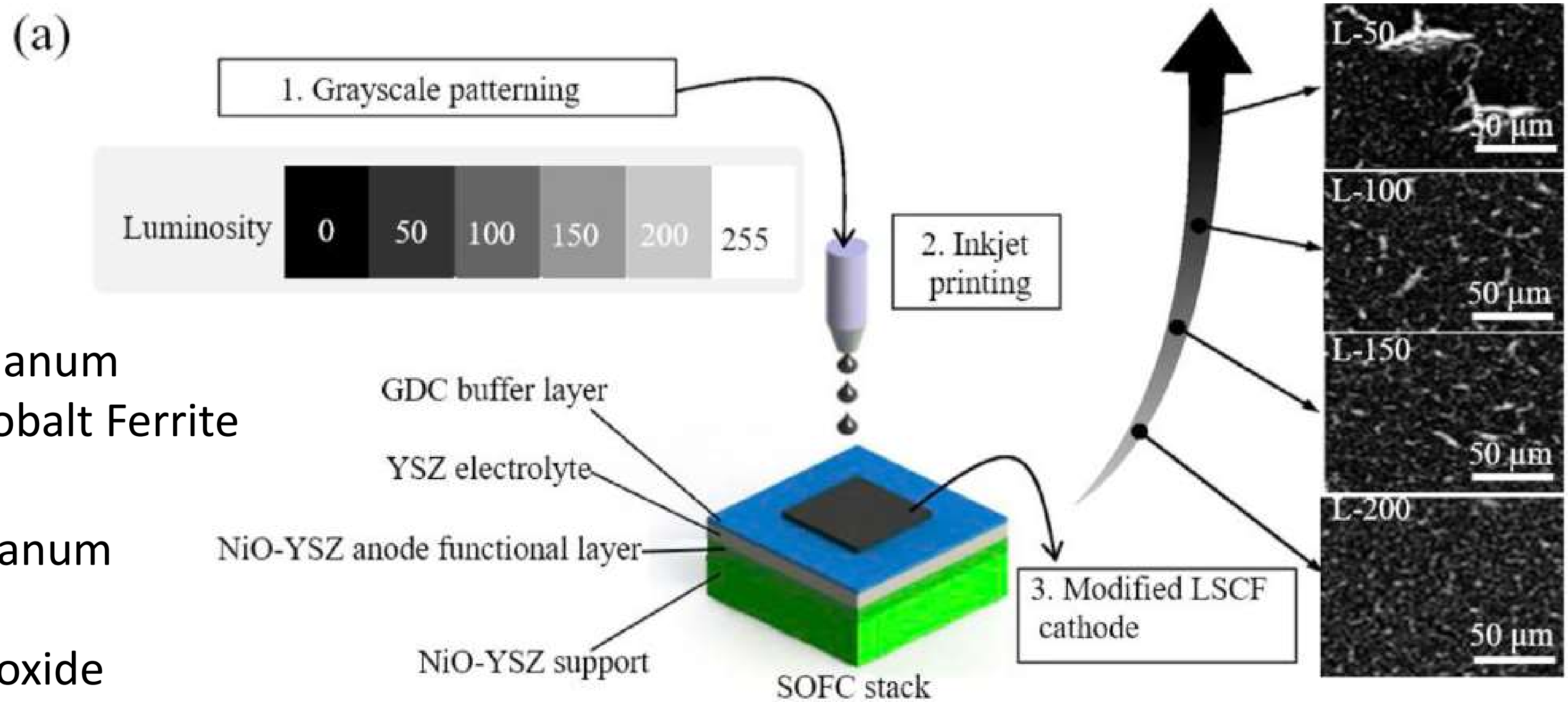
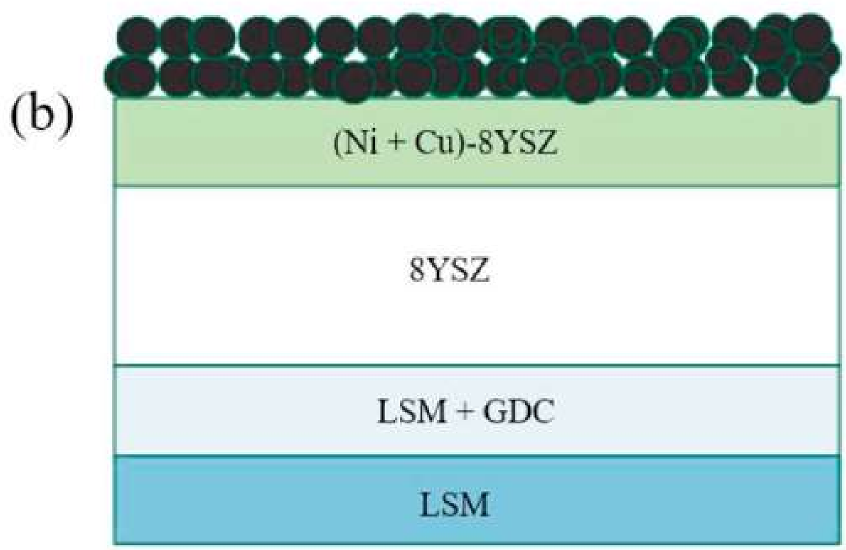
PPC = Printed Porous Copper anode

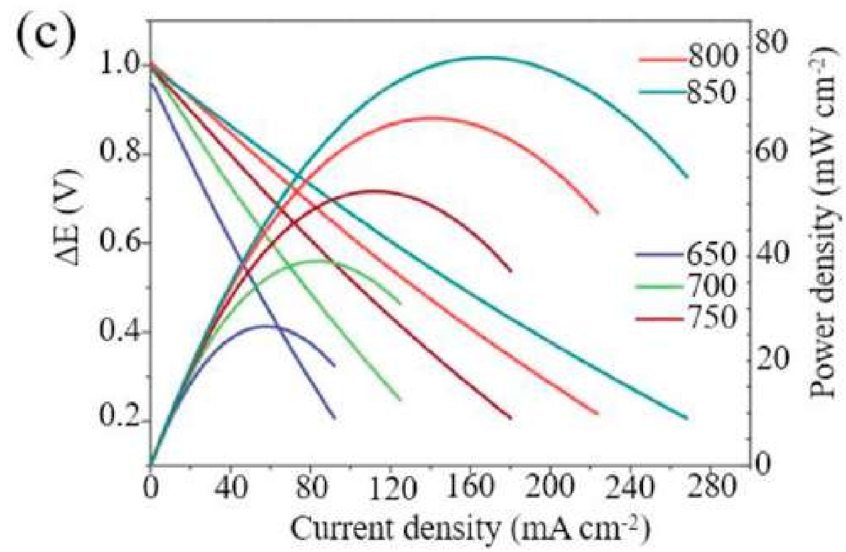
Inkjet Printing of Porous LSCF Cathode of an SOFC



LSCF = Lanthanum Strontium Cobalt Ferrite

LSM = Lanthanum Strontium Manganese oxide





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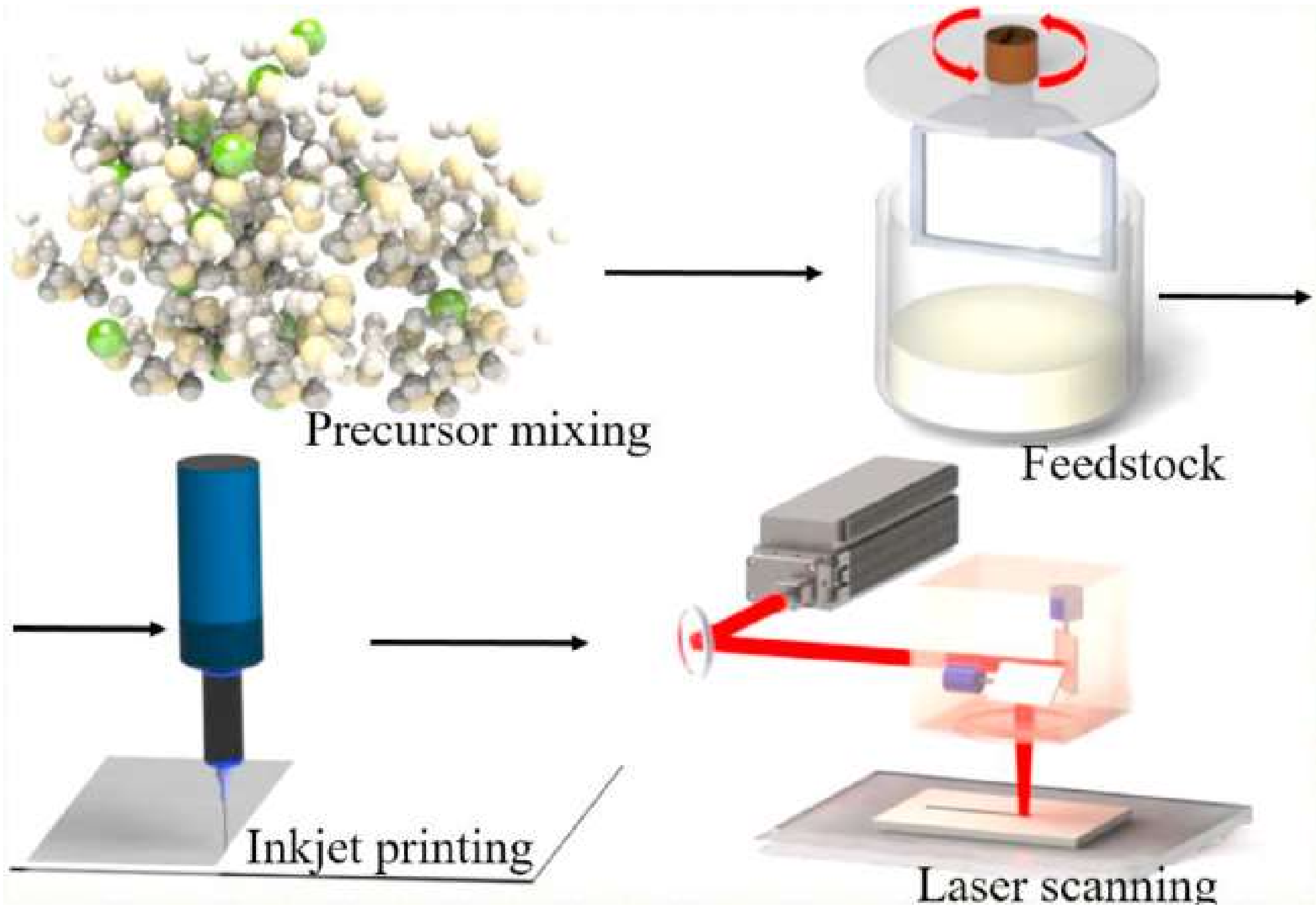
Rapid Laser Reactive Sintering



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3D printed electrolytes & their performance

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GDC	–	IJP	NiO-YSZ/ GDC + YSZ/ LSM-YSZ	–	–	–
YSZ	6.0	IJP	NiO-YSZ/ YSZ-SDC/ LSM	800	0.86	1.05
YSZ	6.0	IJP	NiO-YSZ/ YSZ + SDC/ BSCF	800	1.04	1.10
YSZ	6.0	IJP	NiO-YSZ/ YSZ/LSM + YSZ/LSM	800	0.17	1.01
YSZ	10	IJP	NiO-YSZ/ YSZ/LSM + YSZ	800	0.30	1.10
YSZ	6	IJP	NiO-YSZ/ YSZ/LSM	750	0.17	1.06
SDC	1200	DIW	NCAL/SDC-SC/NCAL	550	0.44	1.00
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ET* = Electrolyte thickness (μm), AMT* = Additive manufacturing techniques, SOFC-E* = SOFC component (anode/electrolyte/cathode), OT* = Operating temperature (°C), OCV* = Open circuit voltage (V), PPD* = Peak power density (W cm^{-2}), NCAL* = $Ni_{0.8}Co_{0.15}Al_{0.05}LiO_{2-\delta}$. SSC* = $Sm_{0.5}Sr_{0.5}CoO_3$, SDC* = $Sm_{0.2}Ce_{0.8}O_{1.9}$, GDC* = $Ce_{0.8}Gd_{0.2}O_{1.9}$, LSM* = $La_{0.9}Sr_{0.1}MnO_3$.

YSZ = Yttria Stabilised Zirconia

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Power Density of 3D printed HFC-PEM

Type of Printing	Printed Element	Other Elements of Fuel Cell	A, mW/cm^2	OCV, V	T, °C	Power Density of Non-3D Printed Analogue
FDM	Catalyst layers	40 wt% Pt/C5, hydroalcoholic Nafion	727	0.98	80	829
FDM	Bipolar plates	40 wt% Pt/C (40 wt% Pt), Nafion solution 5 wt% in water-alcohol	87.1	ND *	25	30.2
FDM	Bipolar plates	Nafion 211 commercial membrane	308.35	1.02	25	ND
FDM	GDL	40 wt% Pt/C, Nafion solution 2 wt% was mixed in ratio 0.25	1200	ND	80	ND
SLS	GDL	0.5 mg Pt/cm^2 on either side of the Nafion membrane	0.5	ND	75	ND
Inkjet printing	Catalyst and membrane layers	Commercial Nafion® 115 membrane (125 mm thickness)	800	0.5	60	~650
Inkjet printing	Membrane	Nafion D2020 dispersion	190	ND	120	110
Inkjet printing	Catalyst layers	Nafion ionomer (5 wt%), 50 wt% Pt/C	579	ND	25	ND
Inkjet printing	Catalyst layers	Nafion ionomer dispersion (4.24 wt% of total, or 0.21 wt% Nafion), 50 wt% Pt/C	550	ND	70	220

* ND—no data.

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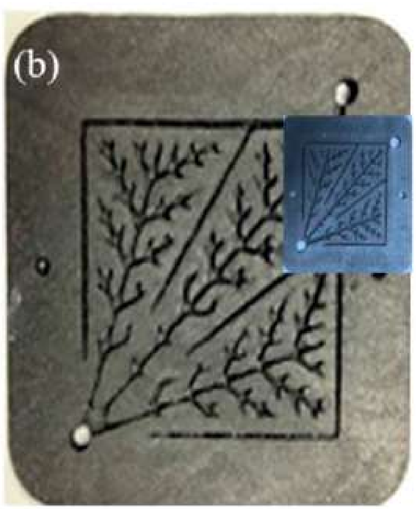
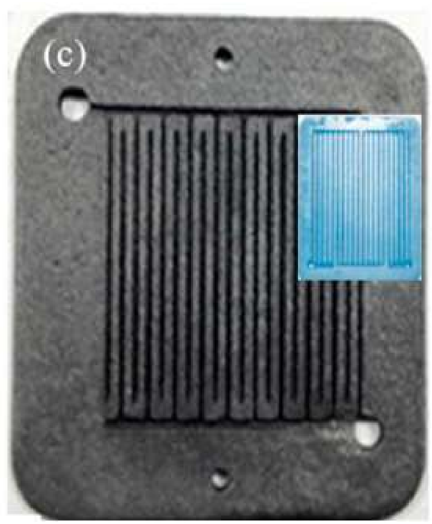
3D printed BPPs and their performance

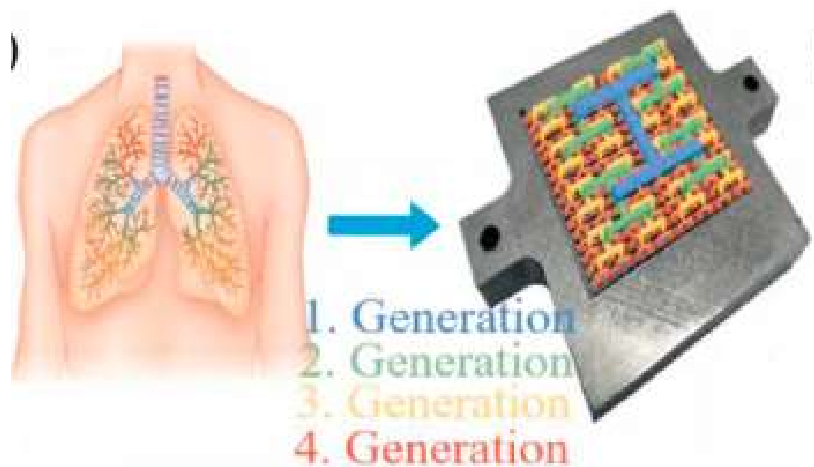
3Dprinted BPP	AMT	Geometry	PEMFC component	PPD	OCV	OT
ABS	FDM	Lung-bronchioles	End plate/MEA/BPPs/End plate	0.99	0.425	70
Graphite	SLS	Serpentine	End plate/MEA/GDL/BPPs/End plate	0.38	0.90	75
Graphite	SLS	bio-inspired	End plate/MEA/BPPs/End plate	0.70	0.90	75
Graphite	SLM	Serpentine	End plate/MEA/GDL/BPPs/End plate	0.1	0.50	–
Graphite	SLS	Leaf-veins	End plate/MEA/GDL/BPPs/End plate	0.53	0.95	75

FDM* = fusion deposition method, ABS* = Acrylonitrile-butadiene-styrene.

ET* = Electrolyte thickness (μm), AMT* = Additive manufacturing techniques, SOFC-E* = SOFC component (anode/electrolyte/cathode), OT* = Operating temperature (°C), OCV* = Open circuit voltage (V), PPD* = Peak power density (W cm^{-2}), NCAL* = $Ni_{0.8}Co_{0.15}Al_{0.05}LiO_{2-\delta}$. SSC* = $Sm_{0.5}Sr_{0.5}CoO_3$, SDC* = $Sm_{0.2}Ce_{0.8}O_{1.9}$, GDC* = $Ce_{0.8}Gd_{0.2}O_{1.9}$, LSM* = $La_{0.9}Sr_{0.1}MnO_3$.







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Summary

- Different methods for manufacture of Bipolar plates, including sheet forming methods were discussed
- A number of 3D printing methods for bipolar plates have been compared
- Large number of Bipolar plates are needed; 3D printing methods need to be speeded up

Thank you