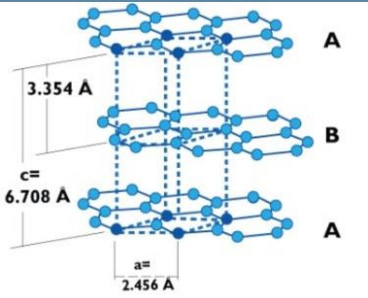

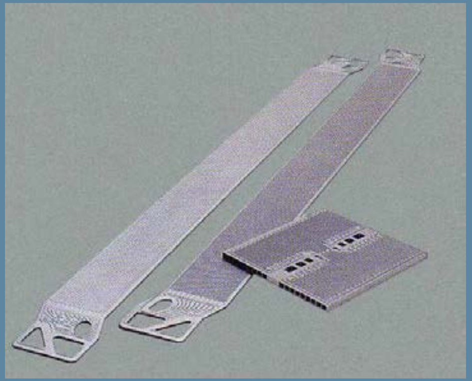

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Graphite - Based Bipolar Plates for PEM Motive Fuel Cell Applications

Julian Norley
Fellow of the American Carbon Society
Vice President Innovation & Technology
Advanced Energy Technologies LLC

DOE Bipolar Plates Workshop
Feb 14th 2017

THE FUEL CELL CORRIDOR™
Global Center of the Fuel Cell Industry

Outline

- Introduction to Advanced Energy Technologies LLC
- Review of Carbon & Graphite Bipolar Plate Technologies
  - Expanded/Flexible Graphite Materials
  - Molded/Filled/Particulate/Composite Graphite Materials
  - Carbon & Graphite Coated Metallic Plates
- R&D Needs
- Simon Farrington (AFCC) will talk later on forming and manufacturing issues in automotive bipolar plate production

Advanced Energy Technologies LLC (AET)

- A subsidiary of GrafTech International
- 100 year + company headquartered in Cleveland, Ohio
- Manufacturer of flexible graphite materials for electronic thermal management, fluid sealing, automotive gasket, fire retardant and fuel cell applications
- www.graftechaet.com

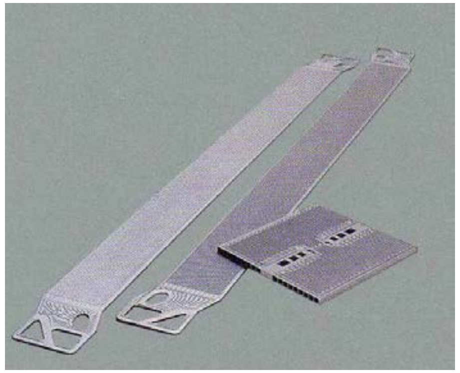

Plate & module photos courtesy of Ballard Power

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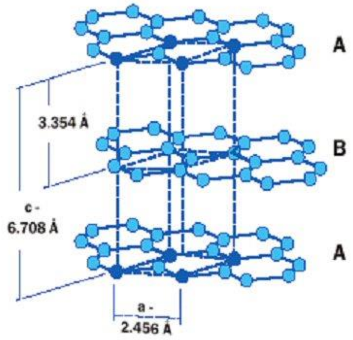
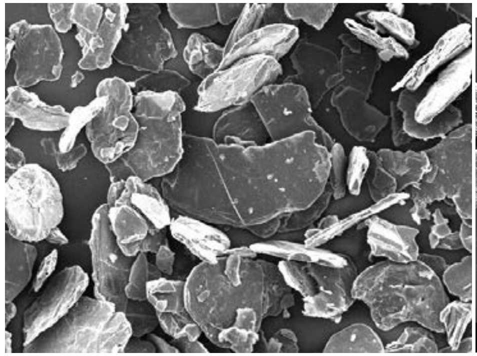
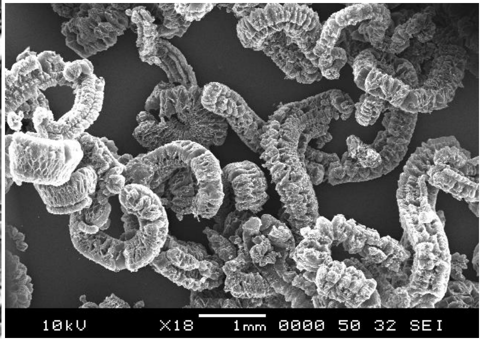
Expanded/Flexible Graphite Materials

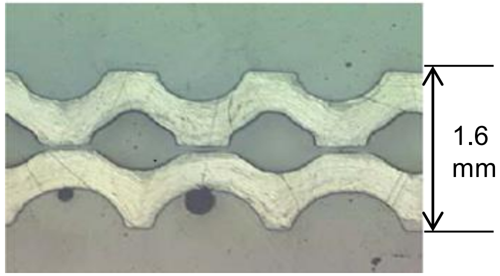
Manufacture

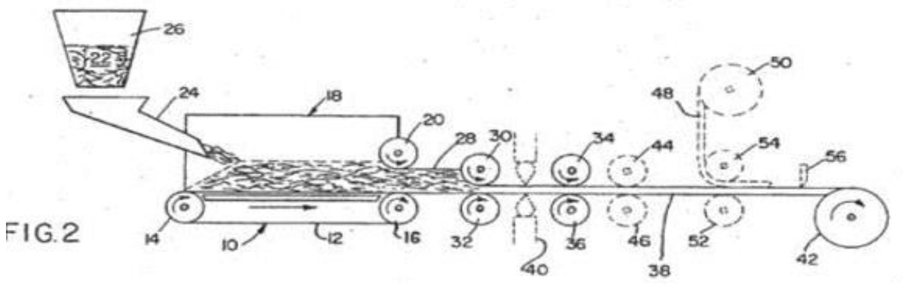
- Expanded graphite materials are derived from naturally occurring flake graphite
- The flake is chemically intercalated and then heated to expand the graphite
- The expanded graphite is then gradually compressed into a mat form
- The mat blank is then compression molded into a half-plate comprising gas and coolant channels
- The graphite preform is then impregnated with resin and cured to form the finished half-plate
- Fuel and oxidant half-plates are adhesively bonded and cured to form the finished bipolar plate
- Bipolar plate/minimum web thickness
  - ~ 2.0 mm/0.45 mm current field use
  - ~ 1.6 mm/0.32 mm GrafTech/Ballard DOE project
  - ~ 1.1 mm/0.15-0.2 mm “State-of the Art”
- More complex flow field designs possible vs corrugated metal plates



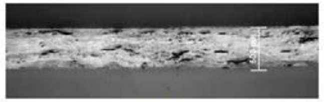






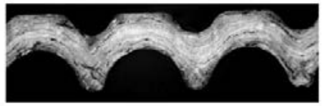


US Patent 3,404,061 JH.Shane et al., Oct 1 1968

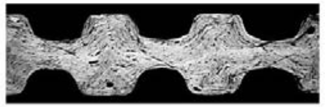


Blank

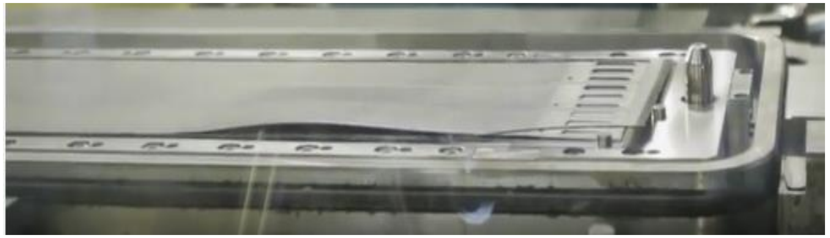
Single Sided or
Double Sided, Perpendicular



Double Sided
Parallel, Corrugated



Double Sided
Parallel, Opposed

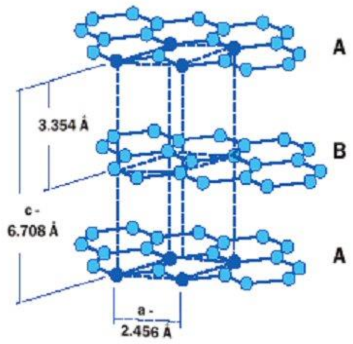


Screen shot courtesy of Ballard Power

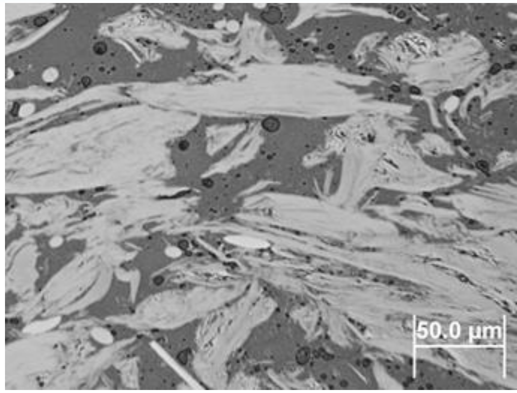
Expanded/Flexible Graphite Materials

Properties

- Expanded graphite materials retain the anisotropic structure of the starting flake with the result that in-plane (xy) and through thickness (z) properties are very different
- Expanded graphite materials comprise a continuous graphite phase with resultant higher in-plane thermal & electrical conductivity than bulk molded compounds but lower through plane properties
- Higher thermal conductivity exploited in higher current density designs
- Lower density than steel and do not corrode
- Lower strength and electrical conductivity than steel



Cross section of compressed expanded graphite sheet



Cross section of typical bulk molding compound

Property	Expanded Graphite	Bulk Molded Compound (BMC 940)	Stainless Steel 316L (coated for corrosion results)	2020 DOE Target or Target impacted
Density g/cm3	1.7	1.89	8.0	Plate Weight < 0.4 kg/kWnet
Thermal Conductivity W/mK	280 (xy) 5 (z)	13	15	n/a
Electrical Conductivity S/cm	1100 (xy) 20 (z)	70 (xy) 30 (z)	13500	> 100 S/cm
CTE (μm)	1.0 (x,y) 90 (z)	30	16	n/a
Tensile/Flexural Strength (MPa)	40/60	28/38	NA/480	Flex > 34 (carbon plate)
Corrosion μA/cm2	None	None	< 0.1	< 1

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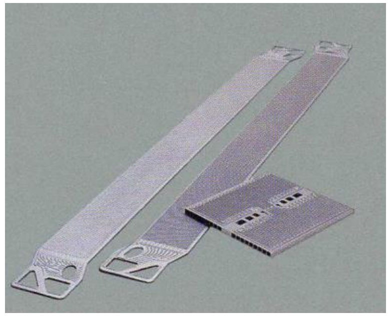
Expanded/Flexible Graphite Materials

History of Field Performance

- Ballard's Mark 900 series liquid-cooled fuel cell stack introduced in January 2000 was the first to use resin impregnated expanded graphite for on-road vehicles
- 2000-2006 Used in early generation automotive prototypes (Daimler-Chrysler NECAR Mercedez Benz A-Class, Ford Focus, Honda FCX, and bus programs (Daimler Chrysler Citaro)
- Introduced into fork lift applications in 2005 with General Hydrogen. > 13,000 Plug Power GenDrive® vehicles now in service
- Used in current generation FCveloCity® modules for bus applications
- > 1,000,000 bipolar plates produced
- Have accumulated :
  - >10 million km of road service in bus and automotive applications
  - Millions of hours of run time in fork lift applications



Field Information and photos courtesy of Ballard Power & Plug Power

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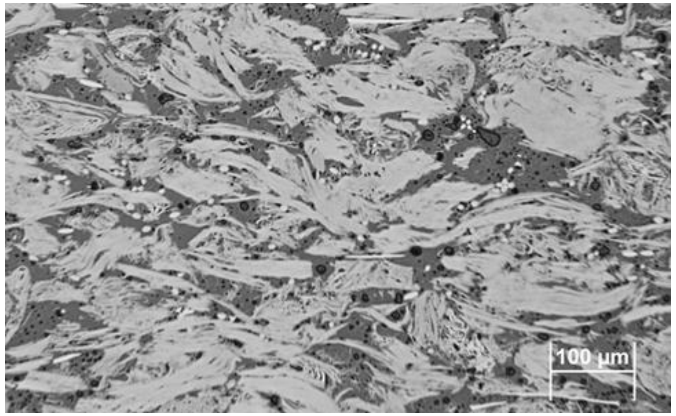
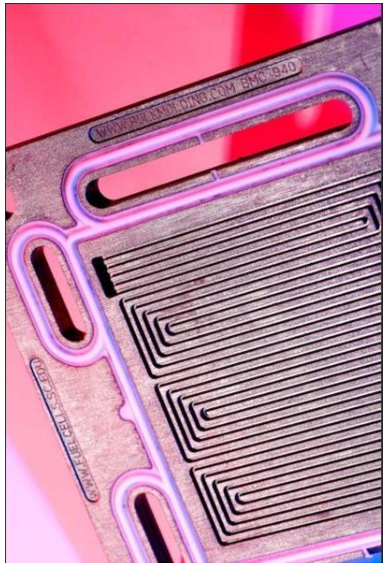
Molded/Filled/Particulate Graphite Composite Materials

Manufacture, Properties & Field Performance

- Use bulk-molding compounds that comprise high fraction loadings (77-87 wt%) of natural and synthetic graphite particulates (d50 ~ 30-60 μm) and carbon fibers in thermoset resins typically epoxy/vinyl-ester/phenolic/bismaleimide resins
- Plates are typically compression molded with typical times of ~ 1-5 minutes at temperatures of 150-180°C at 20-50MPa
- Multiple suppliers of bulk molding compounds and finished plates
- Similar bipolar plate/web thicknesses to expanded graphite materials
  - ~ 1.5 mm/0.30 mm current field use
  - ~ 1.1 mm/0.15-0.2 mm "State-of the Art"
- Have been used successfully in motive applications since 2005 and favored for thicker plates/stationary power applications





Source:- Composites World/BMCI

Source:- Nisshinbo website

Screen shot courtesy of Ballard Power

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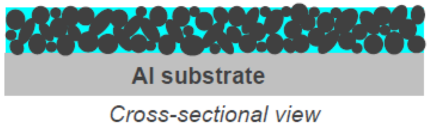
Carbon & Graphite Coated Metallic Plates

Manufacture & Properties

- Argonne National Lab has reported work (Project ID #FC024) on composite fluoropolymer/graphite coatings on aluminum bipolar plates
  - Orion panels show no corrosion; a single cell stack was tested with improved performance vs uncoated aluminum

- Filler: Metal carbide, boride or silicide, graphite, and/or carbon black
- Fluoropolymer: Ethylene tetrafluoroethylene (ETFE) or Polychlorotrifluoroethylene (PCTFE)



- Chung et al and Fukutsuka et al. both utilized carbon-coated 304SS in single and three-cell PEM fuel cells respectively
  - CVD carbon film on Ni-coated 304 SS plates demonstrated chemical stabilities comparable to Poco graphite
  - Plasma assisted CVD carbon film on 304SS – exhibited higher electrical conductivity than uncoated material while maintaining an acceptable level of corrosion resistance
  - Both studies were relatively short term so further study required

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R&D Needs

Focus on High Speed Forming

- For expanded flexible graphite materials, the recommended main focus area needs to be high speed forming, sealing, curing, gluing & cutting operations to meet the automotive volume and cost targets
- Per **DE-FC36-07GO17012** Roller Embossing & Adiabatic Forming have been identified as candidate high speed forming routes to 100k- 500k stacks/yr
- Some encouraging R&D/pilot scale scoping work performed on roller embossing & adiabatic forming
  - Roller embossing demonstrated at 9 meters/min by Terrella Energy – translates into 1 plate/3 seconds. Very high density graphite parts demonstrated which reduces resin content facilitating sealing vs impregnation approach, faster curing, enabling a continuous operation
  - Adiabatic forming - Double sided 160 cm2 test half-plate formed in < 0.1 s using high velocity impact unit. Improved material flow and feature definition. Less energy than identical metal part.
  - Need to update cost analysis to incorporate these new manufacturing scenarios
  - For particulate graphite materials we are suggesting a similar focus on high speed forming and property improvements for high current density (particularly thermal)

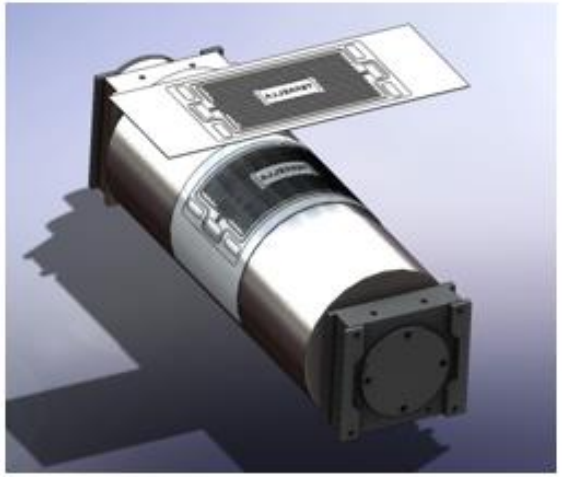
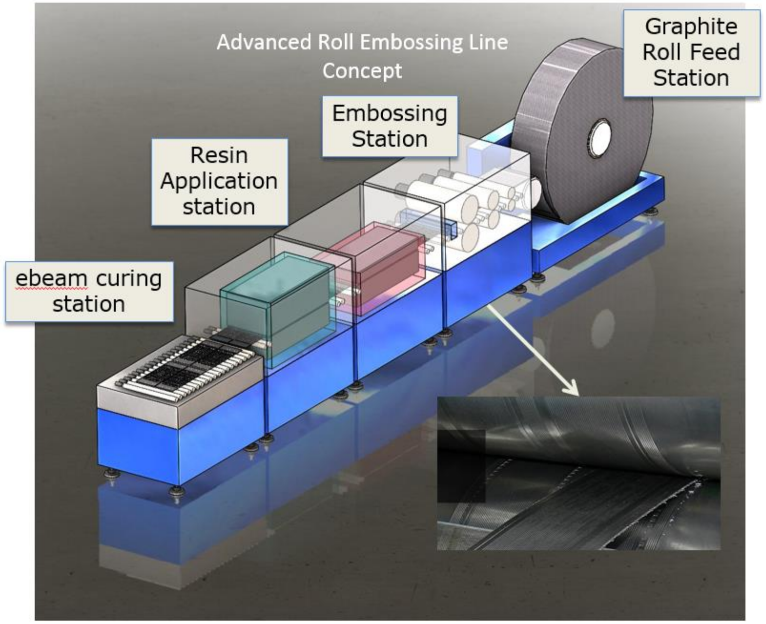


Plate Design wrapped onto a drum

Demonstration for 9 meters/min process



Double sided 160 cm^2 test plate produced by adiabatic forming (< 0.1s)

Summary

- Expanded flexible graphite plates have been used successfully in full-scale motive applications for > 15 years with >10 million km of road service in bus and automotive applications and millions of hours of run time in fork lift applications.
  - Recent high-speed forming work, particularly roller embossing, has demonstrated a path to automotive scale cost and volumes at the current densities required by the industry. This is a recommended area for additional R&D
- Filled/particulate/molded graphite composite plates have been used successfully in full-scale motive applications for > 10 years.
  - R&D needs identified include a focus on high speed forming methods and property improvements (particularly thermal)

Acknowledgements

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  - Simon Farrington of AFCC
  - John Kenna of Terrella Energy
  - Dave Stuart, Ryan Wayne and Matt Getz and of Advanced Energy Technologies LLC.

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- Metallic Bipolar plates with Composite Coatings , Mawdsley et al. Argonne National Laboratory Project ID # FC024, May 11, 2011

Appendix Slides – DOE Bipolar Plate Targets

DOE Bipolar Plate Targets

Technical Targets: Bipolar Plates for Transportation Applications

Characteristic	Units	2015 Status	2020 Targets
Cost[a]	$/kW$_{net}$	7[b]	3
Plate weight	kg/kW$_{net}$	<0.4[c]	0.4
Plate H_2 permeation coefficient[d]	Std $cm^3/(sec\ cm^2 Pa)$ @ 80°C, 3 atm, 100% RH	0[e]	$<1.3 \times 10^{-14}$[f]
Corrosion, anode[g]	$\mu A/cm^2$	no active peak[h]	<1 and no active peak
Corrosion, cathode[i]	$\mu A/cm^2$	<0.1[c]	<1
Electrical conductivity	S/cm	>100[j]	>100
Areal specific resistance[k]	ohm cm^2	0.006[h]	<0.01
Flexural strength[l]	MPa	>34 (carbon plate)[m]	>25
Forming elongation[n]	%	20–40[o]	40

[a] Costs projected to high volume production (500,000 80 kW systems per year), assuming MEA meets performance target of 1,000 mW/cm^2.

[b] Cost when producing sufficient plates for 500,000 systems per year. DOE Hydrogen and Fuel Cells Program Record 15015, "Fuel Cell System Cost—2015."

[c] C.H. Wang (Treadstone), "Low-cost PEM Fuel Cell Metal Bipolar Plates," 2012 Annual Progress Report.

[d] Per the standard gas transport test (ASTM D1434).

[e] C.H. Wang (Treadstone), private communication, October 2014.

[f] Blunk, et al., J. Power Sources 159 (2006) 533–542.

[g] pH 3 0.1ppm HF, 80°C, peak active current $<1 \times 10^{-6}$ A/cm^2 (potentiodynamic test at 0.1 mV/s, -0.4V to +0.6V (Ag/AgCl)), de-aerated with Ar purge.

[h] Kumar, M. Ricketts, and S. Hirano, "Ex-situ evaluation of nanometer range gold coating on stainless steel substrate for automotive polymer electrolyte membrane fuel cell bipolar plate," Journal of Power Sources 195 (2010): 1401–1407, September 2009.

[i] pH 3 0.1ppm HF, 80°C, passive current $<5 \times 10^{-8}$ A/cm^2 (potentiostatic test at +0.6V (Ag/AgCl) for >24h, aerated solution.

[j] O. Adrianowycz (GrafTech), "Next Generation Bipolar Plates for Automotive PEM Fuel Cells," 2009 Annual Progress Report.

[k] Includes interfacial contact resistance (on as received and after potentiostatic test) measured both sides per Wang, et al. J. Power Sources 115 (2003) 243–251 at 200 psi (138 N/cm^2).

[l] ASTM-D 790-10 Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials.

[m] D. Haack et al. (Porvair), "Carbon-Carbon Bipolar Plates," 2007 Annual Progress Report.

[n] Per ASTM E8M-01 Standard Test Methods for Tension Testing of Metallic Materials, or demonstrate ability to stamp generic channel design with width, depth, and radius.

[o] M. Brady et al. (Oak Ridge National Laboratory), "Nitrided Metallic Bipolar Plates," 2010 Annual Progress Report.