Additive Manufacturing of Aerospace Propulsion Components

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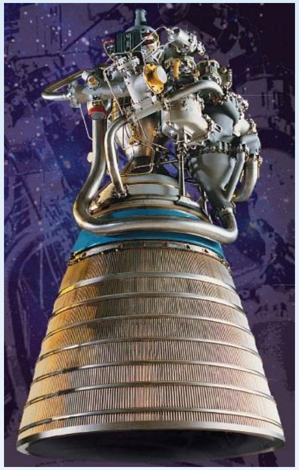
Aerospace Propulsion Systems of Interest



Large Rocket Propulsion

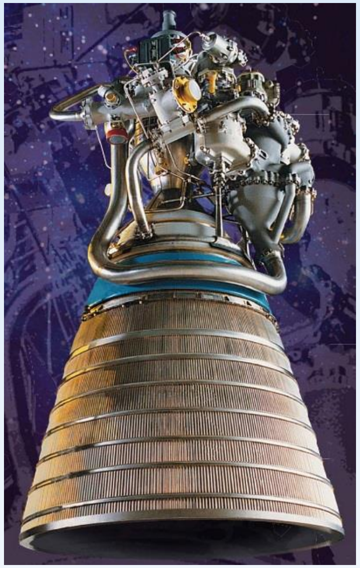
- Reduced complexity
- Faster cycle time
- Complex design features

Aircraft Gas Turbine Engine

Small Propulsion for Cubesat

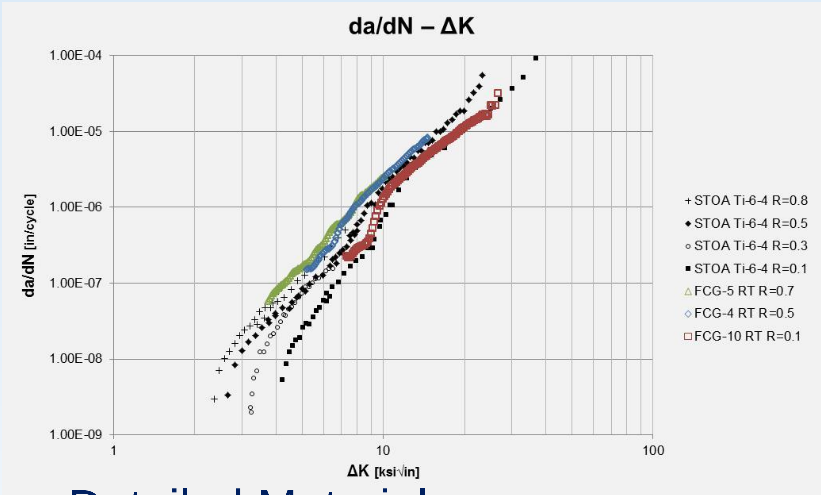
Hybrid Electric Propulsion for Aircraft

Additive Manufacturing of Titanium Alloys



RL-10 Engine

Electron Beam Melted Gimbal Cone at ORNL (Ti-6Al-4V)



Detailed Material Characterization at GRC for Component Design

- Tensile, LCF, HCF, Fatigue crack growth, fracture toughness from cryogenic to 300 ºF temperatures

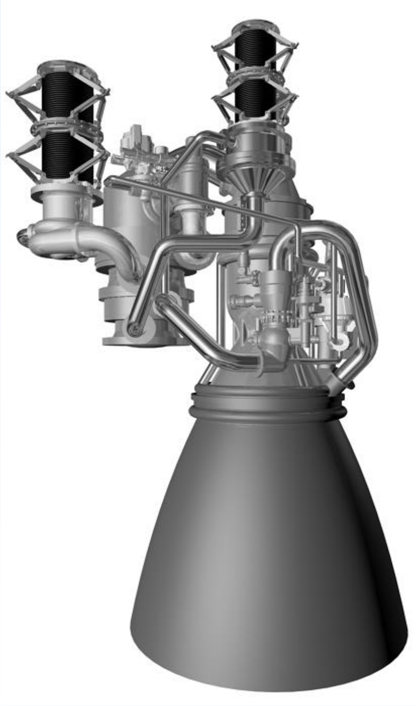
Need:

Characterization and modeling of powder/process/microstructure interrelationship

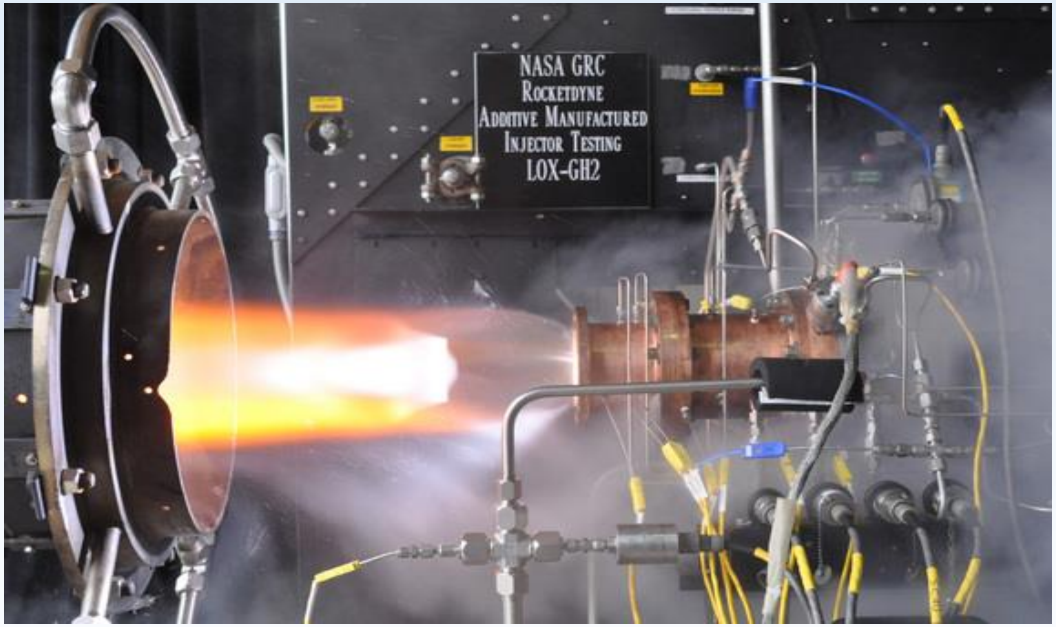
NASA-Air Force – Aerojet Rocketdyne Collaborative Effort

Successful Testing of Additive Manufactured Rocket Engine Injectors

Aerojet AR-1 Rocket Engine



Additively manufactured (selective laser melting) injector successfully tested at NASA GRC Rocket Combustion Lab



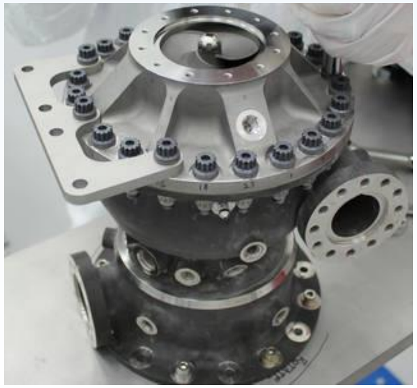
- Reduction of fabrication time from 1 yr to 4 months
- 70 % less cost

NASA-Air Force-Aerojet Collaborative Effort

Development of Additive Manufacturing of Rocket Engine Components at NASA MSFC

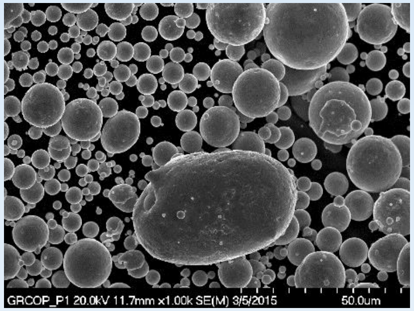
Rocket Engine for Space Launch System

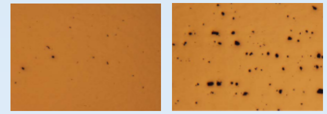
Successful testing of 3-D printed (selective laser melting) rocket engine injector (largest 3-D printed injector) for Space Launch System

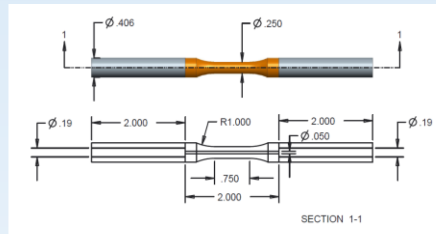


Additive Manufacturing of 3-D Printed Rocket Engine Turbopump (45% fewer parts)

Additive Manufacturing of Rocket Engine Combustion Chamber for Low Cost Upper Stage Propulsion





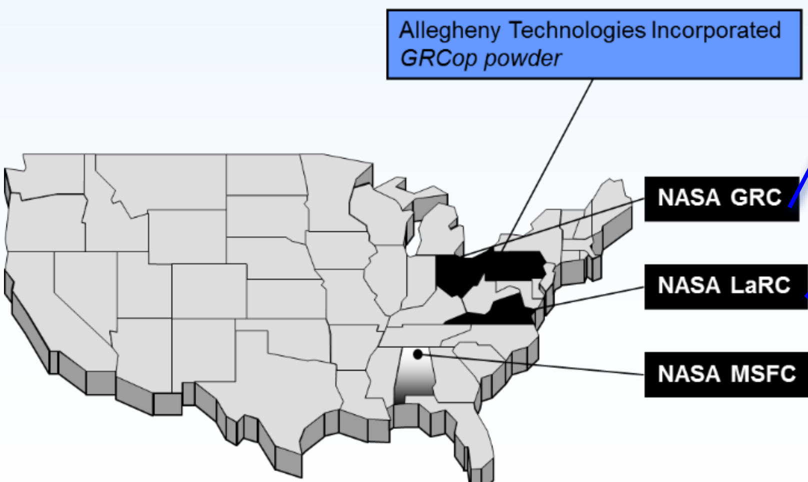


Inconel 625 structural jacket using EB Free Form Fabrication

GRCop-84 Combustion Chamber Liner produced using Selective Laser Melting

Benefits:

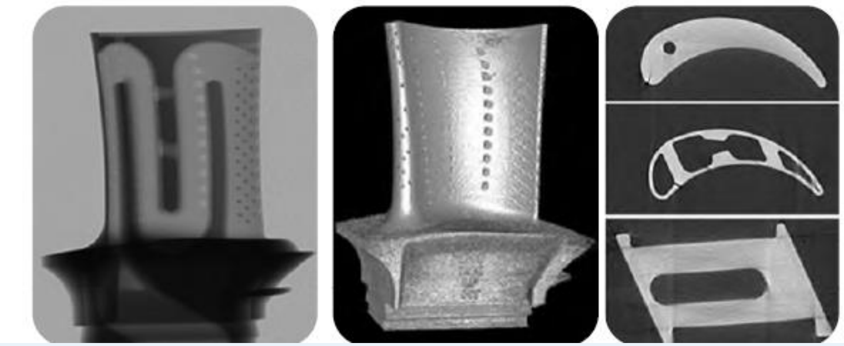
- Reduced cost and schedule to fabricate, also enables design features not conventionally possible.



GRC POC: Bob Carter LMA0

Additive Manufacturing of Gas Turbine Engine Components

3-D Printing of Cooled Turbine Engine Blades at ORNL

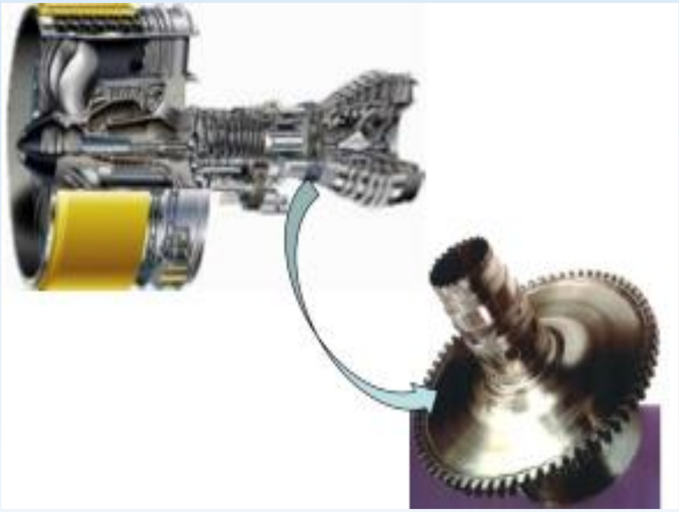


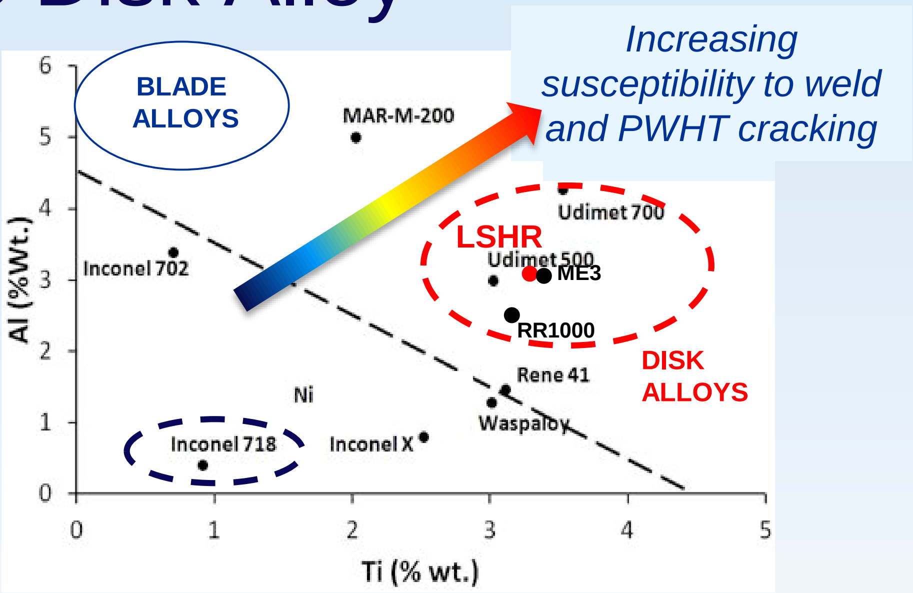
3-D Printing of Small Gas Turbine Engine by GE

3-D Printing of Small Gas Turbine Engine by Researchers in Australia

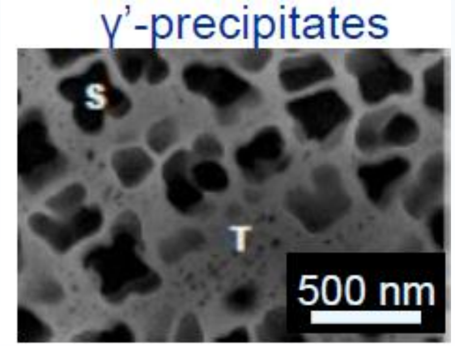
3-D Printing of Low Pressure Turbine Titanium Aluminide Blade (GE)

Additive Manufacturing of Gas Turbine Engine Disk Alloy





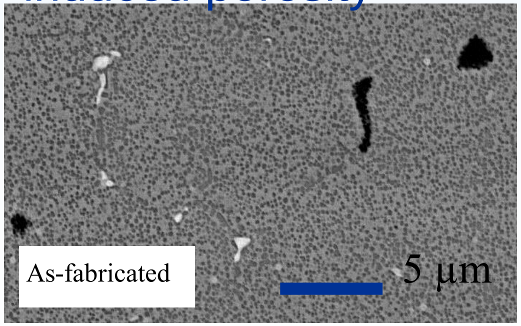
Alloys with >10 elements



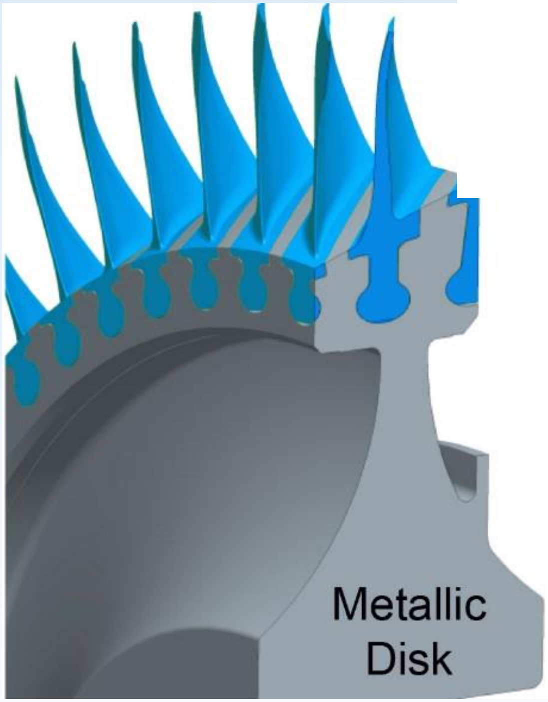
Current Effort: Electron-beam melting

- Heated powder-bed for reduced residual stresses and slower cooling rates
- Multiple beam for faster builds
- Vacuum for lower risk of contamination

Challenge – Process induced porosity



Advanced Turbine Engine Disk Alloys – Opportunities for Additive Manufacturing



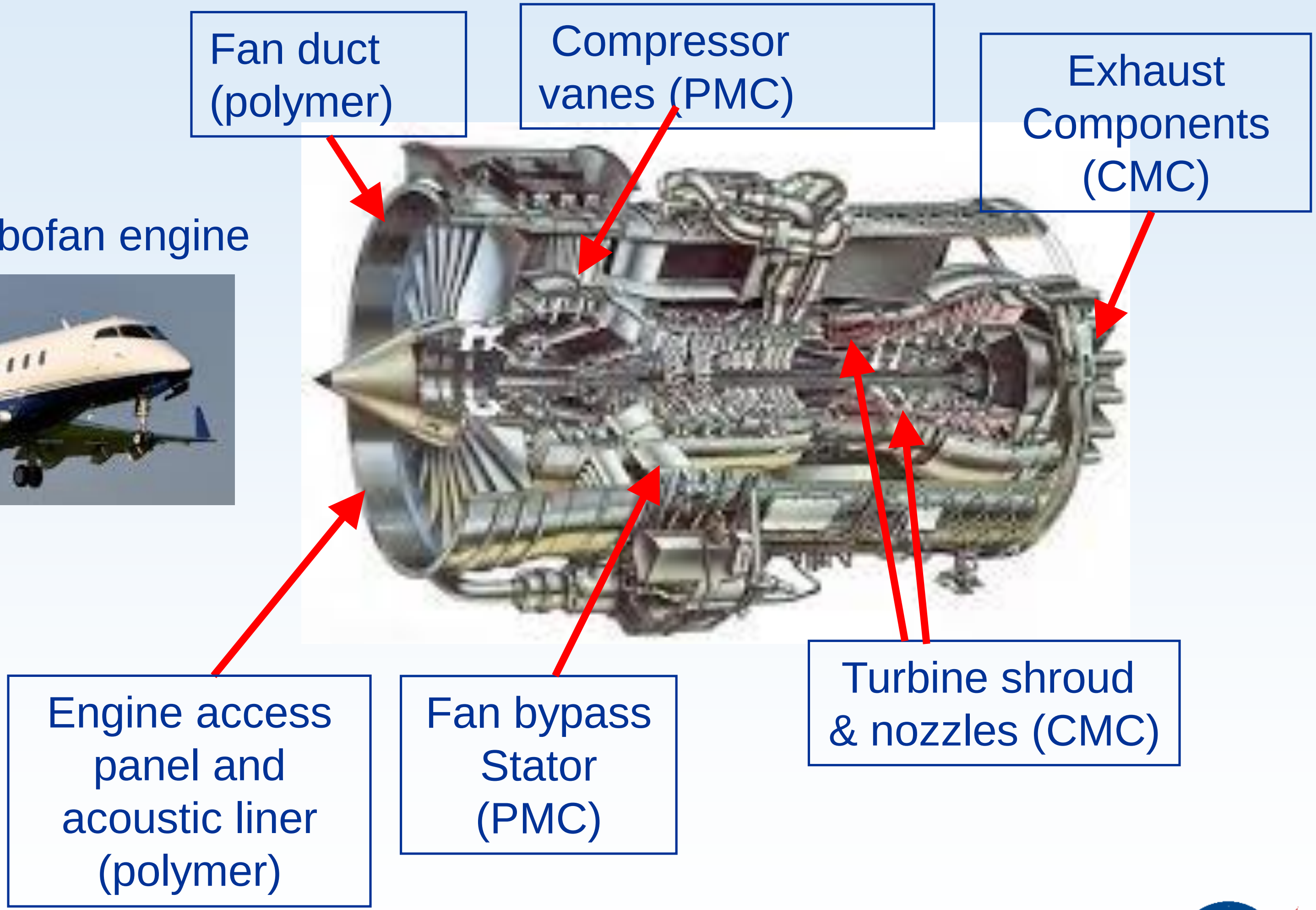
Location	Key Property
1500 °F rim	Need high creep life and crack growth resistance
1300 °F web	Creep/fatigue interaction
800 °F bore	Need high tensile strength and low cycle fatigue life

Need additional manufacturing process to achieve:

- Location specific properties
- Bonding of multiple materials – Multimaterial capability

Additive Manufacturing of Non-Metallic Gas Turbine Engine Components

Business Jet size turbofan engine

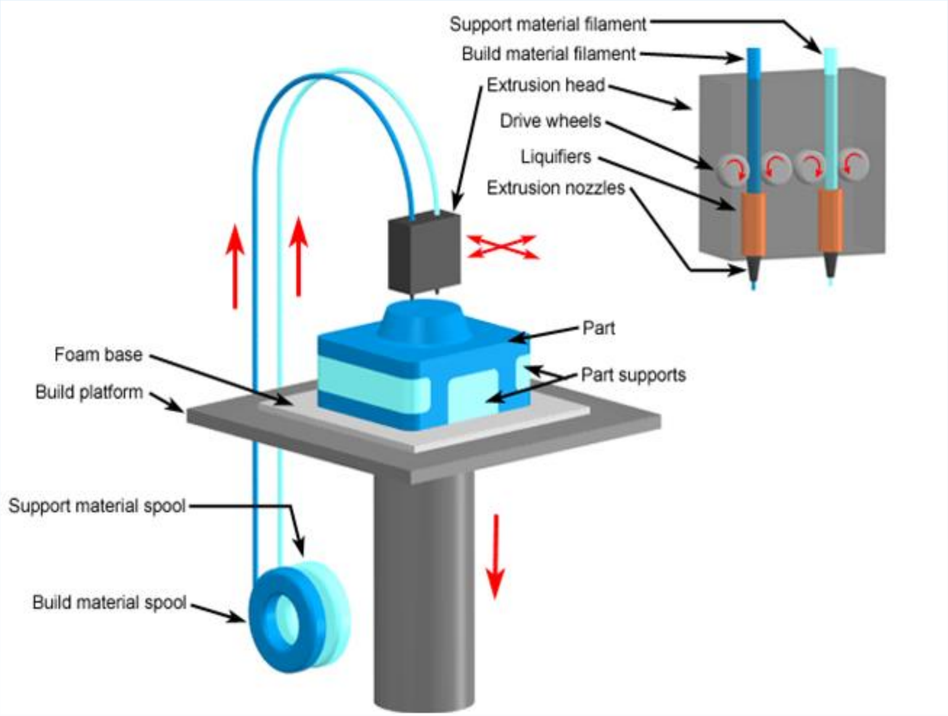


Additive Manufacturing of Polymer and Polymer Matrix Composites (PMCs)

Melts polymer filament and deposits it layer-by-layer following CAD files

Fabrication of high temperature PMC was enable by:

- Chopped-fiber reinforcement
- Moisture reduction in FDM filament
- Versatile printing pattern design

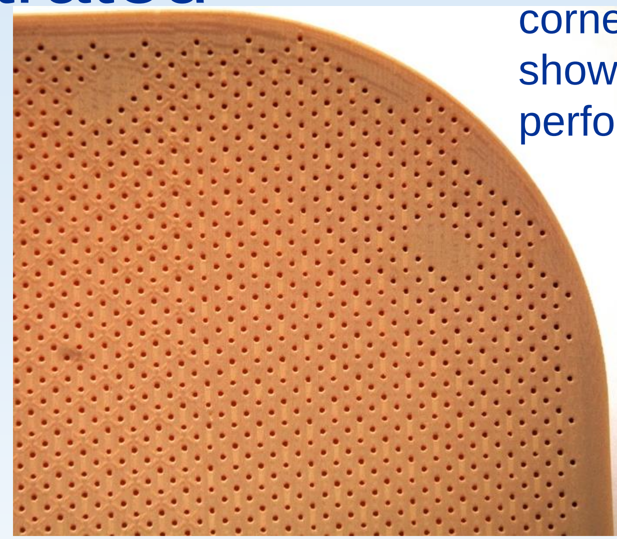


Benefits:

- Quick turn around time for complex parts
- Shorter component production and testing cycle
- Reduced cost of low production volume components

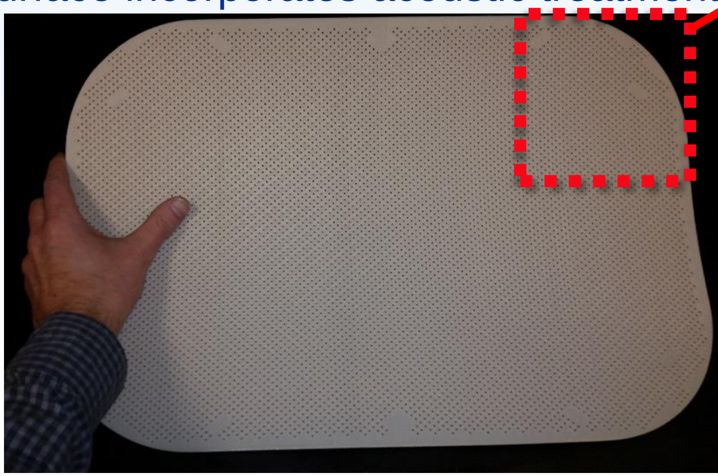
Fabrication of full-scale engine access panel demonstrated

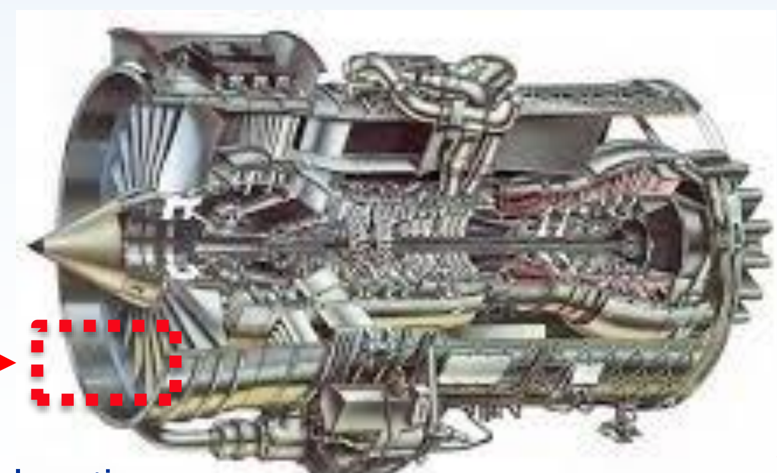
19″



corner detail shows acoustic perforations

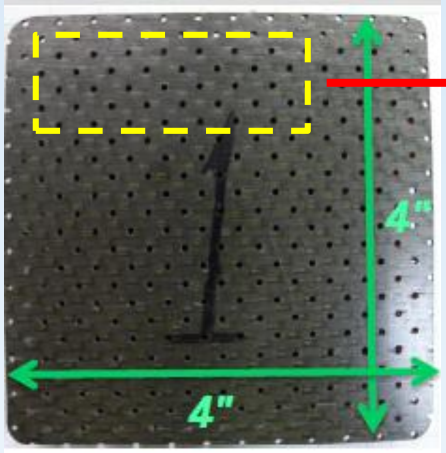
inner surface incorporates acoustic treatment





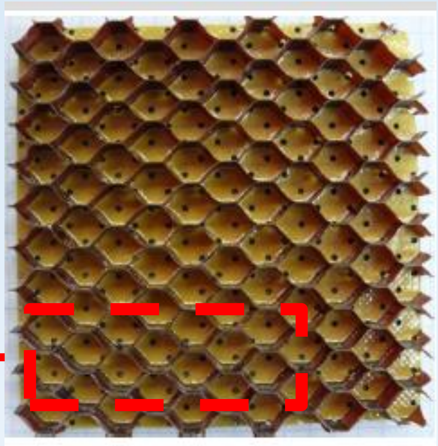
panel location

Fused Deposition Modeling Simplifies Acoustic Liner Fabrication



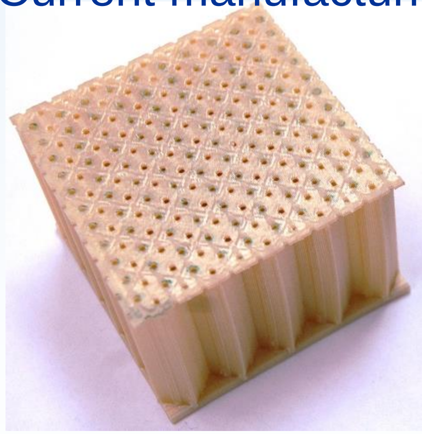
Perforated Facesheet

Bonded Structure



Honeycomb

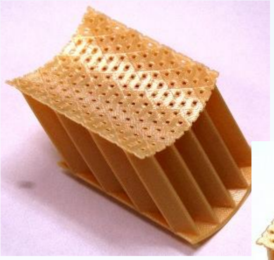
Current manufacturing approach requires metal forming, bonding and drilling

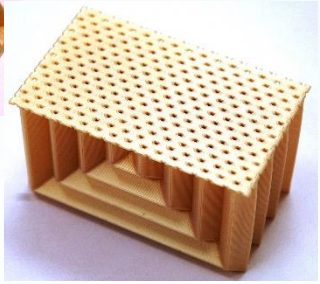


standard liner configuration

integral facesheet/honeycomb structure is fabricated in one step using Fused Deposition Modeling

200^{0}F operating temperature

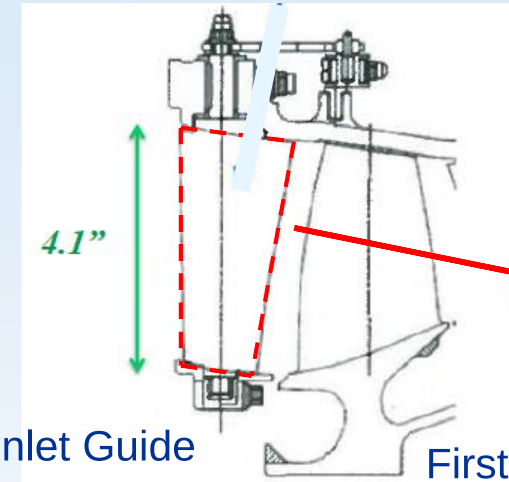




complex geometries

Fabricated with monolithic Ultem 9085 thermoplastic (T_g = 367^{0}F)

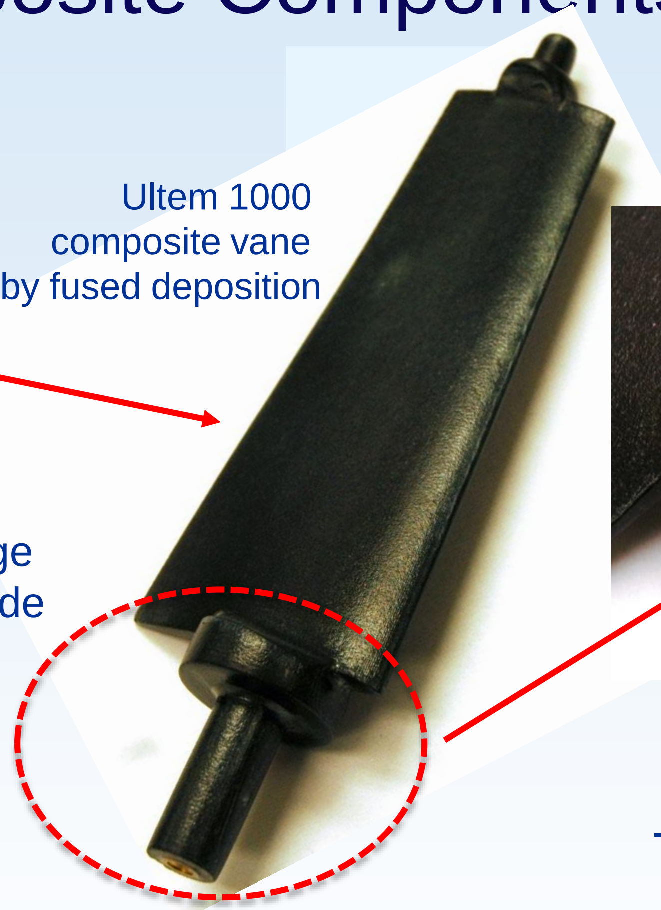
Additive Manufacturing of Polymer Matrix Composite Components

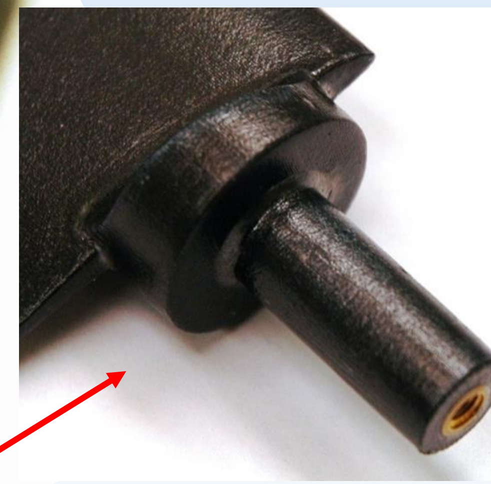


Inlet Guide Vane

First Stage Compressor Blade

Ultem 1000 composite vane by fused deposition

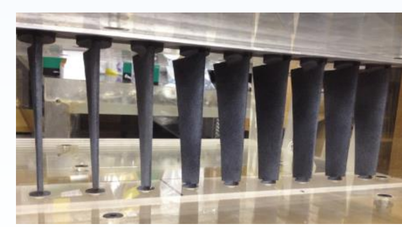




Attachment detail

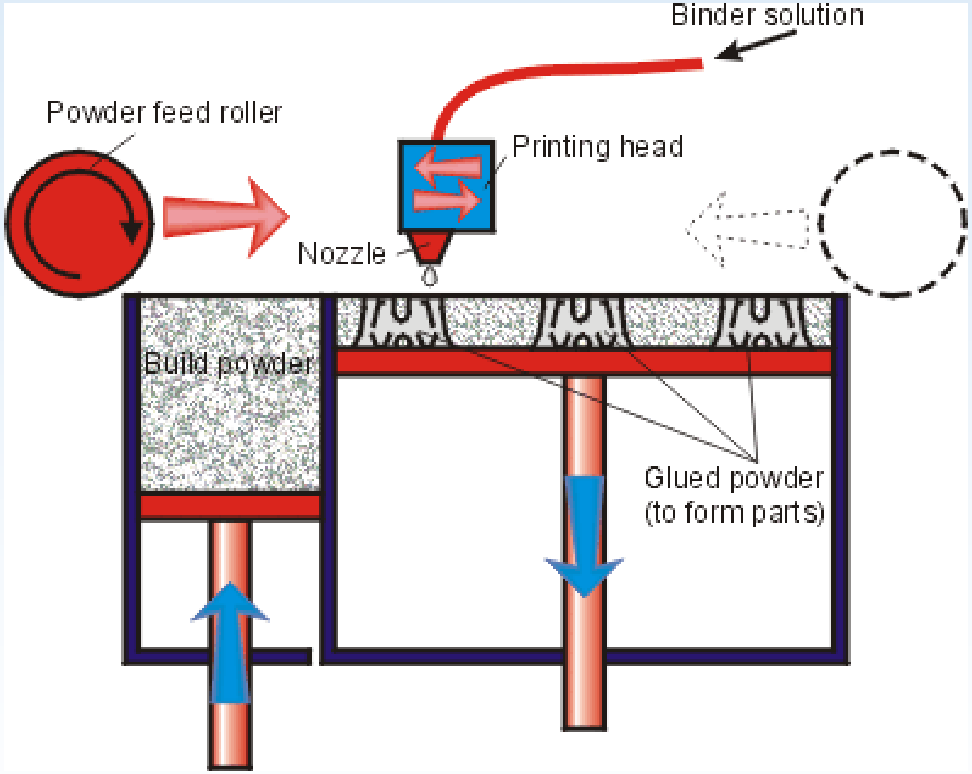
400^0F operating temperature

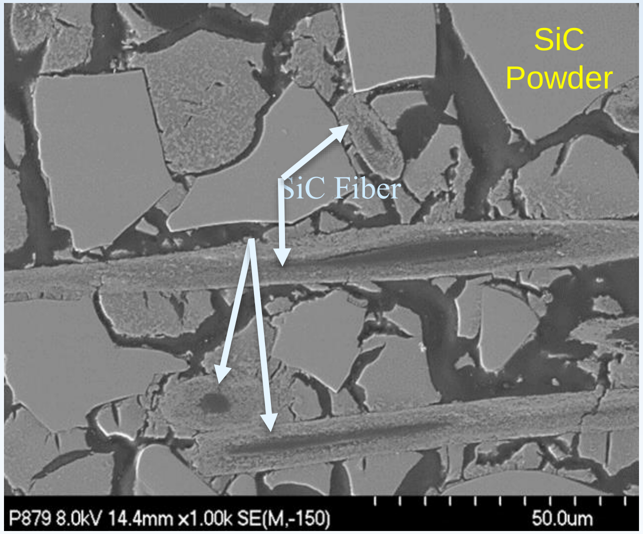
Tested in cascade rig



- Ultem 1000 ($T_g = 423^0$F) with chopped carbon fiber
- First Polyetherimide composite fabricated

Additive Manufacturing of Ceramic Matrix Composite (CMC)

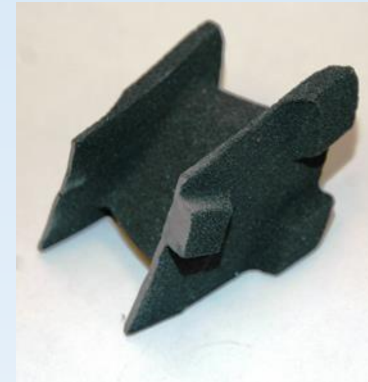




Binder jet printing allows for powder bed processing with *tailored binders* and *chopped fiber reinforcements* for fabricating advanced ceramics

Additive Manufacturing of Ceramic Matrix Composites

high pressure turbine nozzle segments



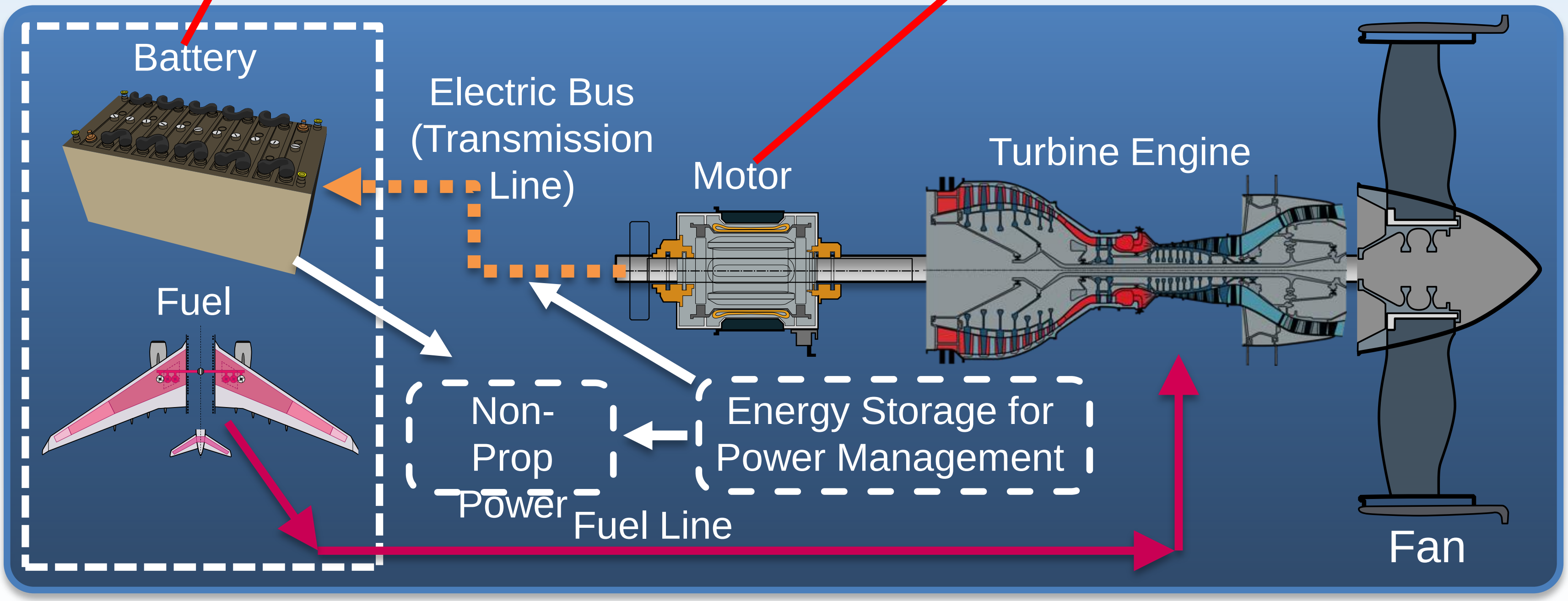
first stage nozzle segments

cooled doublet nozzle sections

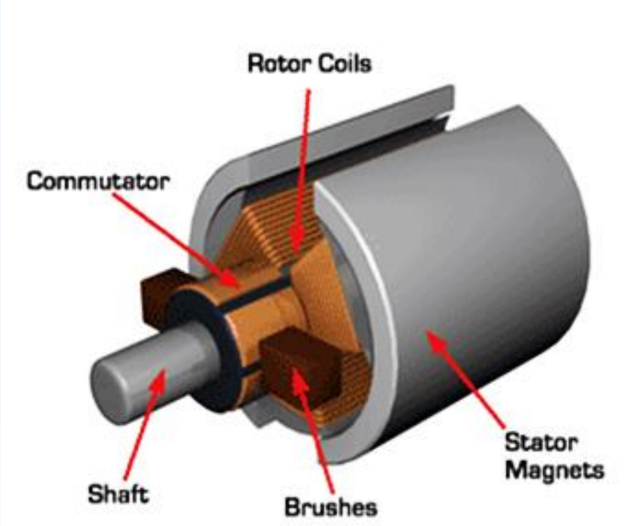
Hybrid Electric Propulsion for Aircraft

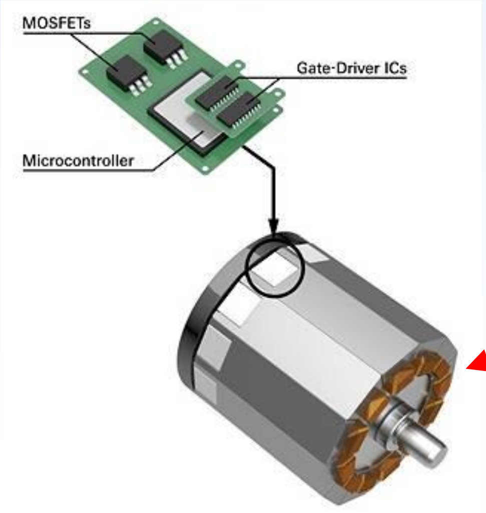
Need 3-5X increase in energy density

Need 3-5X increase in power density



Additive Manufacturing of Electric Motors

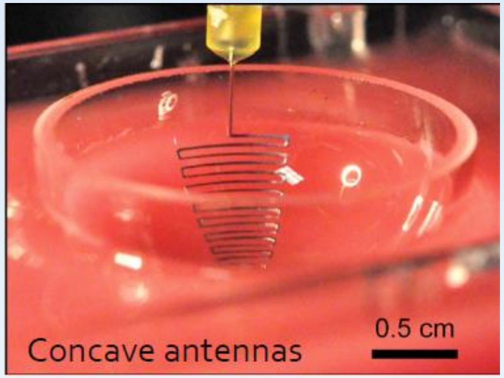




Additively Manufactured Electric Motors for Higher Power Densities

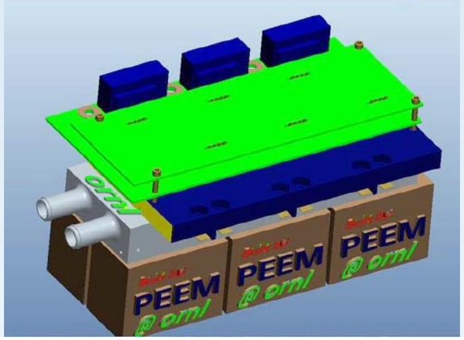
- Better packing density for Cu coils
- Co-printing and firing of the three materials: insulator, conductor, and steel – need multimaterial printing capability
- Intricate cooling channels for thermal management
- New topology enabled by additive manufacturing
- Integration of power electronics in motor

Evolving 3-D Printing Technologies That Will Enable Additive Manufacturing of Electric Motor

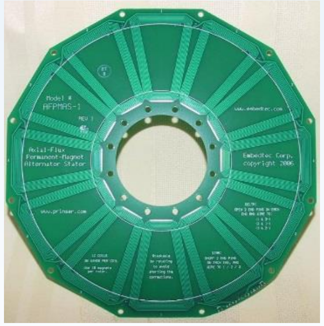


3-D Printing of Electronic Circuitry

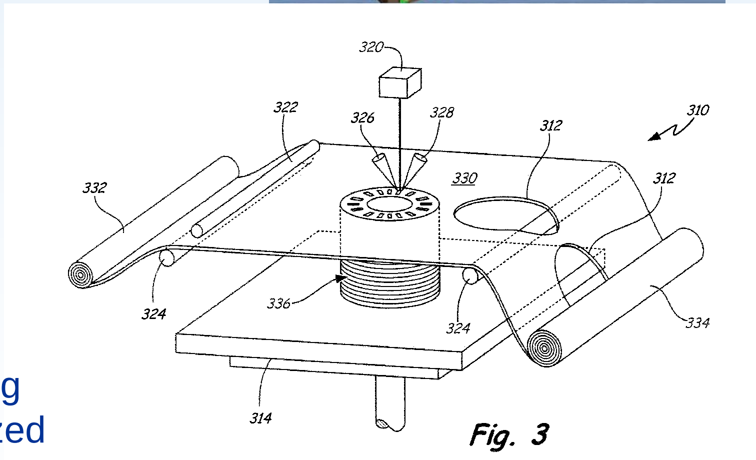
3-D Printing of SiC Power Electronics at ORNL



3-D Printing of Power Electronics Inductors (Stanford Univ.)



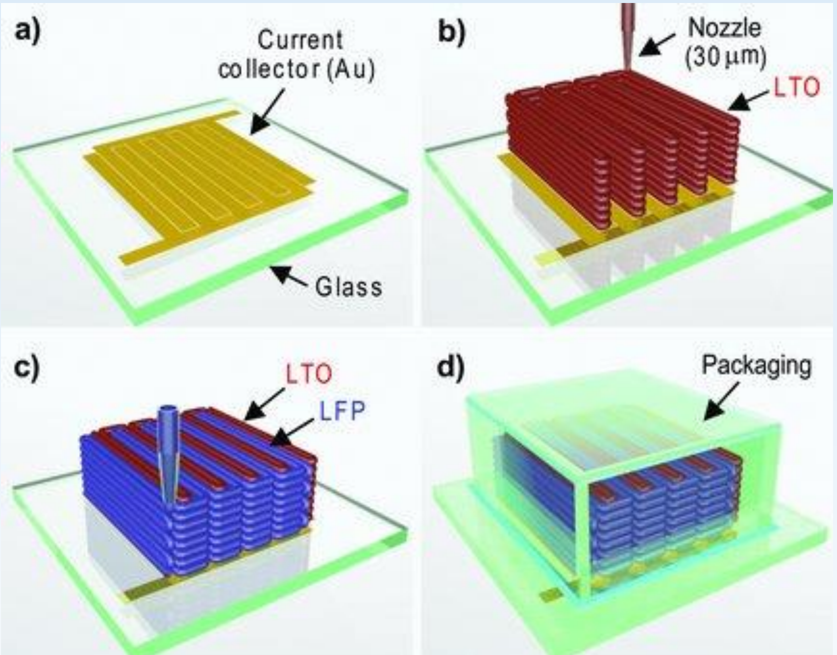
Boulder Wind Power using CORE (conductor optimized rotary energy) technology

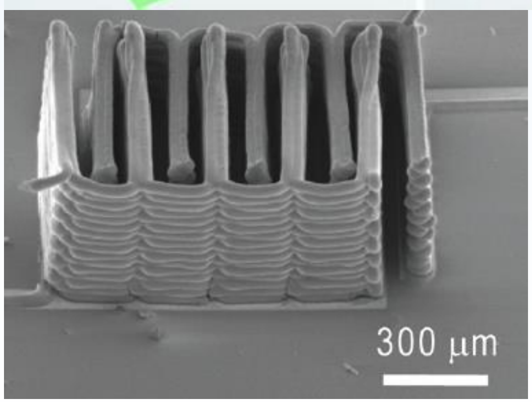


US Patent 20140035423 A1 (2014)

3-D Printing of Batteries and Fuel Cells

3-D Printing of Li Ion Micro batteries





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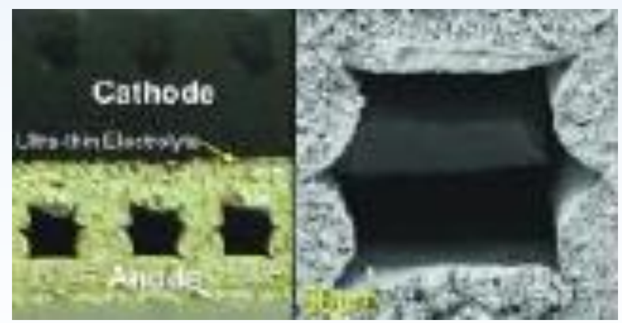
http://onlinelibrary.wiley.com/doi/10.1002/adma.201301036/full#fig1

3-D Printing of Solid Oxide Fuel Cell

JOM
DOI: 10.1007/s11837-015-1296-9



Northwestern University

Opportunities and Challenges

- Extensive use of additive manufacturing of space propulsion components
- Need certification of additively manufactured components
- New high temperature alloy chemistries and powders suitable for additive manufacturing
- Location-specific properties enabled by additive manufacturing
- Additive manufacturing of multimaterial/multifunctional systems
- Additive manufacturing process for fabrication of continuous fiber reinforced composites
- Modeling processing-microstructure-property relationship for additive manufactured components