Additive Manufacturing of Aerospace Propulsion Components

Dr. Ajay Misra

Dr. Joe Grady          Robert Carter

NASA Glenn Research Center
Cleveland, OH

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Aerospace Propulsion Systems of Interest

- Reduced complexity
- Faster cycle time
- Complex design features

Large Rocket Propulsion

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 °F 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

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

Inconel 625 structural jacket using EB Free Form Fabrication

GRCop-84 Combustion Chamber Liner produced using Selective Laser Melting

NASA GRC
NASA LaRC
NASA MSFC

Allegheny Technologies Incorporated
GRCop powder

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 Researchers in Australia
- 3-D Printing of Small Gas Turbine Engine by GE
- 3-D Printing of Low Pressure Turbine Titanium Aluminide Blade (GE)
Additive Manufacturing of Gas Turbine Engine Disk Alloy

Alloys with >10 elements γ’-precipitates

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

Increasing susceptibility to weld and PWHT cracking
Advanced Turbine Engine Disk Alloys – Opportunities for Additive Manufacturing

<table>
<thead>
<tr>
<th>Location</th>
<th>Key Property</th>
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<tbody>
<tr>
<td>1500 °F rim</td>
<td>Need high creep life and crack growth resistance</td>
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<tr>
<td>1300 °F web</td>
<td>Creep/fatigue interaction</td>
</tr>
<tr>
<td>800 °F bore</td>
<td>Need high tensile strength and low cycle fatigue life</td>
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Need additional manufacturing process to achieve:

- Location specific properties
- Bonding of multiple materials – Multimaterial capability
Additive Manufacturing of Non-Metallic Gas Turbine Engine Components

- Fan duct (polymer)
- Compressor vanes (PMC)
- Exhaust Components (CMC)
- Turbine shroud & nozzles (CMC)
- Engine access panel and acoustic liner (polymer)
- Fan bypass Stator (PMC)

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

corner detail shows acoustic perforations

inner surface incorporates acoustic treatment

panel location
Fused Deposition Modeling Simplifies Acoustic Liner Fabrication

Current manufacturing approach requires metal forming, bonding and drilling

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

200°F operating temperature

standard liner configuration complex geometries

Fabricated with monolithic Ultem 9085 thermoplastic ($T_g = 367°F$)
Additive Manufacturing of Polymer Matrix Composite Components

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

400°F operating temperature

Attachment detail

Tested in cascade rig

Inlet Guide Vane
First Stage Compressor Blade

Ultem 1000 composite vane by fused deposition

4.1”
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 power density

Need 3-5X increase in energy 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

3-D Printing of Batteries and Fuel Cells

3-D Printing of Li Ion Micro batteries

3-D Printing of Solid Oxide Fuel Cell

Advanced Materials
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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