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

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

Aerojet AR-1 Rocket Engine

NASA-Air Force-Aerojet Collaborative Effort
Development of Additive Manufacturing of Rocket Engine Components at NASA MSFC

Rocket Engine for Space Launch System

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

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

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

Alloys with >10 elements γ’-precipitates

Increasing susceptibility to weld and PWHT cracking

Challenge – Process induced porosity

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>
</tr>
<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)
- Business Jet size turbofan engine
- Engine access panel and acoustic liner (polymer)
- Fan bypass Stator (PMC)
- Turbine shroud & nozzles (CMC)
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 enabled 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.

The integral facesheet/honeycomb structure is fabricated in one step using Fused Deposition Modeling. Standard liner configuration achieves a 200°F operating temperature for complex geometries.

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

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

4.1”

Inlet Guide Vane

First Stage Compressor Blade

400$^\circ$F operating temperature

Tested in cascade rig

Attachment detail

Ultem 1000 composite vane by fused deposition
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

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

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

3-D Printing of Batteries and Fuel Cells

3-D Printing of Li Ion Micro batteries

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3-D Printing of Solid Oxide Fuel Cell

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