Enabling Additive Manufacturing Technologies for Advanced Aero Propulsion Materials & Components

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Outline

• Background, Applications, and NASA Strategic Thrusts
• AM of CMCs and Polymer Materials for Turbine Engine Applications
  – Laminated Object Manufacturing (OAI) for continuous fiber composites
  – Binder Jet Printing for short fiber composites
  – FDM of polymer-based materials
• AM of Materials and Components for Electric Motors
  – CAMIEM intro: the objectives and approach
  – New component designs for integration into the motor
  – Direct writing of conductors
  – Fabrication and evaluation of a baseline motor
• Summary and next steps
Additive Manufacturing Technologies

Direct Write Printing
Controlled dispensing of inks, pastes, and slurries.

Fused Deposition Modeling
Plastic is heated and supplied through an extrusion nozzle and deposited.

Binder Jetting
An inkjet-like printing head moves across a bed of powder and deposits a liquid binding material.
Components for Turbine Engine Applications

Turbine Engines - Targeted Components (CMCs and PMCs)

- Fan Duct
- Combustor Liners
- Shrouds & Vanes

NASA CMC Components from Conventional Fabrication Methods

- Oxide/Oxide Mixer Nozzle
- SiC/SiC Combustion Liners: Outer Liner and EBC Coated Inner Liner
- EBC Coated SiC/SiC Vanes

CMC Center Body
CMC Mixer Nozzle
Assembled Hardware

EBC Coated SiC/SiC Vanes
Components for Electric Motor Applications

Electric Motors - Targeted Components (structural, functional, and electrical)

Axial Flux Machine
- Stator
- Magnet(s)
- Rotor
- Housing

Radial Flux Machine

Electrified Aircraft
- STARC-ABL
- NASA 15-PAX tiltwing aircraft
- Uber Elevate

NASA Aeronautics Research Six Strategic Thrusts
3. Ultra-Efficient Commercial Vehicles
   - Pioneer technologies for big leaps in efficiency and environmental performance
4. Transition to Low-Carbon Propulsion
   - Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Achieve and exceed N+2 and N+3 goals for increased efficiencies and reduced emissions.
Laminated Object Manufacturing For Silicon Carbide-Based Composites

Prepregs for Composite Processing

- A number of SiC (Hi-Nicalon S, uncoated) fabrics (~6"x6") were prepregged.
- These prepregs were used for optimization of laser cutting process.
- Baseline laser cutting data was also generated for different types of SiC fabrics (CG Nicalon, Hi-Nicalon, and Hi-Nicalon S)

LOM allows for continuous fiber reinforced CMCs.

Universal Laser System (Two 60 watt laser heads and a work area of 32"x18")

SEM specimens cut with different laser power/speeds

Laser cut prepregs used for composite processing

Fabrics and Prepregs cut at different laser powers/speeds
Microstructure of SiC/SiC Composites Fabricated Using Single Step Reaction Forming Process plus Si Infiltration

Fibers Used for Prepregs: SiC (Hi-Nicalon S Fibers, 5 HS weave)
Fiber Interface Coating: None
Prepreg Composition: Prepreg 5A Nano 2 + Si

Green Preforms:
8 layers of prepregs; warm pressed @75-85°C

Heat Treatment:
1475°C, 30 minutes in vacuum

- Dense matrix after silicon infiltration. However, uncoated fibers are damaged due to exothermic Si+C reaction.
- Fiber coatings needed to prevent silicon reaction and provide weak interface for debonding and composite toughness.
Microstructure of SiC/SiC Composites Fabricated Using Single Step Reaction Forming Process plus Si Infiltration

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8 layers of prepregs; warm pressed @75-85°C

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1475°C, 30 minutes in vacuum

Micrographs show good distribution of SiC and Si phases.

Uncoated SiC fibers show no visible damage due to Si exothermic reaction.
Binder Jet Additive Manufacturing of SiC

**Powder Blending**

**Final Part**

**Infiltration**

**Green part**

**De-powdering**

An inkjet printing head moves across a bed of powder and deposits a liquid binding material.

Binder jet printing capability allows for powder bed processing with tailored binders and chopped fiber reinforcements for advanced ceramics.
Binder Jetting of SiC Fiber / SiC Matrix Composites

ExOne Innvoent

Constituents

SiC powder

SiC powder loaded SMP-10

Si-TUFF iSiC fibers (Advanced Composite Materials, LLC)

~70 \( \mu \text{m} \) long and
~7 \( \mu \text{m} \) in diameter

Fiber Reinforced Ceramic Matrix Composite

High pressure turbine cooled doublet vane sections.
Approach for Additive Manufacturing of CMCs

Processing
- Constituents
  • **SiC powders**: Carborex 220, 240, 360, and 600 powders (median grain sizes of 53, 45, 23, and 9 microns respectively). Used solely and in powder blends
  • **Infiltrants**: SMP-10 (polycarbosilane), SiC powder loaded SMP-10, phenolic (C, Si, SiC powder loaded), pure silicon
  • **Fiber reinforcement**: Si-TUFF SiC fiber; 7 micron mean diameter x 65-70 micron mean length

Microstructure
- Optical microscopy
- Scanning electron microscopy

Properties
- Material density (as manufactured and after infiltration steps)
- Mechanical properties: 4-point bend tests

**Processing, microstructure, and property correlations provide an iterative process for improving the CMC materials.**
Binder Jetting: Density of SiC Panels

Densities increased by up to 33% from additional PCS infiltration steps and were maintained even at higher SiC fiber loadings of 45, 55, and 65 vol.%. 

Polymer approach has a limitation on achievable densities.

Demonstration of full densification through silicon melt-infiltration.

Melt infiltration methods such, e.g. silicon melt, can achieve near full density.
Carborex Powder mix with 65 vol.% Si-Tough SiC fiber, SMP-10 w/800 nano SiC particles vacuum infiltration.

Good densities achieved with high fiber loading.
Binder Jetting: 4 Point Flexure Tests of the Monolithic SiC and CMC materials - at R.T.

Bend bars for strength testing

The fiber loaded SiC materials had significantly higher stresses and higher strains to failure.
Recent SiC Binder Jetting Results
- Processing and Mechanical Strength Improvements

- Four point bend tests were conducted on samples after 4 SMP-10 infiltrations
- 50 mm long samples were loaded with a 20 mm loading span and 40 mm support span
- The maximum strength was 111 MPa
- For comparison: Dense CVD SiC and sintered alpha SiC bend strength ranges from 200-450 MPa
- Samples that were tested after 6 infiltrations showed no difference in strength
Demonstration of Polymer Components from FDM

Fortus 400

FDM Process

Engine Panel Access Door

Lightweight Structures

Inlet Guide Vanes from ABS and Ultem 1000

Standard Liner

Complex Geometry

Advanced Liner Design

The focus is on unique structures, high temperature capability, and fiber reinforcement.
FDM of Composite Filaments for Multi-Functional Applications

Potential Missions/Benefits:
- On demand fabrication of as needed functional components in space
- Tailored, high strength, lightweight support structures reinforced with CNT
- Tailored facesheets for functional properties, i.e. wear resistance, vibration dampening, radiation shielding, acoustic attenuation, thermal management

Filaments used: ABS-standard abs, P-premium abs, CNT-w/carbon nanotubes, C-w/chopped carbon, Home-lab extruded filament

Highest strength and modulus in CNT reinforced coupons versus standard ABS Coupons. Less porosity for lower print heights.
Aircraft Utilizing Electric Motors

Urban Air Mobility

- NASA 15-PAX tiltwing aircraft
- Uber Elevate

Large Single Isle Transports

- STARC-ABL
- Hybrid Electric
- Greased Lightning GL-10

X-57: Distributed Propulsion
Objective: Utilize additive manufacturing (AM) methods to achieve new motor designs that have significantly higher power densities and/or efficiency.

Methods:
• New topologies with compact designs, lightweight structures, innovative cooling, high copper fill, and multi-material systems/components.
• New component designs for the rotors, housing, finned stator cooling ring, direct printed stator, and a wire embed stator.
• Compare new components/new motor against a baseline motor.

Mission: efficient, low emission aircraft for Urban Air Mobility.

Compact Additively Manufactured Innovative Electric Motor (CAMIEM) team members: NASA (GRC, LaRC, ARC), LaunchPoint Technologies and the University of Texas - El Paso

- Motor Width: ~ 7.5"
- Total weight ~ 4lbs (1.8 kg)

Already SOA due to compact design, high power density, and halbach array of magnets.

For development of advanced materials, structures, and components.

Projecting a 2x increase in Power Density to 10 kW/kg.
Feasibility Assessment

Baseline Motor Testing for baseline performance

Baseline Motor

Innovative Motor Design

Additive Manufacturing Processes and Advanced Components

Testing of “New” Motor Configurations to Determine Improved Performance

Aircraft Level System Studies

Feasibility Assessed and Benefits Determined
AM and Hybrid Approaches for Electric Motor Components

Electric Motors

Components of a Commercial Axial Flux Motor

NASA Electric Motor with AM Components

Stators

Litz Wire Coreless Stator

PCB Coreless Stator

Iron Core Stator with Direct Printed Coils

Stator Constituents:
- Conductor: copper, silver.
- Insulators: coatings, dielectrics, epoxy, high temp. polymer.
- Soft magnets (for cores): iron alloys.

Rotors

Additively Manufactured Rotor Plate

Rotor Constituents:
- Permanent magnets.
- High strength structure (typically metallic).
Direct Printed Stators

Benefits
- Higher magnetic flux, torque, and motor constant ($K_m$).
- Higher temp. capability of $>220^\circ C$ instead of $160^\circ C$ for baseline stator.
- Direct printed silver coils with high fill.

Concept A

Details of machined features

Stator Plate from Cobalt-Iron Alloy
Cirlex Middle Layer
Outer Rings

nScrypt 3Dn-300

Silver paste
Substrate

4-point probe method

Direct Printed Silver Coils - High Current Test
Additively Manufactured Stator Plates

High Temp. Polymer

FDM from Extem (Tg of 311°C) (left) and Ultem 1010 (TG of 217°C) (right) FDM filament.

Low cost and rapidly manufactured sub-components may be possible with further advancements or alternate AM processes.
Comparison of Methods to Obtain Outside Fabrication for Channeled Plates for Stators

Concept A - Stator Plates from Cobalt-Iron Alloy

Concept B - Stator Plates from Cirlex

Concept B - Stator Plates from Ultem1010

<table>
<thead>
<tr>
<th>Fabrication Method</th>
<th>Machine/EDM</th>
<th>Machine/Mill</th>
<th>3D Print/FDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication Time</td>
<td>4+ months</td>
<td>3 months</td>
<td>1 week (92.3% reduction)</td>
</tr>
<tr>
<td>Fabrication Costs</td>
<td>$21,400</td>
<td>$19,870</td>
<td>$1,000 (95.0% reduction)</td>
</tr>
<tr>
<td>Material Costs</td>
<td>$600</td>
<td>$330</td>
<td>$0 (included in fab.)</td>
</tr>
<tr>
<td>Total Costs</td>
<td>$22,000</td>
<td>$20,200</td>
<td>$1,000</td>
</tr>
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</table>

Currently relying on machined stator plates.
Samples were printed on the nScrypt 3Dn-300.

Crucial Parameters:

– Print Speed
– Dispensing Pressure
– Nozzle Diameter
– Print Offset
– Valve Opening

4-point probe method

Thin Surface and Imbedded Thick 4-Pt Probe Windings

Trace

Substrate
# Evaluation of Silver Pastes

<table>
<thead>
<tr>
<th>Paste Composition</th>
<th>Lowest Resistivity Obtained [$\Omega$m]</th>
<th>Conductivity [$\Omega$m]$^{-1}$</th>
<th>Max Temp (*C)</th>
<th>Vendor Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL-11190 (Heraeus)</td>
<td>2.06 x 10$^{-8}$</td>
<td>4.86 x 10$^{7}$</td>
<td>300</td>
<td>N/A</td>
</tr>
<tr>
<td>CB028 (DuPont)</td>
<td>2.82 x 10$^{-8}$</td>
<td>3.54 x 10$^{7}$</td>
<td>175</td>
<td>7 – 10 (m$\Omega$/sq/mil)</td>
</tr>
<tr>
<td>CL20-11127 (Heraeus)</td>
<td>3.6 x 10$^{-8}$</td>
<td>2.78 x 10$^{7}$</td>
<td>300</td>
<td>N/A</td>
</tr>
<tr>
<td>CB100 (DuPont)</td>
<td>5.23 x 10$^{-8}$</td>
<td>1.91 x 10$^{7}$</td>
<td>175</td>
<td>&gt;7.5 x 10$^{-8}$ $\Omega$m</td>
</tr>
<tr>
<td>Ag-PM100 (Applied Nanotech)</td>
<td>9.13 x 10$^{-8}$</td>
<td>1.10 x 10$^{7}$</td>
<td>300</td>
<td>&gt;5 x 10$^{-8}$ $\Omega$m</td>
</tr>
<tr>
<td>Kapton (DuPont)</td>
<td>2.11 x 10$^{-7}$</td>
<td>4.74 x 10$^{6}$</td>
<td>225</td>
<td>&lt;5 (m$\Omega$/sq/mil)</td>
</tr>
</tbody>
</table>

### Conductivity of bulk metals [$\Omega$m]$^{-1}$:
- Silver: $6.3 \times 10^{7}$
- Copper: $6.0 \times 10^{7}$

Printed conductors will have a higher effective conductivity than the Litz wire conductors.

Litz Wire ~60% fill and less in stator windings.
Additions of Graphene and Carbon Nanostructures

Plain Pastes

<table>
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<tr>
<th>Paste Composition</th>
<th>Resistivity [Ωm]</th>
<th>Conductivity [Ωm]^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain CB028</td>
<td>2.82 E-08</td>
<td>3.54 E+07</td>
</tr>
<tr>
<td>Plain Heraeus</td>
<td>4.124E-08</td>
<td>2.42E+07</td>
</tr>
</tbody>
</table>

Most Conductive Composites

<table>
<thead>
<tr>
<th>Paste Composition</th>
<th>Resistivity [Ωm]</th>
<th>Conductivity [Ωm]^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB028 + 0.2 wt% QUATTRO Graphene</td>
<td>8.148E-08</td>
<td>1.23E+07</td>
</tr>
<tr>
<td>Heraeus + 0.04 wt% CNS</td>
<td>8.297E-08</td>
<td>1.21E+07</td>
</tr>
<tr>
<td>CB028 + 0.1 wt% QUATTRO Graphene</td>
<td>1.036E-07</td>
<td>9.65E+06</td>
</tr>
<tr>
<td>CB028 + 0.085 wt% CNS</td>
<td>1.114E-07</td>
<td>8.97E+06</td>
</tr>
<tr>
<td>Heraeus + 0.14 wt% CNS</td>
<td>1.191E-07</td>
<td>8.40E+06</td>
</tr>
<tr>
<td>CB028 + 0.2 wt% MONO Graphene</td>
<td>1.261E-07</td>
<td>7.93E+06</td>
</tr>
<tr>
<td>CB028 + 0.5 wt% MONO Graphene</td>
<td>1.419E-07</td>
<td>7.05E+06</td>
</tr>
</tbody>
</table>

Peng-Cheng Ma, “Enhanced Electrical Conductivity of Nanocomposites Containing Hybrid Fillers of Carbon Nanotubes and Carbon Black.”
Advanced Sintering Processes for Higher Electrical Conductivity

Photonic Sintering

Investigating the use for photonic sintering for printed silver inks.
- Rapid post processing of conductive patterns
- Few second to minute processing times without damaging/heating the substrate

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Resistance [Ωm]</th>
<th>Conductivity [Ωm]^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>71017G</td>
<td>4.37 x 10^-8</td>
<td>2.29 x 10^7</td>
</tr>
<tr>
<td>71017H</td>
<td>5.75 x 10^-8</td>
<td>1.74 x 10^7</td>
</tr>
<tr>
<td><strong>Heraeus CL20-11127 Thermally Cured on Fiberglass (195°C/1hr due to substrate limitations)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72117A</td>
<td>4.12 x 10^-8</td>
<td>2.42 x 10^7</td>
</tr>
<tr>
<td><strong>Heraeus CL20-11127 Thermally Cured on Vespel (300°C/1hr)</strong></td>
<td></td>
<td></td>
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<tr>
<td>71017A</td>
<td>4.89 x 10^-8</td>
<td>2.05 x 10^7</td>
</tr>
<tr>
<td>71017B</td>
<td>4.55 x 10^-8</td>
<td>2.20 x 10^7</td>
</tr>
<tr>
<td>71017C</td>
<td>6.04 x 10^-8</td>
<td>1.65 x 10^7</td>
</tr>
<tr>
<td><strong>Heraeus CL20-11127 Photonically Cured</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>032917-6</td>
<td>2.82 x 10^-8</td>
<td>3.54 x 10^7</td>
</tr>
<tr>
<td><strong>DuPont CB028 Thermally Cured on Fiberglass (150°C/1hr)</strong></td>
<td></td>
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</table>

Photonic Sintering for high through-put

Resistivity greatly improved from 8 ohm in green state to 1.8 ohm after photonic sintering.
Potential, further optimization by investigating offset distance, kV setting, pulses, duration and nano-sized silver particles.

Thermal/Oven Curing

- Rapid post processing of conductive patterns
- Few second to minute processing times without damaging/heating the substrate
Direct Printed Silver Coils - High Current Test

Temperature capability far exceeds that of the baseline motor which is 180°C.

Temperature decreases with extended heat potentially due to self sintering and decreasing resistance within the paste traces.
Testing of Motor Configurations

**AFRC prop motor testing:**
- Baseline motor
- Motor Version 1: Structural LaRC parts - rotors and housing

**GRC motor testing in a dynamometer:**
- Baseline motor
- Motor Version 2: Structural LaRC parts - rotors, housing, finned cooling ring

**Baseline Motor**
- Mass = 1968 g

**V1. Motor**
- Mass = 1833 g
- (7% less mass)

**V2. Motor**
- Mass = 1870 g
- (5% less mass)
- Total heat sink mass = 92 g

**NASA GRC Dyno**
**Avg Motor Efficiency vs Avg Torque**

- Efficiency (percent)
- Torque (N-M)
- RPM:
  - 3000 RPM
  - 4000 RPM
  - 5000 RPM
  - 6000 RPM
  - 7500 RPM

**Prop Test Stand**

**Dynamometer**
Summary and Conclusions

Summary

• Good progress is being made in applying additive manufacturing methods to the fabrication of components for turbine engine and electric motors.

• LOM offers continuous fiber reinforced CMCs while the binder jet method offers short fiber reinforced SiC-based ceramics.

• AM offers the potential for electric motors with much higher efficiencies and power densities.

• Additive manufacturing technologies were demonstrated to be capable of enabling new innovative direct printed stator designs for electric motors.

• New electric motor component designs will offer performance gains through such improvements as lighter weights, higher coil packing, higher coil electrically conductive, higher temperature operation, and higher magnetic flux.
The CAMIEM Team and Acknowledgements

Support provided by the Convergent Aeronautics Solutions Project within the ARMD Transformative Aeronautics Concepts Program.

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<tr>
<td>Glenn Research Center</td>
<td>Michael Halbig (POC)</td>
<td>PI and GRC POC</td>
<td>Armstrong Flight Research Center</td>
<td>Ethan Niemen (POC)</td>
<td>AFRC POC and ground testing</td>
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<td></td>
<td>Mrityunjay &quot;Jay&quot; Singh</td>
<td>Additive manufacturing</td>
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<td>Otto Schnarr III</td>
<td>Electric propulsion ground testing</td>
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<td></td>
<td>Valerie Wiesner</td>
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<td>Kirsten Fogg</td>
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<td>Chun-Hua &quot;Kathy&quot; Chuang</td>
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<td>Russell “Buzz” Wincheski</td>
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<td>John Newman</td>
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<td>LaunchPoint Technologies</td>
<td>Michael Ricci (POC)</td>
<td>Baseline &amp; innovative motor designs</td>
<td>University of Texas El Paso</td>
<td>Jose Coronel (POC)</td>
<td>Stator winding and cooling efficiency</td>
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<td>David Espalin</td>
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<td>Dave Paden</td>
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<td>Ryan Wicker</td>
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Also Summer Interns at GRC (Anton Salem and Hunter Leonard) and LaRC.