Additive Manufacturing of Multi-Material Systems for Aerospace Applications

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Outline

• Needs, challenges, and applications
• AM of multi-materials in a single feed-stock
  – Direct writing of low resistance conductors
  – Binder jet printing of SiC fiber / SiC matrix composites
  – FDM of polymer-based materials with functional additions
• Hybrid and two-stage AM toward multi-material components
  – Stators for electric motors
  – Lightweight multi-functional components, e.g. thermal management of battery packs
• Summary and Conclusions
Additive Manufacturing of Multi-Materials

Needs:

• Achieving complex shapes and processing not possible from conventional fabrication methods.
• Components with integrated sub-elements of differing materials and structures.
• Tailored material properties: e.g. microstructure, mechanical, electrical, thermal, and magnetic.

Challenges:

• Additive manufacturing for multi-materials is not as mature as for single materials.
• Optimal utilization of several methods, e.g. single machine AM, multi-machine AM, and hybrid approaches (combinations of AM and conventional).
• Post-processing of multi-materials with differing sintering temperatures and material mismatches and incompatibilities.
Components for Aerospace Applications

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

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

Radial Flux Machine

Turbine Engines -
Targeted Components (CMCs and PMCs)

- Fan Duct
- Combustor Liners
- Shrouds & Vanes

Exhaust Components

AM for In-Space and on Terrestrial Planets -
Targeted Components (Functional PMCs)

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

Replacement Part Fabrication

Lightweight Multifunctional Components
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.
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Direct Writing of Low Resistance Conductors

Additions of Graphene and Carbon Nanostructures

<table>
<thead>
<tr>
<th>Plain Pastes</th>
<th>Resistivity [Ωm]</th>
<th>Conductivity [Ωm]^-1</th>
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</thead>
<tbody>
<tr>
<td>Plain CB028</td>
<td>2.82E-08</td>
<td>3.54E+07</td>
</tr>
<tr>
<td>Plain Heraeus</td>
<td>4.12384E-08</td>
<td>2.42E+07</td>
</tr>
</tbody>
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<tr>
<th>Most Conductive Composites</th>
<th>Resistivity [Ωm]</th>
<th>Conductivity [Ωm]^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB028 + 0.2 wt% QUATTRO Graphene</td>
<td>8.14798E-08</td>
<td>1.23E+07</td>
</tr>
<tr>
<td>Heraeus + 0.04 wt% CNS</td>
<td>8.29725E-08</td>
<td>1.21E+07</td>
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<tr>
<td>CB028 + 0.1 wt% QUATTRO Graphene</td>
<td>1.03586E-07</td>
<td>9.65E+06</td>
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<tr>
<td>CB028 + 0.085 wt% CNS</td>
<td>1.1145E-07</td>
<td>8.97E+06</td>
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<tr>
<td>CB028 + 0.14 wt% CNS</td>
<td>1.19059E-07</td>
<td>8.40E+06</td>
</tr>
<tr>
<td>CB028 + 0.2 wt% MONO Graphene</td>
<td>1.26118E-07</td>
<td>7.93E+06</td>
</tr>
<tr>
<td>CB028 + 0.5 wt% MONO Graphene</td>
<td>1.41875E-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
Binder Jetting of SiC Fiber / SiC Matrix Composites

ExOne Innovent

Constituents

SiC powder

SiC powder loaded SMP-10

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

~70 μm long and ~7 μm in diameter

Fiber Reinforced Ceramic Matrix Composite

High pressure turbine cooled doublet vane sections.
Binder Jetting: Density of SiC Panels

Multiple PCS infiltration steps.

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.%. The Polymer approach has a limitation on achievable densities.

Demonstration of full densification through silicon melt-infiltration. Melt infiltration methods such as 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 room temperature and 1200°C

The fiber loaded SiC materials had significantly higher stresses and higher strains to failure.
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

Effect of print layer height

Highest strength and modulus in CNT reinforced coupons Pure ABS Coupons. Less porosity for lower print heights.
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  – Stators for electric motors
  – Lightweight functional components, e.g. thermal management of battery packs

• Summary and Conclusions
Components of a Commercial Axial Flux Motor

**Stators**
- **Litz Wire Coreless Stator**
- **PCB Coreless Stator**

**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).
Wire Embedded Stator: U. of Texas El Paso (NASA CAMIEM)

- Conventional stator by LaunchPoint Technologies
- Ultrasonic embedding horn
- 20 kHz Ultrasonic system
- PC substrate
- Pressing process needed to further densify the stator
- Final stator

Multi3D System

- FDM Machine 1
- FDM Machine 2
- CNC router capable of:
  - Machining
  - Direct-write
  - Wire embedding
  - Robotic component placement

- Six-axis robot arm (Yaskawa Motoman)

- Challenges with feeding wire through ultrasonic horn of required 14 AWG wire.
- Challenges with overprinting polycarbonate onto embedded wire.

Cartridge heated embedding demonstration

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PCB Stator Concepts

Direct Printed Silver Conductor Layer

Direct Printed Dielectric Layer
Direct Printed Stator - Concepts A and B

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

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Additively Manufactured Stator Plates

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

<table>
<thead>
<tr>
<th>Concept A - Stator Plates from Cobalt-Iron Alloy</th>
<th>Concept B - Stator Plates from Cirlex</th>
<th>Concept B - Stator Plates from Ultem1010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication Method: Machine/EDM</td>
<td>Fabrication Time: 4+ months</td>
<td>Fabrication Method: 3D Print/FDM</td>
</tr>
<tr>
<td>Fabrication Time: 4+ months</td>
<td>Fabrication Time: 3 months</td>
<td>1 week (92.3% reduction)</td>
</tr>
<tr>
<td>Material Costs: $600</td>
<td>Material Costs: $330</td>
<td>$0 (included in fab.)</td>
</tr>
<tr>
<td>Fabrication Costs: $21,400</td>
<td>Fabrication Costs: $19,870</td>
<td>$1,000 (95.0% reduction)</td>
</tr>
<tr>
<td>Total Costs: $22,000</td>
<td>Total Costs: $20,200</td>
<td>$1,000 (95.0% reduction)</td>
</tr>
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Currently relying on machined stator plates.
FDM of Multi-Material Test Coupons for Lightweight Multi-Functional Applications

Premium ABS (P-ABS)

5% Carbon Fiber by weight ABS (CF-ABS)

System A
- Half P-ABS
- Half CF-ABS
- P-ABS bottom

System B
- Half P-ABS
- Half CF-ABS
- CF-ABS bottom

System C
- 4 alternating layers of P-ABS and CF-ABS
- CF-ABS bottom

System D
- 8 alternating layers of P-ABS and CF-ABS
- CF-ABS bottom
Microstructures of FDM of Multi-Material Test Coupons

System A
System B
System C
System D

P-ABS
CF-ABS

(upsidedown)
Multi-Material Tensile Testing

FDM Process
- Process: lay down of a melt strand
- Filament
- Prototype
- Nozzle
- Likewise application
- Supporting structure
- Base plate

Multi-material print

Tensile Testing

Hyrel Hydra 645

(DIC)
# Single and Multi-Material Tensile Testing

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<tbody>
<tr>
<td>3DXTech Ultem 9085 CF</td>
<td>H</td>
<td>1992.1</td>
<td>1893.4</td>
<td>53.7</td>
<td>50.5</td>
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<tr>
<td>SABIC ULTEM AM9085F</td>
<td>P</td>
<td>3163.6</td>
<td>2988.7</td>
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<td>2395.3</td>
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<tr>
<td>SABIC 9085+3DXTech 9085 CF</td>
<td>PH</td>
<td>2679.0</td>
<td>2480.6</td>
<td>62.4</td>
<td>59.1</td>
<td>3082.6</td>
<td>3005.3</td>
<td>2.5691</td>
</tr>
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1=3DXTech Ultem 9085 CF
2=SABIC ULTEM AM9085F
Multi-Material Heat Exchanger Designs

Forced Air Cooled

Liquid Cooled

Single Material Battery Case Demonstrations
Conclusions

• Additive manufacturing enables advanced materials, structures, and components.

• AM of multi-materials in a single feed-stock allows for optimized properties and functionality, e.g. electrical conductivity, thermal conductivity, strength, etc.

• Achieving multi-material components requires hybrid and two-stage AM approaches.

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