Additively Manufactured Luminaire: Process and Material Challenges (things that keep me awake at night)

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Luminaire Assemblies: Where are we today?

Typical Luminaire Manufacturing Flow

Traditional Manufacturing Approach

- Assembly line model
- Complex assemblies
- Many designs / components

- Significant labor content
- Complex supply chain
- Large inventory
- Long cycle times
- Long time to market
Luminaire Assemblies: Where do we want to be?

Integrated Roadway Concept

Eaton Concept Prototype (2017)*
- Fully printed, integrated circuitry with LED, driver, sensors and antennas
- Minimal part count
- Simplified assembly

Integrated Manufacturing Flow

Fully Integrated CAD Design
Machine Download and Debug
Manufacture AM Luminaire
Post Process
Test
Inventory
Ship

Metal Material Resource
Polymer Material Resource
Optical Material Resource
Electronics and Sensor Material Resource

Fully Integrated Manufacturing Approach

- “Print on demand” model
- Few components and assemblies
- Integrated mechanical/electronics
- Reduced operations and mfg. footprint
- Consolidated supply chain
- “Near” zero inventory
- Faster time to market

Key Additive Manufacturing (AM) Elements to Consider

- Mechanical Housing
- Thermal Management
- Electronics
- Optics
Mechanical Housing

• Integrate mechanical features (minimize SKU’s)
  • Heat sink
  • Mounting and adjustment hardware
  • Fasteners
  • Gaskets
• Utilize AM techniques to reduce material and weight
  • Skins on scaffolds
  • Vary cross section based on requirements
• Post processing
  • Cost impact so minimize
• Polymer or Metal?
  • Weight, cost impact
  • Environmental exposure requirements (polymer may be better from a corrosion perspective)
  • Polymer may be printed on metal (not vice versa)
Thermal Management

• AM material properties may differ from “wrought”
  • Porosity effects
  • Thermal properties may differ as a function of print direction
  • Filler segregation (in polymers)
• Minimal manufacturing constraints
  • Not limited by traditional heat sink fabrication methods
  • May require some post processing to achieve full properties
• Polymer or Metal?
  • Validate LED junction temperature with thermal simulation
  • New materials emerging every day
    • Metals: Al alloys, Cu, Ni super alloys, Ti, steels
    • Polymer with nano-fillers: ceramic, Carbon, nano-tubes (alignment still an issue), Cu

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (Wm⁻¹K⁻¹)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Aluminum</td>
<td>90-160</td>
<td>Published but actual = 80-90</td>
</tr>
<tr>
<td>Printed Al Alloy</td>
<td>34 - 60</td>
<td>As Printed</td>
</tr>
<tr>
<td>Printed Al Alloy</td>
<td>42 - 72</td>
<td>Estimate, Post Process 1</td>
</tr>
<tr>
<td>Printed Al Alloy</td>
<td>60 - 102</td>
<td>Estimate, Post Process 2</td>
</tr>
<tr>
<td>Thermally Conductive Polymer A</td>
<td>3.5</td>
<td>Molded</td>
</tr>
<tr>
<td>Thermally Conductive Polymer A</td>
<td>3.5</td>
<td>Measured in direction of print</td>
</tr>
<tr>
<td>Thermally Conductive Polymer A</td>
<td>2.5</td>
<td>Measured normal to print direction</td>
</tr>
</tbody>
</table>

Estimated LED junction temperature based on thermal resistance model (1-5 W LED thermal load on a 10×10 cm² x 2.5 mm thick sink).
Optics

3D Printed Optic for Modular Concepts

- Material choices still limited
  - Metals
  - Polyurethanes, acrylics, some polycarbonate
  - Silicones emerging
- Optic design
  - Optical properties still behind traditional methods
  - Reflective ahead of transmissive (material constraint)
  - Complexity typically not an issue
  - Surface finish and color capability still limited
- Environmental exposure
  - Temperature
  - UV exposure still a problem for some materials

3D Printed samples long-term optical testing results under 50°C elevated temperature (reflective on right and transmissive on left)*

Printed Electronics on AM Structures

- Materials
  - Many choices but varied properties
    - **Conductors**: Silver, Copper, **Dielectrics**: polymer and inorganic, **Resistors**: Some availability but chip components are more cost effective
  - Low temperature vs high temperature processing
  - Compatibility with AM substrate materials
    - Adhesion, **Surface finish**, Thermal expansion
  - Design rule development (geometry vs current carrying)
- Take advantage of AM processing
  - Thickness adjustment for high and low current
  - Integrate wiring wherever possible
  - Environmental protection on electronics may be required
- Interconnects
- Component attach: Solder or Electrically Conductive Adhesive?
Printed Electronics and Surface Finish

Surface scan of Printed Electronics area on metal AM sample
- $Ra = 162 \ \mu\text{in} (4.12 \ \mu\text{m})$, $Rz = 999 \ \mu\text{in} (25.39 \ \mu\text{m})$
- $Rz$ is a better measurement for printing electronics
- If $Rz$ is too high, shorting may occur through dielectric isolation layers

Post processing can be used to improve surface finish to acceptable level
AM Metal Fabrication: L-PBF Process Example

- Laser Powder Bed Fusion (L-PBF) is the additive manufacturing industry standard for producing high-density, precision metal parts.
- Metal powder is laser welded layer-by-layer in a controlled process.
- Common materials: Stainless steels, tool steels, cast aluminum alloys, cobalt chrome, Inconels, titanium alloys, etc.
- Typical process time hours to days or less (design dependent)
AM Metal Fabrication: L-PBF Process Example

- Test structure for printed electronics processing
- Development of design rules for printing on 3D surfaces
- Explore placement of LED’s at different angles and levels within the structure
- Fabricated using L-PBF process (Aluminum based alloy)
AM Fabrication of 3D Printed Electronics Test Structure (Time Lapse)

CAD Geometry

Print Layer Progression
Questions

Only easy questions allowed!