Advanced Manufacturing for Aerospace

**A systems approach to understanding additive manufacturing's impact on the aerospace supply chain**

*Bill Bihlman, Bob Kenley, PhD., Gary Cheng, PhD.*

www.incose.org/glrc2018
Part 1: AM Market Overview
Part 2: Aerospace Market Overview
Part 3: AM Process Modeling
Part 4: Case Study ~ Implementing AM
Additive Manufacturing Overview

Part 1
All major aerospace companies have engaged in some type of additive manufacturing (AM)

Recent Investments in Additive

Source: secondary

www.incose.org/glrc2018
AM enables building parts that historically were not possible to machine

Overview to AM Process

Organic Shape Optimization

Internal Lattice Optimization

AM is the process of adding - as opposed to removing - material to create a part

Ultimate benefit is ability to **lightweight** a part, known as topology optimization

Source: analysis

www.incose.org/glrc2018
AM is categorized by material source and energy method, clearly involving benefits/risks

**AM Characterization**

**Classification**

1) **Material source:**
   - Powder bed
   - Powder feed
   - Wire feed

2) **Energy method:**
   - Laser
   - Electron beam
   - Plasma

**Benefits**

- Reduce weight
- Reduce part count
- Reduce lead time
- Increase material yield

**Aerospace Applications**

- Repairs (1980s)
- Tooling (1990s)
- Whole parts (2010s)*

**Risks**

- Microstructure quality
- Process repeatability

* Mostly prototyping, not production

Source: analysis

www.incose.org/glrc2018
Two most common AM “modalities” in aerospace are powder bed and wire feed

<table>
<thead>
<tr>
<th>Powder Bed (Sintering)</th>
<th>Wire Feed (Welding)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growing layers via melting powder metal – developed 1980s for DARPA</td>
<td>Melting wire – similar to welding – to create molten pool to build linear layers</td>
</tr>
</tbody>
</table>

**Advantages**: high near net, complex geometry

**Disadvantages**: limited size, small batches, source material control

**Advantages**: high deposition, economical

**Disadvantages**: more machining, residual stresses, voids/occlusions

*Powder bed favors engine (castings) parts, whereas wire feed is for aerostructures (forgings)*

Source: analysis, secondary
AM process, however, introduces variability and thus risk into production process

**AM Physical Process & Resulting Microstructure**

- AM is complex physics process
- Extreme heating/cooling affect gain and mechanical properties
- Aerospace historically uses *isotropic* metals
- Problems such as creep and fatigue are initiated by grain boundaries

Source: Herzog et al. 2016

www.incose.org/glrc2018
AM parts are economically attract for ‘smaller’ production runs

Notional Marginal Cost Analysis – Traditional vs AM

- Molds (casting) and dies (forging) are expensive and have long development times
- Thus, economies for these tool/die are realized over long production runs
- AM parts are more attractive for short runs
- Break-even depends upon myriad factors clearly complicating a typical ROI study

Source: secondary
Part 2

Aerospace Market Overview
Differences between aircraft and automotive effectively define their manufacturing strategies

Aerospace vs Automotive Industry

<table>
<thead>
<tr>
<th></th>
<th>Aircraft (Units Produced)</th>
<th>Automotive (Units Produced)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Units Produced:</strong></td>
<td>5 thousand*</td>
<td>60 million</td>
</tr>
<tr>
<td><strong>Unit Size:</strong></td>
<td>100 to 200 ft²</td>
<td>5 x 15 ft</td>
</tr>
<tr>
<td><strong>Part Count:</strong></td>
<td>2.5 million</td>
<td>30 thousand</td>
</tr>
<tr>
<td><strong>Design Objective:</strong></td>
<td>Airworthiness</td>
<td>Crashworthiness</td>
</tr>
<tr>
<td><strong>Quality Drivers:</strong></td>
<td>Product integrity</td>
<td>Production integrity</td>
</tr>
<tr>
<td><strong>Supplier Base:</strong></td>
<td>Oligopoly</td>
<td>Globally competitive</td>
</tr>
</tbody>
</table>

Source: analysis, secondary
Aerospace is unique in part due to lower margins-of-safety due to weight constraints

- Aircraft designed with margin-of-safety 1.5 to 2 to **minimize weight**
- Automotive uses 3, pressure vessels 4
- This helps minimize fuel consumption
- Thus aerospace has stringent **quality control** and maintenance schedules

Source: analysis, secondary
FAA certification is costly/arduous to guarantee six-sigma adherence to design and safety

Aircraft Design Substantiation

- Certification is process of substantiating both aircraft design and production
- Engineering proves structure can withstand anticipated static and dynamic loads
- Testing begins with material samples to identify basic material properties
- In certain cases, full-scale testing is required – expensive both time and money

Source: FAA
Part 3

AM Process Modeling
Conventional manufacturing requires numerous steps - often includes manual assembly…

Notional Conventional Manufacturing Scheme

Source: analysis
...whereas, for “targeted” parts, AM machines can make complex assemblies directly.
Consequently, entire AM process needs to be fully understood to ensure part integrity.

Process Control Parameters for AM

1. EQUIPMENT
   - Calibration
   - Machine parameters
   - Software version

2. MATERIAL
   - Purity
   - Shelf life
   - Traceability
   - Reuse

3. LABOR
   - Training
   - Experience
   - Standards
   - Document/Pedigree

4. POST PROCESSING
   - Particle distribution
   - Stress Relief
   - Heat Treat
   - HIP (Hot Isostatic Press)
   - Micro Polish
   - Digital scan

5. INSPECTION
   - Visual

Conformed Final Part

Source: analysis
Business case needs to consider tradeoffs of production efficiency vs mechanical properties

The single most important consideration for AM aerospace parts is **integrity** over the life of the asset

Source: analysis
There are three fundamental decisions involved to determine “fitness” of potential AM parts.

1. Is the part **flight critical**?
2. Does the part conform to: **small**, **complex** and **small lot**?
3. Can we safely assume comparable **material characteristics**?

Source: analysis

www.incose.org/glrc2018
FAA currently lacks specific guidelines for AM part qualification – most companies use “point design”

AM Part Substantiation

- FAA 14 Code of Federal Regulations specifies new parts/process be qualification based upon testing, including: 2X.603 (Materials), 2X.605 (Fabrication), and 2X.613 (Design Values)
- However, FAA lacks formal guidance on AM parts – each applicant must negotiate requirements directly via Special Condition
- Most AM designs are “point design” and qualified by testing
- MMPDS Emerging Technology Working Group is just beginning to discuss AM requirements
- Ultimate solution will likely incorporate: a) process controls, b) damage tolerance framework, and c) sophisticated NDI methods

Source: Jonas - NIAR, Gorelik - FAA

www.incose.org/glrc2018
Case Study: AM Implementation
A simplified framework helps clarify elements necessary for systems modeling

Rudimentary Process Schematic

Processes

Constraints

Matter, Energy, Information

Conversion

Input

Output

Finish Product
GE’s recently introduced turboprop - which is 35% printed - serves as a worthy case study

- GE prints 35% of new gas turbine in 1000-1600 SHP class
- Over **850 parts replaced by 12**, mostly castings
- Parts includes: cases, frames, comb liner, heat exchangers
- AM parts reduced weight by 5% and contribute to 1% improvement in specific fuel consumption (SFC)
- Moreover, a similar GE engine redesign using AM **eliminated 10-15 suppliers** typically required

Source: company website
A trade-off study requires comparing similar work-steps for castings vs AM

Casting vs AM Process Resource Utilization

| Source: analysis |

- **Casting** vs **AM**
  - Information  
    - **Casting**: O  
    - **AM**: O
  - Labor  
    - **Casting**: O  
    - **AM**: O
  - Material  
    - **Casting**: O  
    - **AM**: O
  - Capital  
    - **Casting**: O  
    - **AM**: O

- **Create mold vs Prep job**  
  - **Casting**: O  
  - **AM**: O

- **Pour mold vs Print part**  
  - **Casting**: O  
  - **AM**: O

- **Remove part**  
  - **Casting**: O  
  - **AM**: O

- **Heat Treat & HIP**  
  - **Casting**: O  
  - **AM**: O

- **Machine**  
  - **Casting**: O  
  - **AM**: O

- **Surface Treat**  
  - **Casting**: O  
  - **AM**: O

- **Inspect**  
  - **Casting**: O  
  - **AM**: O

- **Assemble**  
  - **Casting**: O  
  - **AM**: O

- **Weight**  
  - **Casting**: O  
  - **AM**: O

- **Process time**  
  - **Casting**: O  
  - **AM**: O

- **Material yield**  
  - **Casting**: O  
  - **AM**: O

- **Asmb complx**  
  - **Casting**: O  
  - **AM**: O

- **Predictability**  
  - **Casting**: O  
  - **AM**: O

**KEY:**
- ● Favorable
- O Unfavorable

* incl. build plate and support removal for AM
These steps then need to be compared in terms of amount of processing time

For moderately complex castings, creating molds can take from weeks to months

This step is the most variable and most time and resource intensive of any process steps

For low volume production, AM parts can be produced at least twice as fast as castings

Notional Time Per Work Step - Casting vs AM*

- Assemble
- Inspect
- Surface Treat
- Machine
- Heat Treat & HIP
- Remove part
- Pour mold vs Print part
- Create mold vs Prep job

* Assumes CAD model is available

Source: analysis, interviews
AM’s adoption will likely considerably impact casters and CNC machine shops

Supply Chain Impact of Conventional vs Additive Mfg

<table>
<thead>
<tr>
<th>Work Step</th>
<th>Conv Mfg Process</th>
<th>AM Process</th>
<th>Resource Net Chng*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Create mold vs Prep job</td>
<td>Caster</td>
<td>OEM</td>
<td>0.3</td>
<td>Significant negative impact to casters</td>
</tr>
<tr>
<td>Pour mold vs Print part</td>
<td>Caster</td>
<td>OEM</td>
<td>0.8</td>
<td>Decrease in work requirements and need for special processes (i.e. hazmat)</td>
</tr>
<tr>
<td>Remove part</td>
<td>Caster</td>
<td>OEM</td>
<td>1.7</td>
<td>Will require establishing internal machining infrastructure and protocol</td>
</tr>
<tr>
<td>Heat Treat &amp; HIP</td>
<td>3rd party?</td>
<td>OEM</td>
<td>1.2</td>
<td>Slight increase for market but shift from 3rd party to OEM</td>
</tr>
<tr>
<td>Machine</td>
<td>3rd party</td>
<td>3rd party?</td>
<td>0.3</td>
<td>Significant negative impact to 3rd party CNC shops anticipated (and OEMs may further control machining)</td>
</tr>
<tr>
<td>Surface Treat</td>
<td>3rd party?</td>
<td>3rd party?</td>
<td>1.4</td>
<td>Likely increase in surface treatment 3rd party work</td>
</tr>
<tr>
<td>Inspect</td>
<td>OEM</td>
<td>OEM</td>
<td>1.5</td>
<td>Increase unlikely to affect 3rd party market</td>
</tr>
<tr>
<td>Assemble</td>
<td>OEM</td>
<td>OEM</td>
<td>0.5</td>
<td>Decrease unlikely to affect 3rd party market</td>
</tr>
</tbody>
</table>

Source: analysis

* Combination of resource and time reqmt
AM will impact aerospace parts and suppliers, yet timeline is at least a decade hence

Summary of Impact of AM in Aerospace

- AM can achieve optimize part, yet material characterization is difficult due to the unpredictability of the build
- Increasingly, AM is being used to prototype parts, and is moving into serialized production parts
- GE’s advanced turboprop illustrates potential impact of AM in aerospace, targeting structural castings
- A systems model predicts considerable impact on both casting companies and CNC machine shops
- Significant adoption, however, is likely 10-15 years away due to lack of technology maturity and new engine/airframe platforms