INDUSTRY KEYNOTE
Challenges & Opportunities in Aerospace

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Acknowledgements: Moog & Norsk Titanium
Agenda

- Introductions
- State of Aero Additive Manufacturing
- Challenges (Cost, Materials, Certification, Supply Chain)
- Big Potential Opportunities (Cold Spray & Plasma Arc Wire Deposition)
- Outlook & Implications
ICF is one of the world’s largest and most experienced aviation and aerospace consulting firms

- 52 years in business (founded 1963)
- 100+ professional staff
  - Dedicated exclusively to aviation and aerospace
  - Blend of consulting professionals and experienced aviation executives
- Specialized, focused expertise and proprietary knowledge
- Broad functional capabilities
- More than 10,000 private sector and public sector assignments
- Backed by parent company ICF International (Over $1B 2014 revenue)
- Global presence — offices around the world

New York • Boston • Ann Arbor • London • Singapore • Beijing • Hong Kong
ICF’s thought leadership on AM is recognized in the aerospace markets
Additive Manufacturing Innovation Center in Partnership with Pratt & Whitney

Innovation Partnership Building at UConn (2017, $170M)
And additional funds from Next Generation CT ($1.5B investment into STEM)
## MOTIVATION

Aerospace executives face new opportunities and challenges as Additive Manufacturing continues to mature.

### Business Strategy
- Product life cycle strategies
- Opportunity to improve leverage
- Improved cost competitiveness
- Implications for aftermarket revenue
- IP strategies
- New business models

### Design
- Expanded design freedom to improve performance & reduce weight
- Faster development cycles
- Integrated higher level assemblies
- New QC and certification processes
- Need for material & process databases and regulator education

### Operations & Supply Chain
- Reduced material consumption
- Reduced part count
- Reduced tooling costs
- Reduced WIP
- Shorter lead times
- Reduced skilled labor content
- New make-buy dynamics; simpler supply chains

### Aftermarket
- Faster part lead times
- New repairs
- Better support for sunset platforms
- New PMA and DER competitors

*Rebuilt turbine blade tip from Direct Metal Deposition*
ICF uses three key perspectives to identify the AM ‘sweet spot’…

- **Time to market**
- **Buy-to-Fly ratio, Laydown rates**
- **Supply chain leverage**
- **Powder metal or wire cost**

<table>
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<th>Strategic Imperatives</th>
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<td>OEM / Customer posture</td>
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<td>Competitive landscape</td>
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<td>Product life cycle implications</td>
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<td>Supply chain leverage</td>
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<table>
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<th>Cost Benefit</th>
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<td>Part family based analysis</td>
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<td>Design rules &amp; tools</td>
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<td>Material &amp; equipment choice</td>
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<td>Process control, quality assurance &amp; regulatory issues</td>
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<th>Technology Feasibility</th>
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Additive manufacturing can provide competitive advantage

**Additive Manufacturing**

1. Reduced Lead Times
2. Reduced Weight
3. Reduced Cost

- **Whole Parts**
  Assemblies and complex parts are prime candidates

- **Tooling / Fixtures**
  AM is well suited to low volume, high lead time items such as tooling

- **Add Features**
  Protrusions, bosses, and flanges could be added to simplified forged rings

- **Repair**
  Blade tips and other traditional additive repairs
Two main types of processes are used for aerospace additive manufacturing

**Powder Bed Process**
- Examples: DMLS, SLS, EBM, LM
- Size limited by processing chamber
- Good surface finish and resolution

**Direct Energy Deposition**
- Examples: EBWM, PBWM, LENS
- Material deposited during processing
- Relatively high material deposition rates
- May require more post-processing

Source: ICF SH&E secondary research, interviews
Certification and lack of skilled talent are considered a major barrier to AM adoption

Question: What is the biggest challenge for your business in adopting AM?

Survey Participants:
- OEM 12%
- Tier 1 With Design Authority 19%
- Tier 1 - Tier 2 Supplier 19%
- Material Supplier 37%
- Services 13%

Results:
- Qualification & Certification 54%
- Production speed 13%
- Know-how and talent 33%

Almost half are pursuing AM capabilities in-house and 80% are working on production parts.

**How are you pursuing AM?**
- Partnering with both customers & bureaus: 7%
- Partnering with customers: 7%
- Partnering with AM service bureaus: 7%
- Waiting to see if and how it impacts my business: 33%
- Strong internal program: 46%

**What is the focus of your AM?**
- Production parts: 40%
- Prototypes for development programs: 7%
- Tooling + Repairs + Parts: 40%
- None of the above: 13%
Airframe and system applications are currently limited to non-structural components; many are polymer.

**Examples of Additively Manufactured Airframe & Component Parts**

- *787 Production Ducts*
- *A350 Prototype Hinge*
- *Liebherr Prototype Valve Manifold*
- *EOS Prototype*
- *Heat Exchanger*

*Weight reduction & ease of manufacturing has been a frequent motivation*

Source: Boeing, Airbus, ICF SH&E analysis & secondary research
While AM technology focus has been on small and complex parts (e.g. aero-engine components) ………

Source: ICF SH&E analysis, interviews and published sources
Current technologies also allow the additive manufacture of large parts

Source: ICF SH&E analysis, GE Aviation, Avio, Rolls Royce and NTi

Target applications are complex-geometry high BTF parts

Source: ICF SH&E analysis, GE Aviation, Avio, Rolls Royce and NTi
A class of repairs have historically been additive

Repair of Turbine Components Using Direct Metal Deposition (DMD)

Turbine blade squealer tip is built up using DMD

As deposited DMD turbine blade tip

Rebuilt turbine blade tip

DMD includes a patented closed loop feedback control of the deposition process

Source: DM3D, MT Additive
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There are several critical barriers to adoption of additive manufacturing in aerospace.

- Qualification & Certification
- Engineering Mindset
- Quality & Repeatability
- Cost
- Additive Manufacturing Barriers
- Materials Development
- Machine Throughput

Source: ICF International analysis
Ultimately, AM parts will have to buy their way on to the aircraft

*Projected AM Cost For Complex Titanium Casting*

Source: ICF SH&E analysis, interviews,
Quality assurance and certification will also affect supply chain evolution

### 1. Technology Readiness
- System Test, Launch & Operations
- System/Subsystem Development
- Technology Demonstration
- Technology Development
- Research to Prove Feasibility
- Basic Technology Research

#### TRL Levels
- TRL 9
- TRL 8
- TRL 7
- TRL 6
- TRL 5
- TRL 4
- TRL 3
- TRL 2
- TRL 1

### 2. Process Repeatability
- Standardization / specs
- Material characterization
- Machine variables
- Resolution, accuracy
- Process control

### 3. Regulatory Approval

Source: ICF SH&E analysis, interviews,
Challenges with current materials in AM processing include the lack of mechanism-based knowledge.

- Largely empirical to semi-empirical link of input to physical phenomena occurring during AM process.
- Machine parameter-driven approaches (instead of mechanism-driven)

**Physical Phenomena**
- Voids
- Unmelts
- Spatter
- Impurities
- Evaporation
- Oxidation
- Welding-type defects
- Rapid solidification
Aircrafts are majority Al alloys which show little progress in AM

- **Challenges:** high-strength Al alloys difficult to weld (solidification cracking, liquation cracking in heat affected zones,….)

- **Current technology:** focus on Al-Si-Mg alloys (can be processed with additive manufacturing, but are not desirable for many applications)

- **New technology:** modify existing alloys or develop new alloys with combination of theoretical considerations (combination of welding theory, thermodynamics) with first principles calculations and materials genome approach.
The AM value chain is evolving and the traditional supply base may not be ready for the impact

*The Additive Manufacturing Value Chain*

**Example Companies**
- ATI
- Carpenter Technology
- Special Metals (PCC)
- Perryman
- RTI
- Altair
- Autodesk
- Dassault
- Within Labs
- Geomagic
- Materialize
- Netfab
- NTi
- Sciaky
- 3D Systems
- Arcam
- EOS
- ExOne
- Renishaw
- Stratasys
- Optomec
- SLM
- Airbus
- Boeing
- GE
- Pratt & Whitney
- MTU
- GKN
- Service bureaus like Sciaky

Source: Roland Berger, ICF International research
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A. Supersonic Particle Deposition for corrosion repairs
Cold Spray – Characteristics, Benefits and Spray Materials

- HP Bond strengths ~ 80-100 MPa (12-15ksi)
- No oxidation
- Compressive residual stress
- Strain hardening
- High density – low porosity (<1%)
- Thick coatings
- Heat treatable free forms
- Minimal surface preparation
- No distortion of substrate
- Limited masking
- Low substrate temperatures heating<120C (250F)
- Variety of substrates (Al, Mg, Cu, Ti, Steel, Glass)

Source: Moog
Cold Spray can help address the massive cost of corrosion

Table ES-1. Cost-of-Corrosion Studies

<table>
<thead>
<tr>
<th>Study year</th>
<th>Study segment</th>
<th>Annual cost of corrosion</th>
<th>Data baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005–2006</td>
<td>Army ground vehicles</td>
<td>$2.0 billion</td>
<td>FY2004</td>
</tr>
<tr>
<td></td>
<td>Navy ships</td>
<td>$2.4 billion</td>
<td>FY2004</td>
</tr>
<tr>
<td>2006–2007</td>
<td>DoD facilities and infrastructure</td>
<td>$1.8 billion</td>
<td>FY2005</td>
</tr>
<tr>
<td></td>
<td>Army aviation and missiles</td>
<td>$1.6 billion</td>
<td>FY2005</td>
</tr>
<tr>
<td></td>
<td>Marine Corps ground vehicles</td>
<td>$0.7 billion</td>
<td>FY2005</td>
</tr>
<tr>
<td></td>
<td>Coast Guard aviation and vessels</td>
<td>$0.3 billion</td>
<td>FY2005 and FY2006</td>
</tr>
<tr>
<td>2008–2009</td>
<td>Air Force aircraft and missiles</td>
<td>$5.4 billion</td>
<td>FY2006 and FY2007</td>
</tr>
<tr>
<td></td>
<td>Army ground vehicles</td>
<td>$2.4 billion</td>
<td>FY2006 and FY2007</td>
</tr>
<tr>
<td></td>
<td>Navy ships</td>
<td>pending</td>
<td>FY2006 and FY2007</td>
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</tbody>
</table>

*Information from LMI Government Consulting, Report MEC81T2, June 2009
Cold Spray next frontiers for next 5+ years

- Structural component repairs
- Fabrication of structural components
- Application of coatings on glass in lieu of typical plating processes (conductive paths).
- Engine component coatings (new and repair)
- On-site/on-aircraft repairs
B. Plasma Arc Wire Deposition – Aerostructure part
Pre-form to finished component

Source NTi
Encouraging material properties for plasma arc wire deposition parts (testing continues)

<table>
<thead>
<tr>
<th>Production type</th>
<th>Design defect factor</th>
<th>Yield strength (Mpa)</th>
<th>Ultimate tensile strength (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norsk Titanium</td>
<td>N/A</td>
<td>&gt;835</td>
<td>&gt;910</td>
</tr>
<tr>
<td>Plate - Mill annealed</td>
<td>N/A</td>
<td>827</td>
<td>893</td>
</tr>
<tr>
<td>(Standard: AMS 4911, Rev. “M”)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forging</td>
<td>N/A</td>
<td>827</td>
<td>896</td>
</tr>
<tr>
<td>(Standard: AMS 4928, Rev. “S”)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate - Beta annealed</td>
<td>N/A</td>
<td>745</td>
<td>841</td>
</tr>
<tr>
<td>(Standard: AMS 4905, Rev. “D”)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casted</td>
<td>N/A</td>
<td>793</td>
<td>862</td>
</tr>
<tr>
<td>(Standard: AMS T-81915, Rev. “T-81915”)</td>
<td>Applicable due to pores and voids</td>
<td></td>
<td></td>
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Data Source NTi
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Material-related trends for the next 5+ years

I. Powder development

- Reducing cost for existing powder synthesis techniques
- Modifying existing or developing alternative synthesis techniques
- Expand range of available alloy powders
- Improve understanding of pedigree requirements
- Optimizing packing densities in powders bed with specific size distributions
- Identifying additional relevant powder characteristics

II. Build theme development

- More quality build themes (i.e., for more alloy systems)
- Transition from AM machine manufacturers as build theme developers to powder producers as build theme developers??
Material-related trends for the next 5+ years

III. Mechanism-based modeling
Integration of first principles calculations with analytical and experimental studies to understand AM process and current challenges
Example: Formation of voids in additively manufactured parts.

Bubble “escape” mechanisms from theory, data on surface tension from first-principles calculations.
Material-related trends for the next 5+ years

IV. New alloys

- Development in stages: modification of existing alloys, completely new alloys over a longer time
- Existing guiding principles (input, for example, from welding, rapid solidification) with AM-specific input (e.g., surface tension, viscosity aspects)
- Greater role of rapid cooling/metastable phases than in traditional manufacturing
Applications with less stringent certification or safety requirements such as spacecraft and UAVs heavily use AM

**Examples of AM Spacecraft and Experimental Aircraft Parts**

**Spacecraft Components**
- Chamber for production SpaceX rocket engine made by AM

**UAV Components**
- Using AM for many components allowed SelectTech to shorten test & redesign cycle

**Experimental Aircraft**
- Many military and experimental aircraft OEMs use AM to rapidly iterate designs and reduce lead times for low-volume parts

**Space & experimental vehicles have been prime candidates for near-term AM adoption**

Source: SpaceX, Stratasys, ICF SH&E research
Additive manufacturing is just beginning to improve aftermarket support to operators

**RAF Tornado**
- BAE producing protective covers for cockpit radios and guards for power take-off shafts to sustain RAF Tornados via AM
- Parts first flew in December 2013
- These AM parts could cut RAF’s maintenance costs by $1.9M over four years

**Air Transat A310**
- In February 2014 the first AM component – a small plastic crew seat panel – flew on an Airbus customer jetliner
- The aircraft was an A310 operators by Air Transat
- Like most aircraft OEMs, Airbus is working towards “on demand” spare parts

Sources: Daily Mail, Airbus
Disruptive technologies in the long-cycle aerospace industry take time to develop as evidenced by composites

**Composites Penetration In Aerostructures**

Sources: ICF International analysis, Boeing, Airbus, secondary research
Additive manufacturing aerospace market projections vary wildly ….

Roughly $250M out of $150B global aerospace output is additive

- Uncertainties reflect the embryonic stage of AM development
- Just a few high-volume parts in production have the potential to greatly increase total market size
- Early adoption will be in applications with lower certification barriers
- Adoption of composites offers a good learning experience

Source: ICF International analysis, interviews, Wohler’s, Credit Suisse
Market size includes machine sales and parts production
OUTLOOK & IMPLICATIONS

...but it is clear that additive manufacturing is poised to exert greater influence on the aerospace supply chain

**AM Implications for Manufacturers**

- **Design**
  - Expanded design freedom to reconceive parts and reduce weight
  - Faster development cycles
  - New IP strategies for designs, materials, processes
  - Need for material & process databases...and regulator education

- **Manufacturing & Supply Chain**
  - Reduced material consumption
  - Reduced part count
  - Reduced tooling costs
  - Rapid prototyping
  - Shorter lead times
  - Reduced skilled labor content
  - New make-buy dynamics
  - New QC and certification processes

- **Aftermarket**
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Source: ICF International Analysis
Thanks and Questions

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