Additive Manufacturing in the Aviation Industry

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DMDII Project Vision for Rapid Process Certification and Verification for High-Value-Added and Low-Volume Production
## Seven forms of Additive Manufacturing

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>MATERIALS</th>
<th>TYPICAL MARKETS</th>
<th>RELEVANCE FOR METAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder bed fusion</td>
<td>Metals, polymers</td>
<td>Prototyping, direct part</td>
<td></td>
</tr>
<tr>
<td>Directed energy deposition</td>
<td>Metals</td>
<td>Direct part, repair</td>
<td></td>
</tr>
<tr>
<td>Sheet lamination</td>
<td>Metals, paper</td>
<td>Prototyping, direct part</td>
<td></td>
</tr>
<tr>
<td>Binder jetting</td>
<td>Metals, polymers, foundry sand</td>
<td>Prototyping, direct part, casting molds</td>
<td></td>
</tr>
<tr>
<td>Material jetting</td>
<td>Polymers, waxes</td>
<td>Prototyping, casting patterns</td>
<td></td>
</tr>
<tr>
<td>Material extrusion</td>
<td>Polymers</td>
<td>Prototyping</td>
<td></td>
</tr>
<tr>
<td>Vat photopolymerization</td>
<td>Photopolymers</td>
<td>Prototyping</td>
<td></td>
</tr>
</tbody>
</table>
AM Pays When:

1. Conventional methods fail
   - Buy-to-fly ratio is high
   - Too thin or intricate to cast, machine, or forge
2. Assemblies can be replaced with single parts
3. Tooling costs are not acceptable
   - Required quantities are low
   - Time is critical
   - Each part is different
Additive Manufacturing Value Proposition

- Considerations
  - Application / Material Properties
  - Part Quality
  - Lead Time

- Production Volume / Quantity
  - Part Cost
  - Tooling Cost

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<table>
<thead>
<tr>
<th>Method</th>
<th>Lead Time</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDM</td>
<td>8 hours</td>
<td>$50</td>
</tr>
<tr>
<td>SLS</td>
<td>3 Days</td>
<td>$2500</td>
</tr>
<tr>
<td>Rapid Cast</td>
<td>4 weeks</td>
<td>$2000</td>
</tr>
<tr>
<td>Billet</td>
<td>4 weeks</td>
<td>$1500</td>
</tr>
<tr>
<td>Production Cast</td>
<td>2 Months</td>
<td>$5</td>
</tr>
</tbody>
</table>
The Additive Manufacturing Advantage

Optimised 1 mass: 135g, 
reduction: 53%

Optimised 2 mass: 148g, 
reduction: 48%

Original mass: 285g

Courtesy: Boeing work done at 
Univ. Of Nottingham
Higher performance parts: Ex. Aircraft Bracket

**Conventional Machining - Buy-to-Fly Ratio 8:1**
- Primary Processing (15.9 MJ/kg)
  - Ingot (918 MJ/kg embodied energy)
  - Atomization (14.8 MJ/kg)
- Mill Product (slab, billet, etc.)
  - Secondary Processing (8.72 kg)
- Machined Product
- Final Processing
- Finished Part

**Additive Manufacturing - Buy-to-Fly Ratio 1.5:1**
- Powder (0.57 kg)
- Electron Beam Melting (EBM)
- Final Processing (0.38 kg)
- Finished Part

<table>
<thead>
<tr>
<th>Process</th>
<th>Final part (kg)</th>
<th>Ingot consumed (kg)</th>
<th>Raw mat’l (MJ)</th>
<th>Manuf (MJ)</th>
<th>Transport (MJ)</th>
<th>Use phase (MJ)</th>
<th>Total energy per bracket (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining</td>
<td>1.09</td>
<td>8.72</td>
<td>8,003</td>
<td>952</td>
<td>41</td>
<td>217,949</td>
<td>226,945</td>
</tr>
<tr>
<td>EBM (Optimized)</td>
<td>0.38</td>
<td>0.57</td>
<td>525</td>
<td>115</td>
<td>14</td>
<td>76,282</td>
<td>76,937</td>
</tr>
</tbody>
</table>
Current AM Technology

- 3D CAD model
- STL file
- "slicing" of STL file
- Tool path generation

AM System

Powder
### Comparison of DED and PBF

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Laser PBF</th>
<th>Laser DED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Limited and lower experience compared to DED (typically controlled by OEM)</td>
<td>Large diversity of materials/ also capable of creating new materials (i.e. FGM)</td>
</tr>
<tr>
<td>Part Complexity</td>
<td>Nearly unlimited</td>
<td>Limited</td>
</tr>
<tr>
<td>Builds on</td>
<td>flat surfaces</td>
<td>3D surfaces &amp; existing parts</td>
</tr>
<tr>
<td>Layer Thickness</td>
<td>&gt;0.1-1mm</td>
<td>&gt;0.03-0.1 mm</td>
</tr>
<tr>
<td>Build speed</td>
<td>5-20 cm³/hr (~40-160 g/hr)</td>
<td>~ 70 cm³/hr (up to 0.5 kg/hr)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>(+/-) 0.02-0.05 mm per 25mm</td>
<td>(+/-) 0.125-0.25 mm per 25mm</td>
</tr>
<tr>
<td>Detail capability</td>
<td>0.04 - 0.2 mm</td>
<td>0.5 - 1.0 mm</td>
</tr>
<tr>
<td>Surface finish</td>
<td>Ra 4-10 μm</td>
<td>Ra 7-20 μm</td>
</tr>
<tr>
<td>Max. Part size</td>
<td>500 mm × 280 mm × 325 mm</td>
<td>2,000 mm × 1,500 mm × 750 mm</td>
</tr>
<tr>
<td>Average Price</td>
<td>$560,000-$750,000</td>
<td>$630,000-$950,000</td>
</tr>
</tbody>
</table>
Selective Laser Sintering/Melting (PBF)

- Thin powder layer is spread over build platform
- Laser beam scans over area corresponding to first STL cross section of part
- Powder layer in scanned area is fused onto build platform
- Thin powder layer is spread over first fused layer
- Laser beam scans over second STL cross section and fuses to first layer
- Process is repeated until all STL cross sections have been processed and the part is complete.
Images from FIT production GmbH
TRADITIONAL DESIGN

Source: SAVING project

> A conventional steel buckle weights 155 g\(^1\)
> Weight should be reduced on a like-for-like basis within the SAVING project
> Project partners are Plunkett Associates, Crucible Industrial Design, EOS, 3T PRD, Simpleware, Delcam, University of Exeter

AM OPTIMIZED DESIGN

Source: SAVING project

> Titanium buckle designed with AM weighs 70 g – reduction of 55%
> For an Airbus 380 with all economy seating (853 seats), this would mean a reduction of 72.5 kg
> Over the airplane's lifetime, 3.3 million liters of fuel or approx. EUR 2 m could be saved, assuming a saving of 45,000 liters per kg and airplane lifetime

\(^1\) 120 g when made of aluminum
GE Aviation: First Production Parts

- LEAP/9X Fuel nozzle – from 25 braze joints to 5 joints
- 5X durability & 25% lower weight
- 50% reduction in NOx
- 19-20 parts/engine ... 100K+ parts by 2020
- New topology that was previously impossible
- Consolidation of assemblies into single parts: 20 to 1
- Frees constraints imposed by traditional processes
- Production facility in Auburn-AL

“I need very complex shapes. I need shapes that a machine tool cannot generate.”

-Joshua Mook, Lead Engineer
GE Aviation

DED employs the same process fundamentals as laser cladding:

- Powder is fed with a nozzle into a laser generated melt pool.
- Melt pool is translated to follow a tool path covering the 2D area corresponding to the required cross section from the STL file.
- The molten powder re-solidifies as the melt pool follows the tool path.
- This process is repeated for each cross section of the STL file until the part is completed.
**LASER ENGINEERED NET SHAPING (LENS) - PER YEAR COST SAVINGS**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>PART</th>
<th>MATERIAL</th>
<th>PART NUMBER</th>
<th>NEW PART</th>
<th>ESTIMATED</th>
<th>SAVINGS PER PART</th>
<th>PARTS REPAIRED PER YEAR</th>
<th>SAVINGS PER YEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Third (3rd) Stage Turbine Rotor</td>
<td>M3610C/Inconel 713LC</td>
<td>12271565</td>
<td>$8,297</td>
<td>$2,000</td>
<td>$6,297</td>
<td>230</td>
<td>$1,448,416</td>
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<tr>
<td>2</td>
<td>Fourth (4th) Stage Turbine Rotor</td>
<td>M3610C/Inconel 713LC</td>
<td>12281566</td>
<td>$5,485</td>
<td>$2,000</td>
<td>$3,485</td>
<td>230</td>
<td>$801,529</td>
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<tr>
<td>3</td>
<td>Second (2nd) Stage Nozzle</td>
<td>M3602/Inconel 713C</td>
<td>12268886</td>
<td>$6,032</td>
<td>$2,250</td>
<td>$3,782</td>
<td>600</td>
<td>$2,269,140</td>
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<tr>
<td>4</td>
<td>Compressor Stators (H.P. and L.P.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st L.P.</td>
<td>AMS 5510/321 Stainless</td>
<td>12302430</td>
<td>$910</td>
<td>$300</td>
<td>$610</td>
<td>175</td>
<td>$106,759</td>
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<tr>
<td>2nd L.P.</td>
<td>AMS 5510/321 Stainless</td>
<td>12286149</td>
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<td>3rd L.P.</td>
<td>AMS 5510/321 Stainless</td>
<td>12302480</td>
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<td>$300</td>
<td>$310</td>
<td>175</td>
<td>$54,304</td>
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<tr>
<td>4th L.P.</td>
<td>AMS 5510/321 Stainless</td>
<td>12286161</td>
<td>$611</td>
<td>$300</td>
<td>$311</td>
<td>175</td>
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<td>5th L.P.</td>
<td>AMS 5510/321 Stainless</td>
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<td>$701</td>
<td>$300</td>
<td>$401</td>
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<tr>
<td>1st H.P.</td>
<td>AMS 5504/410 Stainless</td>
<td>12286257</td>
<td>$604</td>
<td>$300</td>
<td>$304</td>
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<tr>
<td>2nd H.P.</td>
<td>AMS 5504/410 Stainless</td>
<td>12286261</td>
<td>$1,188</td>
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<td>$888</td>
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<tr>
<td>3rd H.P.</td>
<td>AMS 5504/410 Stainless</td>
<td>12286266</td>
<td>$575</td>
<td>$300</td>
<td>$275</td>
<td>175</td>
<td>$48,038</td>
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<tr>
<td>4th H.P.</td>
<td>AMS 5504/410 Stainless</td>
<td>12286568</td>
<td>$1,893</td>
<td>$300</td>
<td>$1,593</td>
<td>175</td>
<td>$278,782</td>
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<tr>
<td>5</td>
<td>Fourth (4th) Stage Seal Runner</td>
<td>AMS 5662/Inconel 718</td>
<td>12286384</td>
<td>$319</td>
<td>$200</td>
<td>$119</td>
<td>600</td>
<td>$71,268</td>
</tr>
</tbody>
</table>

**Total** | 28,395 | $9,150 | $19,245 | 3,235 | $5,563,617

1/6th scale Ti6Al4V mixing nozzle for gas turbine exhaust.

Used in a small turbine engine for a benchtop demo of the new PATS anti-torque system.

Survived extremely high temperatures in airflow demo.

Time required for producing a casting: 9 weeks.
LENS part delivered in 3 weeks (Build time 8 hours)

Primary Success Driver for Above Application

Faster - Better Material Properties - Lower Cost
The aim is to create the first ever large scale additive manufacturing systems that are locally produced to create full scale components for the aerospace industry.
AEROSWIFT IMPACT

A400M – wingtip
610 × 220 × 70 mm

A400M – wingtip
1860 × 340 × 107 mm
AeroSwift status

• Phase 1: **Machine design and construction completed**
  • Commissioning in progress

• Phase 2: Process development and optimization started.
  • Machine testing, evaluation and optimization
  • Parameter testing and optimization
  • **Milestone:** Flight ready demonstrator part end 2017

• Process development achievements
  • Consolidation rates up to 60mm³/sec demonstrated
  • Low sample porosity (0.5% and lower)
AEROSWIFT IMPACT – First parts created

Above: Test part for Aerospace customer
Below: Part for Advanced High Performance Reconnaissance Light Aircraft
On orbit printing!

SpiderFab™:
On-Orbit & Responsive Additive Manufacturing of Spacecraft Structures

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Dr. Rob Hoyt
Make it BIGGER

SOA
Largest deployable able to stow within a launch shroud
62 m

SpiderFab
124 m

- On-orbit fabrication enables 2X larger starshade with 1/30 stowed volume and same mass

120 m³
7.7 m
4.5 m
1495 kg

1495 kg
Establishing a foundation for rapidly certifying manufacturing processes using physics-based simulation tools and real-time sensors integrated by the efficient Bayesian update framework.

Three missing capabilities in this regard:

- A unified material data structure and process data structure
  Providing a seamless link between material and process modules

- An adaptive Bayesian inference algorithm
  Considering uncertainties in physics-based computational models

- A direct integrated framework
  Developing an efficient computational method in order to update material microstructural and mechanical properties real-time
Methodology

This project can be divided into five technical tasks:

• **Task 1**: Digital material structure
• **Task 2**: Digital process structure
• **Task 3**: Low-volume certification methodology
• **Task 4**: Simulation software integration
• **Task 5**: Verification and validation

Figure 1: Foundation of the Verification Framework
Developing a digital thread for materials based on microstructure and thermo-mechanical properties for improved predictive capability, including heat transfer, thermodynamics and particle movements.

Data structure should be dynamic and flexible, and links with common inputs such as forms of material (powder or bulk) and implicit time-, temperature- and rate-dependent behaviors.

Figure 3: Relationship among different models in the virtual manufacturing framework
Task 2: Process Data Structure

(Northwestern 60%, NIU 20%, Siemens 10%, PDA 10%)

Provides a volumetric-based model powered by a process data structure capable of:

I. Dynamically generate analysis information
II. Store experimental information
III. Encode microstructural information of the product obtained from the digital material structure and in-situ sensors

Octree voxels is being used in order to selectively refine the voxel size, and thus to reduce the memory usage by the data structure.

GPUs are being used to dynamically generate the data structure required for the thermal analysis and mechanical-behavior prediction with reduced computation time for real-time control in the proposed verification framework.
Task 3: Certification Methodology

(Northwestern 80%, PDA 10%, Siemens 10%)

In this task, we apply an adaptive Bayesian inference technique for efficient and cost-effective identification of key unknown parameters in the material model. The spatial random process models will be constructed as surrogates for the expensive simulation models. Markov Chain Monte Carlo and Gaussian process approaches is being proposed for this purpose.

Figure 4: Adaptive Bayesian inference framework
Task 4: Simulation Software Integration

(Siemens 60%, Northwestern 20%, PDA 10%, QuesTek 10%)

This task creates a software framework to integrate together the different components needed to perform virtual validation of manufacturing processes and to facilitate the flow of information from overall input parameters to resulting properties of the manufactured part.

It will be kept generic with respect to manufacturing processes. An interface with NX software will be developed. Compatibility with simulators for other processes, such as casting (PDA) and forming (NU), will be considered.

Figure 5: Structure of the proposed software framework
Task 5: Verification and Validation

(NIU 45%, NU 25%, Siemens 15%, PDA 10%, QuesTek 5%)

Validation samples will be fabricated in NIU AM laboratory using LENS. NIU will use a specified tool path history on a calibration test sample geometry designed for extraction of mechanical test coupons (by EDM) to calibration of the process model. This task include three subtasks:

- Design AM Property QA Witness
- Build Tool Path Design for AM QA Witness
- Validation and Certification

Figure 6: AM with in-situ sensing systems and sample parts