Implementation of Additive Manufactured Ti-6Al-4V Alloy Hardware in Aerospace Components

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Challenge

• Conventional manufacturing route
  – Wrought product\plate procurement, rough machine, Non Destructive Inspection (NDI), final machine, NDI
  – High cost and lag time associated with raw material procurement
  – High cycle time
  – High buy-to-fly (10-20:1)

• Additive Manufacturing (AM)\Digital Direct Manufacturing (DDM) technologies present a potential for providing solutions to several challenges
  – Significant cycle times and cost reduction
  – Low Buy-to-Fly (1.1:1)

• Additional benefits
  – Capability enables design; novel designs no longer limited by manufacturing capability
  – Implementation of titanium electron beam DDM technology positions NGAS to more readily meet customer needs and requirements.
Electron Beam Melting (EBM) Additive Mfg (AM)

• Process
  – Digital file sliced into thin layers in the z-direction (vertical); transferred to EBM platform
  – Alloy powder spread over base
  – Electrons accelerated towards powder bed
  – Beam focus and scanned over powder bed by coils
  – Repeated for 3D product

• Advantages
  – No tooling required
  – Performed in vacuum environment; drastic reduction in contamination (oxidation) opportunity
  – Thermally & environment controlled powder bed
  – Rapid liquid-solid state transition; grain size refinement
  – Low Buy-to-Fly 1.1:1

• Disadvantages
  – Current process parameters produce coarse surface finish
  – Design must allow for powder removal
  – Current platform maximum size 8” x 8” x 14”
Characteristics of E-Beam AM Products

- **Design Flexibility**
  - Capable of fabricating geometries that are challenging or prohibitive to manufacture by conventional means
  - Unitization
    - Allows integral structural design
    - Increased performance
  - Lower life cycle cost/systems cost

- **Tool-Less Process**
  - CAD to component fabrication
  - Development schedule reduction
  - Enables rapid\responsive design iteration

- **Minimal Inventory Required**
  - Components produced from common feedstock
  - Fabricate components as needed
  - Only powder inventory required
Typical Room Temperature Tensile Properties for E-Beam Melted DDM Ti-6Al-4V

<table>
<thead>
<tr>
<th>Material</th>
<th>UTS, ksi (MPa)</th>
<th>YS, ksi (MPa)</th>
<th>El, %</th>
<th>RA, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V (Cast)</td>
<td>145 (1000)</td>
<td>130 (896)</td>
<td>8</td>
<td></td>
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<tr>
<td>Ti-6Al-4V (Wrought, Annealed)</td>
<td>135 (930)</td>
<td>128 (895)</td>
<td>12</td>
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<tr>
<td>EBM - As Deposited</td>
<td>150 (1037)</td>
<td>137 (948)</td>
<td>15</td>
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<tr>
<td>EBM - HIP’d</td>
<td>139 (957)</td>
<td>131 (905)</td>
<td>17</td>
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</tbody>
</table>

Mechanical Properties

Strength (ksi) vs. Elongation (%)

- Wrought (Annealed)
- Cast
- EBM - As Deposited
- EBM - HIP’d
Typical Room Temperature E-Beam Ti-6Al-4V Microstructure

EBM Microstructural Characteristics
- Fine grain
- Columnar
- Lamellar alpha phase
- Larger beta grain
## EBM AM Ti-6Al-4V Static Test Data

### Oxygen Level, %

<table>
<thead>
<tr>
<th>Coupon</th>
<th>Temp, F</th>
<th>Dia, in.</th>
<th>UTS, ksi</th>
<th>YS, ksi</th>
<th>El, %</th>
<th>RA, %</th>
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<td>79.0</td>
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<td>96.0</td>
<td>78.1</td>
<td>19.1</td>
<td>55.6</td>
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Airframe\Space Implementation Opportunities

- Continuing to explore additional opportunities for implementation
  - Subsystem
  - Structural\Mechanisms\Space\Prototype
Component designed to mix hot gas (~350°F) with cold gas (~-50°F)  
As E-Beam DDM Fabricated Configuration

Only seal flange surfaces machined
EBM AM Ti-6Al-4V Fatigue Evaluation

• E-Beam DDM properties assessment
  – Inspection:
    • Visual
    • Radiography
  – Coupon construction:
    • Fatigue samples constructed to evaluate
      – In-plane properties (X-Y)
      – Perpendicular to growth direction (Z)

<table>
<thead>
<tr>
<th>Fatigue Cycles to Failure</th>
<th>Coupon Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000 to 50 000 cycles</td>
<td>X1 X3 Y1 Y3 Z1 Z2 Z3 Z9</td>
</tr>
<tr>
<td>50 000 to 500 000 cycles</td>
<td>X2 X4 Y2 Y4 Z5 Z4 Z6 Z7</td>
</tr>
<tr>
<td>500 000 to 10 000 000 cycles</td>
<td>X5 X7 Y6 Y5 Z11 Z12 Z10 Z8</td>
</tr>
<tr>
<td>10 000 000 + cycles (runout)</td>
<td>X6 X8 Y7 Z15 Z14</td>
</tr>
<tr>
<td>Tensile</td>
<td>Z13</td>
</tr>
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</table>
Results: High Cycle Fatigue Evaluation of Ti-6Al-4V

Data points for notched castings are replotted here. Source: Metals Handbook, Vol 3, 9th ed., Properties and Selection: Stainless Steels, Tool Materials and Special-Purpose Metals, American Society for Metals, 1980, p 411. Most data points are based on $K_t = 3.0$, but some are for smooth specimens ($K_t = 1$). Each symbol represents data from a different source.
Fabrication History

• Feasibility Demonstration
  – CalRAM fabricated demo component (24 hour build cycle)
  – NGC machined and tested
• Subjected to extensive point design qualification

As-Fabricated

Post Machining and NDI
Warm Air Mixer Testing\NDI Conducted

- Chemical Composition
  - Conforms to AMS-T-9047 for Ti-6Al-4V

- Structural Requirements
  - Tensile Properties
    - Minimum Tensile Strength: 130 ksi
    - Minimum Elongation: 5%
    - Minimum Yield Strength: 119 ksi

- Fatigue Life
  - RT tests per ASTM E466:
    70 ksi at R = 0.1 to 200,000 cycles (minimum)

- Environment
  - Salt Spray: ASTM B117 - 168 hrs of exposure
  - Temperature
    - -50°F to ~350°F

- Inspection Requirements
  - Penetrant Inspection of all machined surfaces
  - Radiography
    - Inspect ASTM E1742
    - Acceptance criteria per ASTM E 1320, Grade A
NGAS Implementation Summary

EBM AM Ti-6Al-4V Subsystem Component

• Performance requirements met or exceeded
  – Feasibility process viability demonstrated for UCAS subsystem flight hardware
    o Rapid, near-net shape process (multiple unit/24hr cycle fabrication demonstrated)
  – Mechanical point design qualification requirements met or exceeded
  – Uniform microstructure exhibited
  – High cycle fatigue design data developed for primary build directions (X, Y, Z)

• Cost trade study demonstrated cost reduction compared to traditional manufacturing options
  – Decreased buy-to-fly
  – Reduced machining time\cost
  – Cycle time enhancement
  – Tool-less fabrication
Additive Manufacturing Near Term Challenges

- Current surface finish of E-Beam DDM metal components results in excessively rough surface finish for fatigue rated components
- Rough metal surface finish prohibits use of baseline surface NDI techniques (penetrant, Eddy current, UT, etc.) for accurate quality assurance.
- High cost of powder raw material stock
- Lack of AM specific design capabilities\tools within majority of engineering community