Electron Beam Freeform Fabrication: A Fabrication Process that Revolutionizes Aircraft Structural Designs and Spacecraft Supportability

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ARMD Technical Seminar on May 22, 2008
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Outline

- Technology inception
- Characterization
- Technical challenges
- Current applications
- Influence on future designs
- Supportability in space
Outline

- Technology inception
  - Motivation
  - EBF^3 process description
  - Benefits
- Characterization
- Technical challenges
- Current applications
- Influence on future designs
- Supportability in space

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Structural Metals in Aircraft

- Aluminum, Al-Li
- Titanium
- Steel
- Titanium
- Inconel

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Motivation

- New metals technology
  - Efficient, lightweight structures
  - Cost-effective
  - Enable new alloys

- Disruptive technology

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## Metal Deposition Processes

<table>
<thead>
<tr>
<th>Laser</th>
<th>E-Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10%</td>
<td>95%</td>
</tr>
<tr>
<td>Continuous gated pulsed</td>
<td>Continuous, rastered</td>
</tr>
<tr>
<td>Mirrors or fiber optics</td>
<td>Magnetically steered</td>
</tr>
<tr>
<td>Inert gas</td>
<td>Vacuum</td>
</tr>
<tr>
<td>Powder, 5-85%</td>
<td>Wire, ~100%</td>
</tr>
<tr>
<td>0.5-9 lb/hr</td>
<td>&gt; 30 lb/hr</td>
</tr>
</tbody>
</table>

*Energy efficiency*
EBF³ Core Technology

- Rapid metal fabrication process
  - Layer-additive process
  - No molds or tools
  - Properties equivalent to wrought
  - Demonstrated on Al, Ti, Ni, Fe-based alloys
EBF³ Process

- Slice CAD drawing
- E-beam creates melt pool
- Add wire to pool
- Translate layer-by-layer
LaRC EBF$^3$ System #1

- 42 kW gun
- 60 kV max
- 6-axis positioning

- 78” x 108” x 100” vacuum chamber
- 24” x 48” x 60” build envelope

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LaRC EBF³ System #2

- 3 kW gun
- 30 kV max
- 4-axis positioning

- 36” x 36” x 36” chamber
- 12” x 12” x 8” build envelope

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EBF³ Demonstration
Benefits of EBF³

- Near-net shape
  - Minimize scrap
  - Reduces part count

- Efficient designs
  - Lightweight
  - Enhanced performance

- Complex unitized components
  - Integral structures
  - Functionally graded materials

- “Green” manufacturing
  - Minimal waste products
  - Energy and feedstock efficient

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Ti Processing Steps

Conventional
1. TiCl₄
2. Sponge
3. Refine
4. Ingot
5. Forge
6. Billet Slab
7. Forge
8. Pre-form
9. Form
10. Mill Product
11. Machine
12. Final Product

Direct Fabrication
1. TiCl₄
2. Powder
3. Wire
4. EBF³
5. Machine
6. Final Product

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EBF$^3$ Saves Resources

**Conventional Machining:**

- 3000 lbs.
- 2850 lbs.
= 150 lbs.

**Additive Manufacturing via EBF$^3$:**

- 100 lbs.
- 100 lbs.
- 50 lbs.
= 150 lbs.

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Outline

- Technology inception
- Characterization
  - Microstructure
  - Mechanical properties
  - Structural integrity
- Technical challenges
- Current applications
- Influence on future designs
- Supportability in space

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2219 Al Microstructure

Machined from plate

Built by EBF³

0.01 in

0.01 in

http://www.nasa.gov
2219 Al EBF\(^3\) Microstructure

As-deposited

Rapid cool cast:
- Cu segregation
- Dendrites

0.004 in

T6 Condition

Transformed:
- Grain boundaries retained
2219 Al Tensile Data

- EBF³ tensile properties comparable to handbook data
Functionally Graded Al

100% Pure Al

50% Pure Al + 50% 2219 Al

100% 2219 Al

0.2 in

0.02 in

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Graded Deposit Hardness

2219 → 1100 Al

2219 → 2195 Al

Graded Deposit Hardness

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Ti-6Al-4V Microstructure
Ti-6Al-4V Tensile Data

- EBF³ Ti-6-4 equivalent to annealed wrought product

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Unitized Structural Tests

Uniaxial compression buckling tests

Machined
Riveted
EBF$^3$
• EBF³ panels 5% lower than machined
• Reduction due to distortion
Outline

- Technology inception
- Characterization
- Technical challenges
  - Preferential vaporization
  - Process control
  - Residual stress
- Current applications
- Influence on future designs
- Supportability in space
Loss of Al in Ti-6Al-4V

- Al loss in vacuum
- Function of temperature and pressure
- Process repeatability
- Issue with other alloys too
Need for Process Control

- Melt pool changes with temperature
- Monitor for process control
Closed loop process control

Collaboration with L-M and UTSl
Thermal Residual Stresses

- Localized heat induces distortion and residual stress
Baseplate Distortion

Clamp Distance from Deposit

Vertical Displacement (inch)

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NASA-Industry Alliance

- Joint-funded alliance
  - Boeing
  - Lockheed-Martin
  - Spirit AeroSystems
  - NASA
  - AFRL

- Develop process standards
- Catalyze growth of supply web
- NASA lead
  - Public benefit without private preference

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Outline

- Technology inception
- Characterization
- Technical challenges
- Current applications
  - Replace existing parts
  - Potential industries
- Influence on future designs
- Supportability in space

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Add Details onto Forgings

- Add features onto simplified preform
- Reduces billet sizes and buy-to-fly ratio
Cryotank Concept

- Form cylinder
- EBF$^3$ stiffeners
- Tailored stiffener arrays

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Complex Shapes

- Build entire part
- Unitized structures
- Allows internal cavities
Potential Industries

- Aerospace
- Tool & dies
- Automotive
- Medical implants
- Sporting goods
- Repairs in remote locations
Outline

- Technology inception
- Characterization
- Technical challenges
- Current applications
- Influence on future designs
  - New unitized structural designs
  - Functionally-graded structures
  - Integrated systems
- Supportability in space

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Curved stiffeners can be optimized for:

- Performance
- Low weight
- Low noise
- Damage tolerance
Aeroelastic Tailoring

Monocoque wing  Coupled bending-torsion wing
Design for Acoustics

- Optimize stiffeners to tailor natural resonance frequencies
Functional Gradients

Locally control:
- Chemistry
- Microstructure
- Properties

Lengthwise gradient

Build height gradient

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Integrated Systems

- Sensors for health monitoring
- Selective reinforcement

Outline

- Technology inception
- Characterization
- Technical challenges
- Current applications
- Influence on future designs
- **Supportability in space**
  - In-space repair
  - EBF$^3$ in 0-g
  - Space applications

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Need for Supportability

- Long duration missions
- Support autonomy
- Minimize resupply from Earth
- Fab or repair parts
- Enhances mission success
System Evolution

Ground-based: 100,000 lbs.  ➔  Portable: 1,800 lbs.  ➔  Space-based: (concept) <100 lbs.
Height vs. Cooling Path

- Cooling path influences temperature

First layer

After multiple layers
In 0-g, surface tension dominates.

- Function of temperature
Microgravity Testing

- NASA JSC’s C-9
  - 15-20 sec. at $10^{-2}$ g
  - 1.8 g pullout
  - 40 per flight

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Successful 0-g Deposits

- Wetting forces attract molten pool
Successful 0-g Deposits

- 0-g deposit comparable to 1-g
EBF³ in 0-g

- Surface tension dominates in 0-g
Learning in 0-g

- Height control required in 0-g

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Lunar Surface Repairs

- Concept to support long duration human exploration missions

Automated

Hand-held

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On-Orbit Assembly

- Concept for fabrication of large space structures

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Remote Terrestrial Repairs

Similar self-supportability needs on Earth:

- Navy ships
- Army supply in-theater
- Remote science bases

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Summary

- Led by LaRC since inception
- Disruptive technology
- Cross-cutting:
  - Aeronautics
  - Space
  - Other industry sectors
- Enables new structural designs
- Demonstrated in 0-g for use in-space

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EBF³ Timeline