Electron Beam Additive Manufacturing: State-of-the-Technology, Challenges & Opportunities

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Electron Beam Freeform Fabrication (a.k.a.: EBF³, EBFFF, EBAM)

- Electron beam deposition with wire feed
- High deposition rates, large part sizes
- Near-net shape with finished machining
Ti-6Al-4V Processed by EBF$^3$

- Large columnar grains grow epitaxially from substrate
- Forms typical alpha-beta lath structure within grains

Properties of EBF$^3$ deposited Ti-6-4 equivalent to annealed wrought product
History of EBF³ Development

Technology Inception
- Define EBF³ system specs
- EBF³ system installed at NASA LaRC

Technology Maturation
- Increasing part complexity
- Unitized & graded structures
- EBF³ process understanding
- Microgravity testing
- Patent on portable EBF³ concept issued 1/07

Timeline:
- 2001
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007
Future of EBF³

Commercialization
- Computationally guided process maturation
- Closed loop control

Current Applications
- First production parts on aircraft

Influence Future Designs
- Selective reinforcement/integrated sensors
- ISS demo of EBF³ system

Timeline:
- 2007
  - Detailed property testing for certification
- 2008
  - Process certified
- 2009
- 2010
- 2011
- 2012
- 2013 & beyond

- 2007
  - Retire prototype portable system
- 2008
  - Next Gen EBF³ lunar systems build and test
- 2009
- 2010
- 2011
- 2012
- 2013 & beyond

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Need for Process Control

Problem:
Melt pool changes with temperature from one layer to the next

Current Solution:
Monitor melt pool size as indication of temperature for process control

Required Work:
• Complete integration of sensors into control system
• Refine control logic to correct for other process anomalies (wire irregularities, change in direction)
**Problem:**
Al loss in Ti-6-4 due to melting in vacuum (function of temperature & pressure)

**Current Solution:**
- $\uparrow$ Al in wire composition
- $\downarrow$ thermal input

**Required Work:**
- Quantify losses at standard operating parameters to ensure consistency
- Process development to reduce Al loss by reducing thermal input
Problem:
Part-to-part and machine-to-machine variations limit repeatability

Current Solution:
Define tight process specification & conduct allowables testing

Required Work:
- Compare parts built on different machined with similar build parameters
- Beam probe analysis to monitor beam degradation with filament life
- Generate & maintain database with pedigree data from multiple deposition sites
Distortion and Residual Stress

Problem:
Temperature gradients induce residual stresses & distortion

Current Solution:
• Balanced deposition on both sides of baseplate
• Frequent thermal stress relief steps

Required Work:
• Post-deposition stress relief
• Modeling & validation of distortion & residual stress
• Process development to reduce distortion in one-sided deposits
Problem:
Irregular surface finish of as-deposited EBF$^3$ parts obscures NDE results

Current Solution:
NDE inspection after final machining

Required Work:
• NDE technique development to detect internal flaws without machining
• Process development to eliminate flaws
• Sensors incorporated into process control system to enable real-time NDE during deposition

Lack of fusion at substrate/deposit interface
**EBF\(^3\) as a Green Manufacturing Process**

**Conventional Machining:**

- 3000 lb. forged billet
- 2850 lb. chips
- 150 lb. finish machined part

**Additive Manufacturing via EBF\(^3\):**

- 200 lb. rolled sheet
- 100 lb. wire
- EBF\(^3\)
- 150 lb. finish machined part

*EBF\(^3\) saves significant resources over current methods:*

- raw materials, energy, fewer chemicals (cutting fluids), lead time = cost

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**Opportunity:**
Repair capability for large damaged parts that are irreparable by current technologies
- High value components (new or damaged in service)
- Reduce lead time to repair

**Required Work:**
- Tolerance control (residual stress, distortion)
- Material condition (HAZ, heat treat)
- Repair design (programming, stress analysis)
- Qualification (MRB)

*LM Aero ADP currently has three such parts and seeks funding to develop the technology*
• Freeform fabrication of unitized structure allows use of functionally graded, locally controlled features

• New structural design & analysis tools allow concept development of structures with contoured stiffeners that follow load paths

• New manufacturing process coupled with novel structural analysis and design enables performance enhancements and reduced cost, weight
EBF³ Far Term Possibilities

- Complex geometries not possible with conventional processes
- Integrated multi-functional components
- Functional gradient materials
- Selectively reinforced metals
- Controlled microstructures
- Integrated sensors