Effect of Electron Beam Freeform Fabrication (EBF³) Processing Parameters on Composition of Ti-6-4

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Ti6-4 EBF³ Team Contributions

- NASA Langley Research Center
  - Developed and conducted Ti-6-4 EBF³ depositions (single bead and multi-bead) for processing study
  - Sample preparation and specimen photography
  - Metallographic analysis
  - Multi-bead micro-chemical analysis (wavelength dispersive spectroscopy)

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- Spirit AeroSystems, Inc.
  - Single-bead bulk chemistry analysis (inductively coupled plasma technique; samples provided by NASA LaRC)
  - Correlation of single bead deposit chemistry with processing parameters

*Helen Ehlers, Rahbar Nasserrafi, and Bryan Woods*
Evolution of Metallic Aerospace Structures: EBF³ Enables Paradigm Shift in Design

**Designed for Assembly**
- Built-up Structure
- Integrally Stiffened

**Skin and stiffeners**
- machined from plate
- Multiple parts and fasteners

**High:**
- cost, scrap, weight, and assembly time

**Skin machined from sheet & integrated with near net stiffeners (SPF, extrusions, etc.)**
- Replace fasteners (FSW, RSW)

**Reduce:**
- cost, weight, parts, fasteners, and assembly time

**Designed for Performance**
- Unitized Structure

**EBF³ combines fabrication of material+structure**
- Enhanced performance through multi-functional novel design

**Minimize:**
- scrap, weight, fasteners and assembly time

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Electron Beam Freeform Fabrication (EBF³) Capability at NASA LaRC

**Capability**
- Computer controlled, electron beam gun (42kW), dual wire feed, 6-axis positioning, in a high vacuum
- Build envelope (6’x 2’x 2’) with a heating platen (900°F)

**Process**
- Layer-additive process: wire fed into molten pool created by an electron beam (100% dense)
- Built from a CAD file: 2-D slices representing 3-D object
- Produces near-net shape parts with material properties equivalent to annealed wrought product
Challenges of Molten Pool Processing in a Vacuum

- EBF$^3$ process occurs in a high vacuum (10^{-5} \text{ torr}) and requires sustaining a molten pool
- EBF$^3$ of Ti-6-4 processing occurs at 1800°F above melting temperature of the alloy
- Selective vaporization of Al occurs
- Study conducted to understand the influence of processing parameters on composition and microstructure changes related to Al loss

Variation in Vapor Pressure of Elements with Temperature
**EBF³ Process Development for Ti-6-4**

**Objectives**
- Optimize EBF³ processing parameters to avoid selective vaporization of Al
- Evaluate deposit chemistry and microstructure as a function of beam power, wire feed & translation speed

**Approach**
- Conduct a Design of Experiment (DOE) to identify process parameter ranking and interactions
- Composition analysis (Bulk and Micro-chemistry)
- Conduct systematic trials (single/multi-bead) of outer processing envelope limits
Design of Experiment (DOE) Approach to Control the EBF³ Process and Reduce Variation

**Taguchi Design (L27)**
- 3-Factorial, 3-Level design (fully balanced, mutually orthogonal array)
- Ability to separate and rank effects of each parameter and any interactions
- Randomly selected deposit schedules

**Process variables (3 parameters @ 3 levels)**
- Beam Power (BP): Baseline, 2 and 3 times
- Translation Speed (TS): Baseline, 2 and 7 times
- Wire Feed Rate (WF): Baseline, 4 and 8 times

**Process Constants**
- Voltage, Focused Beam, Wire diameter (0.063 in), Acid cleaned base plate (0.39 in), Preheat, Deposited same day at temperatures ≤ 150°F
Processing Envelope Energy Density (ED) Levels per Unit Volume of Material Deposited

- Taguchi 3x3 matrix
- Conducted randomly

ED = BP/[Area WIRE *WF*time], kW/in³
- ED levels varied from baseline to 24 times
Bulk Chemistry Analysis of Ti-6-4 EBF³ DOE Single-bead depositions

- Single layer deposits produced at NASA LaRC
- Bulk analysis conducted on material excised from deposit bead only
- Bulk chemical analysis performed by Spirit AeroSystems, Inc. using ICP
  - Al, V, Ti, and Fe
Bulk Chemistry Analysis of Ti-6-4 EBF³
DOE (3x2) Single-bead depositions

Subset: 3 parameters at 2 levels

<table>
<thead>
<tr>
<th></th>
<th>Al wt%</th>
<th>V wt%</th>
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<tbody>
<tr>
<td>Ti-6-4 Specification Limits</td>
<td>5.50 - 6.75</td>
<td>3.50 - 4.50</td>
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<tr>
<td>Base Plate</td>
<td>6.25</td>
<td>3.87</td>
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<tr>
<td>Wire</td>
<td>6.39</td>
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<table>
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<tr>
<th>Run #</th>
<th>BP</th>
<th>TS</th>
<th>WF</th>
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<th>V wt%</th>
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<tr>
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<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>4.97</td>
<td>3.97</td>
</tr>
</tbody>
</table>

- For WF = Low Al wt% < specification limits (except # 9)
- Average Al wt% in DOE schedules = 5.66 wt%
- Drop in Al content varied (0.27 – 1.42 %)
Effect of EBF³ Process Parameters on Al Content

- Wire Feed rate has the greatest impact on Al content
- Beam Power also plays a significant role
- Translation Speed is insignificant
Significance of Process Parameters: Ranking and Interactions

- WF had strongest impact on Al content (WF >> BP, TS)
- BP & TS had minimal effect, strong coupling results in 2nd largest Al loss
- All parameters and 2-level interactions > TS
- TS and 3-level coupling are statistically insignificant
Micro-Chemistry Analysis of Multi-bead (10) Deposit:

- Deposit was 10 beads high; fabricated at NASA LaRC
- Wavelength Dispersive Spectroscopy (WDS) using a scanning electron microscope (SEM)
- Higher fidelity than energy dispersive spectroscopy
  - Automation allows scans at micron level increments
  - Standardization performed on base plate using bulk chemistry
Micro-Chemical Results of Multi-bead (10) Deposit: BP=High TS=Low WF=Medium

WDS Line Scan in 500 μm increments

- Discrete change in Al and Ti Wt % at base plate/bead intersection
- Slight loss of Al through deposit
- Al loss independent of microstructure and bead interfaces
- V is unaffected by EBF³ process

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<table>
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<th>Wt %</th>
<th>Ti</th>
<th>Al</th>
<th>V</th>
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</tr>
<tr>
<td>5.3</td>
<td></td>
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<td></td>
</tr>
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<tr>
<td>3.6</td>
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Micro-Chemical Results of Multi-bead (10) Deposit: BP=High TS=Low WF=Medium

100 μm increment across mixing zone

250 μm across width of bead

5 mm

90.5

Wt %

89.5

100 μm increment across mixing zone

5 mm

91

Wt %

90

6.6

Al

6.2

5.4

Microchemical Results of Multi-bead (10) Deposit: BP=High TS=Low WF=Medium
Micro-Chemical Results of Multi-bead (10) Deposit: BP=Medium TS=Low WF=Medium

500 μm increments

5 mm increments

91.5
89.5
Wt %
6.6
4.6
4.2
3.6

Ti

Al

V

250 μm increments

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Bulk Composition Results of Single-bead Deposit
Ti-6-4 EBF³ DOE (3 factor x 2 level)

Effect of process parameters on Al Loss

Individual impact of Parameters (BP, TS and WF):
- WF has greatest impact on Al loss (WF>>BP,TS)
- BP also plays a significant role
- TS is insignificant

Impact of Parameter Coupling:
- WF and all 2-level interactions had more impact on Al loss than either BP or TS
- BP and TS separately had minimal effect but together caused 2nd largest Al loss
- TS was equivalent to the 3-level coupling and both were insignificant
Micro-Chemistry Results of Multi-bead Deposit (10)

Effect of reducing BP while holding TS and WF constant

- Discrete change in Al and Ti wt% at the base plate and deposit intersection
- Slight loss of Al through deposit
- Al loss is independent of microstructure and bead interfaces
- V content is unaffected by the EBF$^3$ process
Future Work

- Complete DOE composition study for bulk and micro chemistries
  - Conduct micro-chemistry of single-bead deposits

- Examine bead microstructure and geometry resulting from processing parameters

- Develop better understanding of the effect of energy density level on bead geometry and chemistry