Development of Nuclear Quality Components using Metal Additive Manufacturing

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Outline

- RadiaBeam overview
- AM research at RadiaBeam
- Overview of EBM AM technology
- Goals and relevance of the Phase I/II project
- Phase I/II work
Who we are

- RadiaBeam has two core missions:
  - To manufacture high quality, cost-optimized accelerator systems and components
  - To develop novel accelerator technologies and applications
- Currently > 50 employees and growing
  - Consists of PhD Scientist (10), Engineers (18), Machinists (10), Technicians (8), and Administrative (4)
Capabilities

- Design (RF, magnetic, thermal-mechanical)
- Engineering
- Fabrication
- Assembly
- Testing
- Installation
- Service
Facilities

- Machine shops (clean and regular)
- Assembly area
- Magnetic measurements lab
- Optics lab
- Hot test cell (up to 9 MeV)
- Clean room
- Chemical processing
- RF test lab
- Currently 16,000 sq. ft., and looking to expand to > 30k by mid 2016!
Products

- Turnkey accelerators
  - Cargo inspection and Radiography
  - High-power Irradiation
  - Self-shielded irradiators
- E-beam diagnostics
  - Beam profile monitors
  - Bunch length monitors
  - Charge, emittance, etc.
- RF structures
  - RF photoinjectors
  - Bunchers
  - Linacs
  - Deflectors
- Magnetic systems
  - Electromagnets
  - Permanent magnets
  - Systems (chicanes, final focus, spectrometers)
Growing list of customers...
Multiple Funding Agencies

- SBIR/STTR, BAA, commercial funded and self-funded R&D to develop new products and technical solutions
AM development at RadiaBeam

- 2006 to present: DOE and DHS SBIR/STTR, as well as Internal R&D funded
  - $3.5M invested in copper, niobium, and multi-material EBM AM R&D
- Active collaboration with NC State, UTEP, JLab, UC Berkeley, LANL
- Developed accelerator designs and methods exploiting AM
- Dissimilar metal joining (Inconel 718 to 316 SS)
  - Applications in nuclear (fission and fusion) and concentrated solar power components (DOE Nuclear Energy Phase I/II (DE-SC0011826))
- RadiaBeam-led collaborations first to developed EBM AM process parameters for pure copper and niobium for NCRF and SRF components
Why make accelerators using AM?

- Improve average power performance (thermal load)
  - Efficient cooling designs
- Improve peak power performance (RF breakdown)
  - Superior (engineered) material properties
- Revolutionize cavity design
  - Eliminate brazing/joining; monolithic design
  - Realize truly novel designs (and materials)
- Reduce time and cost of fabrication
Exploring AM for:

- Alternative (non rare-earth) permanent magnets
- Intermetallics compounds for SRF accelerator applications
- Ceramics for Dielectric Wakefield Accelerator applications
- Amorphous metals for induction accelerators
- Multi-material capability
- Repair (high value) damage components
- Refractory metals for x-ray converters
Arcam Electron Beam Melting (EBM)

1. Thermionic gun (60 kV)
2. Magnetic optics
3. Hoppers
4. Mechanical rake
5. Built part
6. Building platform
Project Goals and Relevance to DOE Nuclear Power

- **Project Goal**
  - Phase I – Experimentally demonstrate feasibility of joining dissimilar metals using EBM AM.
  - Phase II – Further the fundamental understanding of dissimilar metal joining using EBM AM

- **DOE NE Relevance**
  - Avoids use of filler materials
  - Vacuum (~$10^{-4}$ Torr) limits contamination of oxides and nitrides
  - High quality joint while minimizing the thermal damage to surrounding material
  - Promise of realizing complex multi-material parts
Research explored the feasibility of joining Inc718 and 316L SS using EBM AM.

Simple geometries suitable for material testing were fabricated (Inc718 on 316L and 316L on Inc718) using Arcam EBM, and the joints characterized.

Material testing showed reduced presence of precipitates and narrower HAZ when compared to traditional welding processes.

Change in mechanical properties in the HAZ and the substrate were not greatly affected.

A. Hinojos et. al., *Joining of Inconel 718 and 316L Stainless Steel using powder bed fusion additive manufacturing technology*, Mater. Sci. Eng.: A, Pending review (Sept. 2015)
Joint Characterization

Inconel 718 (EBM) on 316L Stainless Steel

316L Stainless Steels (EBM) on Inconel 718

- XRD scans were done 4mm from the interface and the edge in both the substrate and the build.
- XRD showed characteristic peaks of γ-Fe (FCC a=3.60 Å), γ'-Ni (FCC a=3.59 Å), γ''-Ni3Nb (BCT a=3.60 Å c=7.41 Å).

Microhardness

<table>
<thead>
<tr>
<th>Distance from Interface (mm)</th>
<th>Hardness (HV)</th>
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<tbody>
<tr>
<td>-3.0</td>
<td>150</td>
</tr>
<tr>
<td>-2.0</td>
<td>200</td>
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<tr>
<td>-1.0</td>
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<tr>
<td>0.0</td>
<td>300</td>
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<tr>
<td>1.0</td>
<td>350</td>
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Metallography

- Figures A-D are EBM-fabricated Inc 718 on SS.
- Figures E-F are EBM-fabricated SS on Inc 718.
- Figures A & E represent areas beneath the start plate showcasing the HAZ.
- Figures B-C & F-G show the joined interface.
- D & H are the microstructures of the EBM-fabricated materials.
Phase II

- Phase II goal: Further the fundamental understanding of dissimilar metal joining using EBM AM
  - Introduce simulations to guide material choice in joint design
  - Extend EBM processing to ferritic alloys
  - Extend material testing to nuclear reactor environmental conditions (high temperature, pressure, radiation)
Project schedule

1) Multi-material alloy optimization
   - 1.1) Selection of alloys
   - 1.2) Initial CALPHAD simulations
   - 1.3) CALPHAD simulations optimization

2) Procurement of feedstock material
   - 2.1) Purchase alloy feedstock (RBS - Sandvik)
   - 2.2) Powder validation (RBS/UTEP)

3) EBM AM system upgrades
   - 3.1) Design/Engineering
   - 3.2) Procurement
   - 3.3) Fabrication
   - 3.4) Installation
   - 3.5) Testing

4) EBM optimization for new alloys/geometries
   - 4.1) EBM alloy optimization
   - 4.2) Basic material testing
   - 4.3) EBM multi-material optimization
   - 4.4) Basic material testing

5) Detailed material characterization
   - 5.1) Microstructure
   - 5.2) Phase identification
   - 5.3) Tensile testing
   - 5.4) Corrosion testing
   - 5.5) Radiation testing
   - 5.6) Analysis

6) Milestones
   - 6.1) Kickoff Meeting
   - 6.2) Determine alloy composition
   - 6.3) Machine upgrade review at UTEP
   - 6.4) Machine upgrade implementation
   - 6.5) DOE REVIEW (2nd year funding)
   - 6.6) Validate multi-material interface
   - 6.7) Demonstrate mechanical properties
   - 6.8) Demonstrate radiation tolerance
   - 6.9) Final report
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