Additive Manufacturing of Fuel Injectors

NETL – 2017 Crosscutting Research and Rare Earth Elements Portfolios Review

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Solar Turbines
A Caterpillar Company

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David Teraji, (PM)

Sydni Credle (PM)
Process Equipment Overview

Laser PBF
EOS M280

Electron Beam PBF
Arcam A2X

Material Extrusion
Stratasys Fortus 450mc

Binder Jetting
ExOne Innvoent

Sheet Lamination UAM
Fabrisonic
Process Equipment Overview

Laser and Arc-DED
Commercial Robot

EB-DED
Sciaky EBAM

Laser DED
RPM 557

Targeting $10-$15M
AM equipment investment in Buffalo
Solar Turbines Overview

- World’s Largest Manufacturer of Industrial Gas Turbines (1 to 22 MW)
- Over 15,000 Gas Turbines Sold
- Over 6,000 Gas Compressors Sold
- Installations in over 100 Countries
- Direct End-to-End Sales & Service
- More than 2 Billion Fleet Operating Hours
- Global Workforce (7,000) Employees
- Based in San Diego, California, U.S.A.
- Subsidiary of Caterpillar Inc. Since 1981
Motivation

- **Gas turbine components**
  - Very specific design (difficult to cast)
  - Long lead time
- **Fuel injector tip**
  - Alloy X
  - Ni-Cr-Fe-Mo alloy
  - Solid Solution Strengthened

Additive manufactured fuel injector courtesy of Solar Turbines
Objective

- To develop a novel process to qualify the AM technique of laser powder bed fusion (L-PBF) for complex gas turbine components made of high temperature nickel-based alloys
- To investigate the effect of input powder stock and AM process variables on resultant microstructure and mechanical properties for the alloy material
- Post-processing, including heat treatment and the use of finishing technologies will also be employed in order to achieve required dimensional and surface finish requirements for the component.
Relevance to Fossil Energy

- Alloy-X is used in many industrial gas turbine applications.

- AM will enable design and energy efficiencies:
  - Faster and less costly design optimization.
  - Future applications could enable more energy efficient designs by reducing design constraints
    - Increasing fuel efficiency
    - Providing higher operating temperature
Milestones

- **Milestone 1: Powder Characterization**
  - Complete
- **Milestone 2: NIST Test Artifacts Complete**
  - Complete
- **Milestone 3: Process Parameter Report Delivered**
  - Complete
- **Milestone 4: Property Data Curves Delivered**
  - In-progress
- **Milestone 5: Specification Document Delivered**
Milestone 1- Powder Evaluation

- **Powder evaluation:**

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Type</th>
<th>Min. Desired Size (µm)</th>
<th>Max. Desired Size (µm)</th>
<th>Fine (%)</th>
<th>Coarse (%)</th>
<th>Cost Comparison per lb. (350 lb order)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>Fine</td>
<td>5</td>
<td>38</td>
<td>0.1% &lt; 5 um</td>
<td>0.8% &gt; 38 um</td>
<td>100%</td>
</tr>
<tr>
<td>V1</td>
<td>Coarse</td>
<td>20</td>
<td>45</td>
<td>4.2% &lt; 20 um</td>
<td>0.5% &gt; 45 um</td>
<td>132%</td>
</tr>
<tr>
<td>V2</td>
<td>Fine</td>
<td>5</td>
<td>38</td>
<td>2% &lt; 5.5 um</td>
<td>1 &gt; 38 um</td>
<td>190%</td>
</tr>
<tr>
<td>V2</td>
<td>Coarse</td>
<td>16</td>
<td>45</td>
<td>1% &lt; 16 um</td>
<td>1% &gt; 45 um</td>
<td>195%</td>
</tr>
</tbody>
</table>

![Particle Size Distribution](image1.png)

![Particle Size Distribution](image2.png)

![Particle Size Distribution](image3.png)

![Particle Size Distribution](image4.png)
Milestone 2 - NIST Test Artifacts Complete

- **Minimum Feature Size:**
  - The L-PBF process was capable of producing fine features, and met capabilities of investment casting

- **Surface roughness measurement:**
  - Fine powders were slightly better ($S_a$).
  - Typical allowable limit for the surface finish of investment casting
    - (Ra) less than 125 µin. (3.17 µm)
**Stress relief heat treatment:**
- All of the specimens underwent the stress relief heat treatment, while still attached to the build plate
  - 2150°F
  - 1 hour
  - Rapid argon cooling.
Milestone 3

**Mechanical test:**

- Tensile
  - Room temperature
  - Elevated temperature (1500°F/815.5°C)
- Creep
  - Elevated temperature (1500°F/815.5°C)
  - Stress: 15 ksi
- Low cycle fatigue
  - Elevated temperature (1000°F/538°C).
  - Total strain range: 0.6%
  - Stress ratio: -1
Milestone 3

Fractography:
- Room temperature tensile test
  - Intergranular fracture morphology
  - Dimples on the fracture surfaces
  - Secondary cracking
  - LOF surrounded by un-melted powder particles.
Milestone 3

**Powder down select:**

<table>
<thead>
<tr>
<th>Powder / Properties</th>
<th>Cost Comparison</th>
<th>Powder Compatibility with AM Machine (ProX300)</th>
<th>Microstructure (Micro cracks)</th>
<th>RT- Tensile Test</th>
<th>ET- Tensile Test</th>
<th>Creep</th>
<th>Fatigue</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UTS</td>
<td>UTS</td>
<td>Hrs (rpt.)</td>
<td>El% (rpt.)</td>
</tr>
<tr>
<td>V1-C</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No HT</td>
<td></td>
</tr>
<tr>
<td>V1-F</td>
<td>132%</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td>190%</td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>V2-F</td>
<td>195%</td>
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</table>

- Vendor 1
  - V1-C:
    - Lowest creep and fatigue properties
    - Powder leakage
  - V1-F
    - Low ductility at high temperature as well as the short creep rupture time could be improved using a proper heat treatment
    - Originally developed with the OEM.
    - Favorable powder cost
### Powder down select:

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- **Vendor 2**
  - V2-C
    - Powder leakage
  - V2-F
    - Similar or better tensile properties than those of V2-C
    - Longer fatigue life
    - Lower creep life.
    - Unfavorable powder cost
    - Unfavorable microstructure (micro-cracks)
Milestone 3

- Heat Treatment Optimization (Microstructure Screening)
  - The team investigated eight HTs.
    - As printed (no HT)
    - Solution Annealing
      - Temperature (#2)
      - Time (#5)
    - HIP
    - Post annealing
  - Microstructural screening to downselect to four heat treatments for mechanical testing

<table>
<thead>
<tr>
<th>HT Procedure</th>
<th>Solution Annealing</th>
<th>HIP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temp. (°F)</td>
<td>Time</td>
</tr>
<tr>
<td>1-a</td>
<td>2150</td>
<td>15 min.</td>
</tr>
<tr>
<td>1-b</td>
<td>2150</td>
<td>40 min.</td>
</tr>
<tr>
<td>1-c</td>
<td>2150</td>
<td>1 hr</td>
</tr>
<tr>
<td>2</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>6*</td>
<td>2150</td>
<td>4 hr</td>
</tr>
<tr>
<td>7</td>
<td>2150</td>
<td>8 hr</td>
</tr>
<tr>
<td>8</td>
<td>2200</td>
<td>1 hr</td>
</tr>
</tbody>
</table>

AC: Argon cooling
**Milestone 3**

- **Heat Treatment Optimization**
  - Annealing time
  - Annealing temperature
  - External pressure (HIP)

  - Grain growth
  - Dissolution of precipitates

1a, 1c, and 7 had an annealing temperature of 2150°F, but with the annealing times of 15, 60, and 240 minutes.
**Milestone 3**

**Heat Treatment Optimization (Mechanical testing)**

- Additional test walls were produced.
- Four heat treatment procedures were selected for the further analysis of mechanical properties.
  - Room temperature tensile test
  - Elevated temperature tensile test
  - Low cycle fatigue (LCF)
  - Creep

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<th>HIP</th>
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<tbody>
<tr>
<td></td>
<td>Temp. (°F)</td>
<td>Time (hr)</td>
<td>Post Cooling</td>
</tr>
<tr>
<td>R1</td>
<td>2150</td>
<td>1</td>
<td>AC</td>
</tr>
<tr>
<td>R2</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>R3</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>R4</td>
<td>2150</td>
<td>4</td>
<td>AC</td>
</tr>
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</table>

AC: Argon cooling
Milestone 3

◆ LCF
  - Longer fatigue life in the HIP’d samples
    - Reduction of internal defects
    - Higher volume fraction of intergranular precipitates

LCF - Longer fatigue life in the HIP’d samples
- Reduction of internal defects
- Higher volume fraction of intergranular precipitates

Average Cycles to Failure (Nf)

Heat Treatment Procedure

R1  R2  R3  R4
Milestone 3

- LCF
  - Small LOF and solidification crack discontinuities
  - Non-metallic SiMo and AlMnMg inclusions
    - New crack initiation mechanism
    - Scattering in the results
**Milestone 3: Optimized Heat Treatment Down-Select**

- HIP improved both LCF and Creep properties
- Post HIP reduced creep performance
- R2 selected for Milestone 4 activities

<table>
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<th>Solution Annealing</th>
<th>HIP</th>
<th>Solution Annealing</th>
<th>Mechanical Properties</th>
</tr>
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<tbody>
<tr>
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<td>Temp. (°F)</td>
<td>Time (hr)</td>
<td>Post Cooling</td>
<td>Temp. (°F)</td>
</tr>
<tr>
<td>R1</td>
<td>2150</td>
<td>1</td>
<td>AC</td>
<td>---</td>
</tr>
<tr>
<td>R2</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>2150</td>
</tr>
<tr>
<td>R3</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>2150</td>
</tr>
<tr>
<td>R4</td>
<td>2150</td>
<td>4</td>
<td>AC</td>
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AC: Argon cooling
Milestone 4 - Property Data Curves Delivered

- **Builds**
  - Complete
- **Heat treatment**
  - Complete
- **Mechanical Testing**
  - In-progress
Future Work

- **Milestone 4**
  - Generation of Property Data Curves
    - Room Temperature tensile
    - Elevated temperature tensile
    - LCF
    - Creep

- **Milestone 5**
  - Development of the specification document
    - Powder
    - Process Parameters
    - Design

- **Final report**
Summary

The influences of powder feed on the dimensional accuracy and mechanical properties of additively manufactured Hastelloy X were analyzed.

- One powder was down selected.
- Process parameters were optimized.

Heat treatment procedure was optimized for the additively manufactured Hastelloy X.

- Eight heat treatment conditions were analyzed.
- Microstructural and mechanical analysis were performed.
- Improvements in LCF & Creep properties demonstrated
Questions

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