Wire Arc Additive Manufacturing of Advanced Steam Cycle Components Using Location Specific Design Enhanced by High-Throughput Experiments and Machine Learning

PI: Wei Xiong, Co-PI: Albert To
NETL Collaborator (RIC-POC): Chantal Sudbrack
weixiong@pitt.edu
http://www.pitt.edu/~weixiong

Physical Metallurgy and Materials Design Laboratory
University of Pittsburgh, Pennsylvania, USA

Acknowledgements: Luis Pizano, Soumya Sridar, Santanu Paul, Xavier Jimenez
Outline

• Background
• Recrystallization studies
• Grain structure modeling
• γ’ precipitation behavior
• Builds for high-throughput experiments
• Future work
Motivation: A-USC Coal Power Plants Eco-Efficiency

- T ~ 700-760 °C
- P = 30-38 MPa
- 50 % efficiency
- Lower CO₂ emission
Wire Arc Additive Manufacturing (WAAM)

- AM process that is similar to directed energy deposition
- Uses electric arc as heat source
- Solid wire is the feedstock material
- Main advantages are
  - high deposition rates
  - minimum wastage of materials
- Low running cost and short production cycle
- Ability to build large parts
- Main disadvantage is
  - lower precision in as-built parts


ARC 605: 5-axis machining: Production of metallic components up to 0.8 m³ with a maximum mass of 500 kg.
Haynes 282

Chemical Resistance
• Oxidation
• Corrosion

Mechanical Resistance
• Traction
• Fracture
• Impact
• Creep

**γ phase**, fcc

**γ’ phase** (L12), $Ni_3(Al, Ti)$

Primary TiN and Ti, Mo-rich MC phases

Secondary/Primary Mo-Ni rich $M_6C$ and Cr, Mo-rich $M_{23}C_6$ carbides

$MC + γ \rightarrow M_{23}C_6 + γ'$

$(Ti, Mo)C + (Ni, Cr, Al, Ti) \rightarrow Cr_{21}Mo_2C_6 + Ni_3(Al, Ti)$

$MC + γ \rightarrow M_6C + γ'$

$(Ti, Mo)C + (Ni, Cr, Al, Ti) \rightarrow Mo_3(Ni, Co)_3C_3 + Ni_3(Al, Ti)$

$k_{Co}^{Ni} = 1, k_{Cr}^{In718} = 1.03, k_{Al}^{In718} = 1, k_{Ti}^{In718} = 0.69, k_{Mo}^{In718} = 0.82$

Y. Yang, MICROSTRUCTURAL EVOLUTION IN CAST HAYNES 282 FOR APPLICATION IN ADVANCED POWER PLANTS.
A. Ramakrishnan, Microstructure and mechanical properties of direct laser metal deposited Haynes 282 superalloy, 2019
Systems Design Chart for Haynes 282

**PROCESS**
- Aging
- Solutionization
- Homogenization (w/ and w/o HIP)
- Wire-Arc Additive manufacturing (Wire composition)

**STRUCTURE**
- Matrix fcc phase
  - Grain texture
  - Grain size
  - Homogeneity
- Precipitation
  - L12-γ’ particle
  - MC carbide
    - M23C6
    - M6C
  - μ phase
  - σ phase
- As printed microstructure
  - MC, D024-Ni3Ti, and μ
  - Porosity
  - Grain texture and grain size
  - Residual stress (low)

**PROPERTY**
- UTS
  - 760C: 856 MPa (124 ksi)
  - RT: 1147 MPa (166 ksi)
- Yield Strength
  - 760C: 628 MPa (91 ksi)
  - RT: 715 MPa (104 ksi)
- Ductility
  - 760C: 22%
  - RT: 30%
- Creep at 760C
  - 100h, 393 MPa (57 ksi)
  - 1000h, 283 MPa (41 ksi)
- Oxidation Resistance in Flowing Air
  - 982°C for 1008h
  - Metal loss: 5 µm
- Hot cracking resistance
Printing strategy difference: Meander vs. Single Bead

Multitrack Meander Haynes 282

Multitrack Single Bead Haynes 282

Zigzag, Meander

Single bead
As-printed microstructure: Meander vs. Single Bead

Zig-zag (meander) vs. Single bead

Fusion line

X-Z plane

Build direction, Z

5 mm

1 inch

5 mm
As-printed microstructure: Meander vs. Single Bead

Similarities can be found between **X-Z plane of Meander** and **Y-Z (transverse) plane of Single bead**

**Y-Z (transverse) plane of Meander** and **X-Z plane of Single bead**

Multitrack **Meander**

- **X-Z plane**
- **Transverse plane (Y-Z)**

Multitrack **Single Bead**

- **X-Z plane**
- **Transverse plane (Y-Z)**
As-printed microstructure: Meander vs. Single Bead

**Hardness Map of Meander**

- **TOP**
  - Multitrack Meander
  - Multitrack Single bead

- **MIDDLE**
  - 500 μm
  - 1 mm

- **BOTTOM**
  - 500 μm
  - 1 mm

**Hardness Map of Single Bead**

- **TOP**
  - Multitrack Meander
  - Multitrack Single bead

- **MIDDLE**
  - 500 μm
  - 1 mm

- **BOTTOM**
  - 500 μm
  - 1 mm

304 ss
Outline

• Background
• Recrystallization studies
  • Grain structure modeling
  • γ’ precipitation behavior
  • Builds for high-throughput experiments
• Future work
Determination of phase transformation temperature

**Single-Bead**

- First heating curve
- Second heating curve
- Third heating curve
- Heating rate: 10 K/min
- Heating range: 1200°C to 1450°C
- Exothermic peaks at 1357°C, 1361°C, and 1364°C
- Cooling range: 1284°C to 1356°C
- Cooling rate: 10 K/min
- Cooling range: 1284°C to 1353°C

**Meander**

- First heating curve
- Second heating curve
- Third heating curve
- Heating rate: 10 K/min
- Heating range: 1200°C to 1450°C
- Exothermic peaks at 1284°C, 1286°C, and 1356°C
- Cooling range: 1284°C to 1353°C
- Cooling rate: 10 K/min
- Cooling range: 1286°C to 1359°C
## Determination of phase transformation temperature (cont’d)

<table>
<thead>
<tr>
<th>Transformation temperature</th>
<th>CALPHAD prediction</th>
<th>Meander</th>
<th>Single bead</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Heating (10 K/min)</td>
<td>Cooling (10 K/min)</td>
</tr>
<tr>
<td>Solidus</td>
<td>1300 °C</td>
<td>1287.4 ± 3.6</td>
<td>1285.0 ± 1.4</td>
</tr>
<tr>
<td>Liquidus</td>
<td>1400°C</td>
<td>1360.0 ± 4.0</td>
<td>1358.0 ± 4.6</td>
</tr>
</tbody>
</table>
Recrystallization Study: Choice of temperatures

Temperature (°C)

1400  Liquidus temperature TC-Equilibrium
1360  Liquidus temperature of WAAM 282 (DTA)
1300  Freezing range
      Solidus temperature TC-Equilibrium
1285  Solidus temperature of WAAM 282 (DTA)
1250  Test #2: 1, 2, 4 h
1250  Test #3: 1, 2, 4 h
1225  Test #1: 1, 2, 4 h
Heat treatment at 1300°C did not cause bulk melting, however, initial melting can be observed.
Recrystallization studies for build using Multi-Track **Single Bead**

- **1300°C**
  - 1 h: 500 µm, GS: 621 µm
  - 2 h: 500 µm, GS: 863 µm
  - 4 h: 500 µm, GS: 894 µm
  - As Built: 500 µm, GS: 502 µm

- **1250°C**
  - 1 h: 500 µm, GS: 547 µm
  - 2 h: 500 µm, GS: 457 µm
  - 4 h: 500 µm, GS: 870 µm

- **1200°C**
  - 1 h: 500 µm, GS: 484 µm
  - 2 h: 500 µm, GS: 600 µm
  - 4 h: 500 µm, GS: 620 µm

**Grain Size, diameter (µm)**

Signs of recrystallization observed at 1250°C 1-2h, and fully recrystallizes at 1250°C 4h
Recrystallization studies for build using Multi-Track Single Bead, Hardness

- **1300°C**
- **1250°C**
- **1200°C**

**Optimum → 1250°C / 2h**
## Summary of recrystallization studies

<table>
<thead>
<tr>
<th>No.</th>
<th>Temperature [°C]</th>
<th>Time [h]</th>
<th>Single Bead</th>
<th>Meander</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>HV&lt;sub&gt;300g&lt;/sub&gt;</td>
<td>Std Dev</td>
</tr>
<tr>
<td>1</td>
<td>1200</td>
<td>1</td>
<td>230</td>
<td>12.2</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>2</td>
<td>225</td>
<td>8.75</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>4</td>
<td>226</td>
<td>12.14</td>
</tr>
<tr>
<td>4</td>
<td>1250</td>
<td>1</td>
<td>216</td>
<td>13.9</td>
</tr>
<tr>
<td>5</td>
<td><strong>1250</strong></td>
<td><strong>2</strong></td>
<td><strong>210</strong></td>
<td><strong>6.33</strong></td>
</tr>
<tr>
<td>6</td>
<td>1250</td>
<td>4</td>
<td>223</td>
<td>9.91</td>
</tr>
<tr>
<td>7</td>
<td>1300</td>
<td>1</td>
<td>215</td>
<td>9.91</td>
</tr>
<tr>
<td>8</td>
<td>1300</td>
<td>2</td>
<td>209</td>
<td>7.98</td>
</tr>
<tr>
<td>9</td>
<td>1300</td>
<td>4</td>
<td>214</td>
<td>11.69</td>
</tr>
</tbody>
</table>

Optimum
Outline

• Background
• Recrystallization studies
• Grain structure modeling
  • $\gamma'$ precipitation behavior
  • Builds for high-throughput experiments
• Future work
Discrete dendrite dynamics (DDD) model

Substrate and deposit → identical or almost identical lattice dimensions → Epitaxial dendrite growth

\[ \Delta G_{\text{nuc}}^0 \gg \Delta G_{\text{epitaxy}}^0 \]

Discretized melt pool

High \( G \) at the S/L interface and a low growth rate \( (R) \) → high \( G/R \) → Epitaxial Growth

Meander (Longitudinal)-Calibration
Meander (Transverse)-Validation
Multitrack (Longitudinal)-Calibration

Build Direction

20mm

20mm
Multitrack (Transverse)-Validation

Build Direction

X

Z

304 ss

20mm

15mm
Process Simulation

- Haynes 282 parameters
- Cylinder of 22 layers
- Mesh size: 500 microns
- Meshing time: 40 min
- Preprocessing time: 15 min
- Simulation time:
  - 2 hours for thermal
  - 29 hours for thermomechanical
Weld cooling time

- Cooling time can be adjusted on a weld by weld basis
- Cooling time: ~60 seconds
Comparison against thermocouple data

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graphs showing temperature over time for different locations](image-url)
Outline

• Background
• Recrystallization studies
• Grain structure modeling
• γ’ precipitation behavior
  • Builds for high-throughput experiments
• Future work
Precipitation strengthening study for calibration of precipitation simulation

Characterization methods

- Precipitate type
- Grain Structure
- Hardness
- Precipitate type
- Hardness
- $\gamma'$ Size and distribution
- Hardness
- Tensile Test*

Temperature, °C

- Solutionization
  - MC precipitation
  - Water Quench (WQ)
  - 1250°C, 2h
  - 1150°C, 2h

- 1st Aging
  - $M_2\text{C}_6$ precipitation
  - 1010°C, 2h

- 2nd Aging
  - $\gamma'$ precipitation
  - 788°C, 2h
  - 4 h
  - 6 h
  - 8 h

Time, hours
Solutionization – Phase stability

1250°C/2h
(Ti, Mo)C

1150°C/2h
(Ti, Mo)C

As-built
(Ti, Mo)C

γ' observation in as-printed microstructure

Lower Magnification Higher
Solutionization & 1st Aging – Phase stability

1250°C/2h

1250°C/2h + 1010°C/2h

1150°C/2h

1150°C/2h + 1010°C/2h

(Ti, Mo)C

(Cr, Mo)23C6

(Cr, Mo)23C6
2nd Aging – γ’ precipitation

1250°C/2h + 1010°C/2h + 788°C/xh

1150°C/2h + 1010°C/2h + 788°C/xh
2nd Aging – hardness due to $\gamma'$ precipitation

$1250^\circ C/2h + 1010^\circ C/2h + 788^\circ C/xh$

$1150^\circ C/2h + 1010^\circ C/2h + 788^\circ C/xh$
2nd Aging – **hardness due to \( \gamma' \) precipitation**

**Comparison of Hardness**

![Graph showing hardness comparison between 1150°C/2h and 1250°C/2h for various times.](image)

**Comparison of average size of \( \gamma' \) precipitation**

![Graph showing average size comparison between 1150°C/2h and 1250°C/2h for various times.](image)
Outline

• Background
• Recrystallization studies
• Grain structure modeling
• γ’ precipitation behavior
• Builds for high-throughput experiments
• Future work
WAAM builds for high-throughput experiments

- Heavy distortion was observed at one end of the base plate while negligible distortion on the other end for the wall builds.
- Distortion in the front end also varies along the longitudinal direction where the wall build at the middle is expected to possess a much higher distortion in comparison with the other two.
WAAM builds for high-throughput experiments

Side view

Front view

Cone build showed heavy distortion in the middle in comparison with the circumference
High-throughput experiment (ongoing)

Gradient temperature furnace heat treatment
- Bars in B (3 bars): (13,14,15) Study of Aging time in the graded furnace with varying temperature at different times
- Uniform temperature heat treatment
  - Bar in A (1 bar): (16) Applying the traditional heat treatment to show the heterogeneity
  - Bar in C (1 bar): (17) Applying the optimized heat treatment to show the homogeneity
## Databank collection for location specific microstructural analysis

<table>
<thead>
<tr>
<th>Location</th>
<th>Printing Parameters</th>
<th>Composition Variation [wt.%]</th>
<th>Experimental Variables</th>
<th>Modeling Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Height (Z):</strong> Top</td>
<td>Printing Pattern</td>
<td>Ni, Co</td>
<td>Phase fraction &amp; composition</td>
<td>Phase fraction &amp; composition</td>
</tr>
<tr>
<td>Middle</td>
<td>Voltage/Current Pulse Power</td>
<td>Ti, Al</td>
<td>Precipitate size</td>
<td>Precipitate size</td>
</tr>
<tr>
<td>Bottom</td>
<td>Layer Thickness Interlayer temperature</td>
<td>Nb, Cr, Mo</td>
<td>Grain Size &amp; morphology</td>
<td>Grain Size &amp; morphology</td>
</tr>
<tr>
<td><strong>Radius (±R):</strong> Left</td>
<td>Interlayer Idle time</td>
<td>C, B</td>
<td>Dislocation Density</td>
<td>Dislocation Density</td>
</tr>
<tr>
<td>Center</td>
<td>Wire Feed Rate Torch Traveling Speed &amp; Working Distance Shielding Gas</td>
<td>Fe, Mn, Si</td>
<td>Residual Stresses</td>
<td>Residual Stresses</td>
</tr>
<tr>
<td>Right</td>
<td></td>
<td></td>
<td>Texture</td>
<td>Texture</td>
</tr>
</tbody>
</table>

**Input for ICME/ML models**
Planned studies in this project

Identify an approach to introduce more uniform structure-property correlations in large prints.

Can we identify a good approach to post-heat treat the sample minimizing anisotropic structure-property relationship?

Yes

Can we apply this to other types of geometry?

---

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT WAAM sample with gradient temperature and processing parameter</td>
<td>Complex geometry build for location specific ICME design</td>
</tr>
</tbody>
</table>

Cone shape
Dissemination

Published research paper

Manuscript under development

Conference presentations and invited seminars
- “Materials Genome, ICME, and Additive Manufacturing”, AM Seminar Series, Virtual, National Institute of Standard and Technology, Jan. 20, 2022
Disclaimer: "This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

Acknowledgment: "This material is based upon work supported by the Department of Energy Award Number UCFER RFP 2020-06 / DE-FE0026825."