Microstructure and Properties of Hastelloy X Fabricated by Additive Manufacturing

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Project Objectives

• Optimize additive manufacturing (AM) fabrication processes for solution strengthened Hastelloy X (HX, Ni-22Cr-19Fe-9Mo) gas turbine components (Fuel injector, Combustor)

• Effect of annealing / HIP’ing on microstructure and mechanical properties of parts fabricated by Selective Laser (SLM) and Electron Beam Melting (EBM)

• Generate data for AM Hastelloy alloy (Tensile, Fatigue, Creep, Oxidation) relevant for Fossil Energy (FE) applications

• Compare properties along and perpendicular to the build direction
HX Made by EBM and SLM

Ebeam (Arcam S12)

Faster
Heated bed = lower residual stress

Smaller beam size
Better resolution
Pulsed laser beam

Laser (Renishaw AM250)
Fabrication of EBM and SLM Rods & Plates For Tensile, Creep, Fatigue and Oxidation Testing

Initial specimen surface removed by machining
### Similar Composition For EBM, SLM and Wrought HX Except for Si & Mn

Hastelloy X (Ni-22Cr-19Fe-9Mo)

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>Mo</th>
<th>Co</th>
<th>Mn</th>
<th>Si</th>
<th>W</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBM Alloy</td>
<td>Bal.</td>
<td>21.38</td>
<td>18.55</td>
<td>9.05</td>
<td>1.55</td>
<td>0.01</td>
<td>0.05</td>
<td>0.64</td>
<td>0.078</td>
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<tr>
<td>EBM(Si,Mn) Alloy</td>
<td>Bal.</td>
<td>21.43</td>
<td>18.87</td>
<td>9</td>
<td>1.56</td>
<td>0.67</td>
<td>0.71</td>
<td>0.65</td>
<td>0.048</td>
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<tr>
<td>SLM-1 Powder</td>
<td>Bal.</td>
<td>21.47</td>
<td>18.83</td>
<td>8.96</td>
<td>1.51</td>
<td>0.01</td>
<td>0.16</td>
<td>0.63</td>
<td>0.07</td>
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<tr>
<td>SLM-2 Powder</td>
<td>Bal.</td>
<td>21.72</td>
<td>18.51</td>
<td>8.87</td>
<td>1.51</td>
<td>0.01</td>
<td>0.06</td>
<td>0.6</td>
<td>0.08</td>
</tr>
<tr>
<td>Wrought</td>
<td>Bal.</td>
<td>22.06</td>
<td>17.86</td>
<td>9.53</td>
<td>1.8</td>
<td>0.65</td>
<td>0.31</td>
<td>0.6</td>
<td>0.067</td>
</tr>
</tbody>
</table>

- Alloy composition consistent with EBM powder composition
- High concentration of Mn and Si in EBM(Si,Mn) and wrought HX
- Specification: Mn and Si <1%
EBM: Textured & Elongated Grains

Perpendicular to build direction

Large defects
~1mm from edge

Along the build direction

Fabrication of contour first

Edge

Center

5mm

500µm

500 µm
Elongated Grain Along the Build Direction & Greater Number of Precipitates for EBM (Si,Mn)

EBM(Si,Mn) = Larger grains (Mo, Si)-rich Carbides

EBM = Larger voids Mo and (Cr, Mo)-rich carbides
Both EBM & EBM (Si,Mn) HX Alloys Exhibit Good Ductility Along BD But Lower Strength < 800°C

Meet cast HX AMS requirement
Lower Strength for EBM & EBM(Si,Mn) HX Alloys
Due to Elongated Grains + Weak Grain Boundary Interface
EBM & EBM(Si,Mn): Good Low-Cycle Fatigue Properties at 800°F/425°C Along the Build Direction

- Crack initiation at interface, not defects
EBM & EBM (Si,Mn) = Lower Creep Strength at 750 and 816ºC but High Ductility

Wrought expected lifetime:
- 160MPa: 100h
- 110MPa: 1000h
EBM HX Alloys: Decrease of UTS & Elongation in the Transverse Direction

**Graph 1:**
- **Y-axis:** Stress (MPa)
- **X-axis:** Strain (%)
- **Curves:** Longitudinal and Transverse
- **Label:** 20°C, EBM

**Graph 2:**
- **Y-axis:** Elongation (%)
- **X-axis:** Temperature (°C)
- **Curves:** EBM Longitudinal, EBM Transverse, Cast HX Min requirement

**Graph 3:**
- **Y-axis:** UTS (MPa)
- **X-axis:** Temperature (°C)
- **Curves:** EBM Longitudinal, EBM Transverse, Cast HX Min requirement

**Image:**
- 1mm scale bar
HIP’ing at 1177°C/2h/150MPa, “Fast Cooling”

EBM Fully dense, Fewer precipitates  EBM(Si,Mn) Micro voids+precipitates at GB

HIP’ed 2h/1177°C/150MPa

Local recrystallization

Voids & precipitates

EBM Fully dense, Fewer precipitates  EBM(Si,Mn) Micro voids+precipitates at GB

HIP’ed 2h/1177°C/150MPa

Local recrystallization

Voids & precipitates
Significant Improvement of Tensile Properties after Hip’ing Perpendicular to the BD
Improvement of the Creep Properties After Hip’ing for EBM but not for EBM(Si,Mn). Lower Creep Properties Perpendicular to the Build Direction

Wrought expected lifetime:
- 160MPa: 100h
- 110MPa: 1000h
SLM: Small Elongated Grains, No Precipitate, Hot Tearing Cracks

Typical of SLM microstructure
Could further optimize the SLM parameters
SLM HX Exhibits High Strength but Moderate to low Ductility, Above all at $T > 600^\circ$C for SLM-2
SLM 2: Low Ductility Perpendicular to The Build Direction Due to The Presence of Cracks

Local defects of effect of temperature?
SLM: Very Low Creep Rate and Good Lifetime but Limited Ductility. Significant Decrease of Lifetime for SLM-2 Perpendicular to the Build Direction.
SLM-1: Fully Dense Material After HIP’ing at 1177°C/2h/150MPa + Recrystallization
SLM: Fully Dense Material After HIP’ing at 1177°C/2h/150MPa + Recrystallization
Significant Void Formation in EBM & EBM(Si,Mn) Alloys Related to Mo-rich Precipitates

- Cr consumption leads to gradient of Cr concentration at the surface and destabilization of carbides
- Void formation is directly related to carbide disappearance
SLM: Very good oxidation behavior. Thicker Scale For The As-Fab Surface

- Higher Mass Gains Only For the first 1000h & related to higher roughness
- Surface roughness could be optimized
Fabrication and Characterization of Hastelloy X EBM and SLM Components

Determination of optimum print strategies
Conclusion

- EBM HX shows great ductility, acceptable tensile strength, great LCF performance but limited creep strength
- Low EBM tensile properties perpendicular to the BD can be improved by HIP’ing. HIP’ing can also improve creep resistance
- SLM HX exhibited good tensile and creep strength but limited ductility along the B.D. Low Creep strength & ductility perpendicular to the BD.
- HIP’ing of SLM HX removed hot tearing Cracks & led to recrystallization
- Hip’ing resulted in isotropic creep behavior for SLM HX similar to wrought HX