Optimization of Heat Treatment for Ti-6Al-4V Produced by Directed Energy Deposition

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Presentation Plan

- Brief Introduction to Directed Energy Deposition Additive Manufacturing
- Objectives of the project
- Materials and methods
- Results and Discussion
- Conclusion
DED Technology

- High energy source (Laser, EB, arc plasma)
- Powder or wire Feedstock
- Inert Atmosphere (Ti, Al)
- Multiple crucial parameters
  - Laser Power, Spot size, Travel Speed, etc...
- Limited geometry due to lack of support structure
- Allows repairs
- Multiple Powder Feeders
- Functionally graded materials
Context

- Successful repair of cast part with low distortion;
- However, YS is too low following AMS 4999a.
Objective

- To optimize the heat treatment process for Ti-6Al-4V by DED produced parts
Second Objectives

- Evaluate if HIP is necessary;
- Considering the rapid cooling rate of DED, can martensite conversion/aging be used as the unique heat treatment to optimize mechanical properties
Materials and Methods

- LENS 450XL from Optomec;
- 100 x 255 x 170 mm (Y-X-Z);
- 4 Powder feeders;
Materials and Methods

- Plasma atomised Ti-6Al-4V powder (Grade 5, Grade 23)
- Particle distribution
  - +45/-150 µm

<table>
<thead>
<tr>
<th>Powder</th>
<th>Grade</th>
<th>Al</th>
<th>V</th>
<th>Fe</th>
<th>C</th>
<th>O</th>
<th>N</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%wt</td>
<td>5</td>
<td>6.38</td>
<td>3.98</td>
<td>0.195</td>
<td>0.007</td>
<td>0.135</td>
<td>0.012</td>
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<tr>
<td></td>
<td></td>
<td>23</td>
<td>6.32</td>
<td>4.05</td>
<td>0.124</td>
<td>0.011</td>
<td>0.073</td>
<td>0.011</td>
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</tbody>
</table>
# Materials and Methods: Deposition Parameters

<table>
<thead>
<tr>
<th>DED Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzles/part distance</td>
<td>8.9 mm</td>
</tr>
<tr>
<td>Laser power</td>
<td>542 W</td>
</tr>
<tr>
<td>Travel speed</td>
<td>16.93 mm/s (40′′/min)</td>
</tr>
<tr>
<td>Powder feedrate</td>
<td>4.0 rpm</td>
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<tr>
<td>Layer thickness</td>
<td>0.46 mm (0.018′′)</td>
</tr>
<tr>
<td>Hatch spacing</td>
<td>0.61 mm (0.024′′)</td>
</tr>
<tr>
<td>Hatch shrink</td>
<td>0.30 mm (0.012′′)</td>
</tr>
<tr>
<td>Deposition strategy</td>
<td>45°, 90° and 135°</td>
</tr>
</tbody>
</table>
### Materials and Methods: Heat Treatment

#### AMS 4999a
- **HIP 900°C**
  - (900°C - 2h - >100 MPa)
- **HIP + Anneal**
  - (900°C - 2h - >100 MPa and 915°C - 2h)
- **HIP + Anneal + Age**
  - (900°C - 2h - >100 MPa and 915°C - 2h – Argon Quench and 538°C – 4h)

#### AMS 2801B
- **Anneal**
  - (704°C – 2h)
- **HIP + Anneal**
  - (900°C - 2h - >100 MPa and 704°C - 2h)
- **HIP + STA**
  - (900°C - 2h - >100 MPa and 948°C - 2h – Water Quench and 482°C – 8h30)
- **HIP + STOA**
  - (900°C - 2h - >100 MPa and 948°C - 2h – Water Quench and 704°C – 4h30)

#### Various HT
- **Anneal 2h**
  - (900°C – 2h, 4999a)
- **Anneal 4h**
  - (900°C – 4h, 4999a)
- **HIP 704°C**
  - (704°C - 2h - >100 MPa)

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All samples have been stress relieved first! (593°C – 2h)

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## Density

<table>
<thead>
<tr>
<th>Heat Treatment</th>
<th>Density (%)</th>
<th>Archimedes' principle</th>
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</thead>
<tbody>
<tr>
<td>Stress Relief</td>
<td>&gt; 99.9</td>
<td>&gt; 99.9</td>
</tr>
<tr>
<td>Anneal 2h 704°C</td>
<td>&gt; 99.9</td>
<td>&gt; 99.9</td>
</tr>
<tr>
<td>HIP</td>
<td>&gt; 99.9</td>
<td>&gt; 99.9</td>
</tr>
</tbody>
</table>
AMS 4999a

<table>
<thead>
<tr>
<th>Treatment</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>El. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anneal 2h - Gr. 5 - AMS 4999A</td>
<td>738</td>
<td>980</td>
<td>14.5</td>
</tr>
<tr>
<td>Anneal 4h - Gr. 5 - AMS 4999A</td>
<td>854</td>
<td>988</td>
<td>16.1</td>
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<tr>
<td>HIP - Gr. 5 - AMS 4999A</td>
<td>928</td>
<td>1015</td>
<td>15.9</td>
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<tr>
<td>HIP + Anneal - Gr. 5 - AMS 4999A</td>
<td>868</td>
<td>975</td>
<td>18.6</td>
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<tr>
<td>HIP + Anneal + Age - Gr. 5 - AMS 4999A</td>
<td>901</td>
<td>996</td>
<td>18.2</td>
</tr>
<tr>
<td>ASTM B367</td>
<td>825</td>
<td>895</td>
<td>6</td>
</tr>
<tr>
<td>AMS 4999A</td>
<td>799</td>
<td>889</td>
<td>6</td>
</tr>
</tbody>
</table>
AMS 4999a
AMS 4999a

Anneal 2h – Gr.23

HIP 2h – Gr.23
AMS 2801B

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AMS 2801B

Anneal 2h 704°C – Gr.23

HIP 2h 704°C – Gr.23

HIP (900°C) +STOA – Gr.23
AMS 2801B

Anneal 2h 704°C– Gr.5

HIP + Anneal + Age – Gr.5 – AMS 4999a

HIP + Anneal 2h 704°C– Gr.5
Optimized Heat Treatments

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### Optimized Heat Treatments

- **Optimized Heat Treatments**

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield Strength (MPa)</th>
<th>UTS (MPa)</th>
<th>El. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anneal 2h - Gr. 23 - AMS 2801B</td>
<td>877</td>
<td>1042</td>
<td>11.3</td>
</tr>
<tr>
<td>HIP 704°C 2h - Gr. 23</td>
<td>978</td>
<td>1051</td>
<td>9.3</td>
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<tr>
<td>HIP - Gr. 23 - AMS 4999A</td>
<td>847</td>
<td>947</td>
<td>16.5</td>
</tr>
<tr>
<td>HIP + Anneal + Age - Gr. 23 - AMS 4999A</td>
<td>828</td>
<td>936</td>
<td>18.6</td>
</tr>
<tr>
<td>HIP + Anneal - Gr. 23 - AMS 2801B</td>
<td>872</td>
<td>953</td>
<td>16.6</td>
</tr>
<tr>
<td>HIP + STOA - Gr. 23 - AMS 2801B</td>
<td>891</td>
<td>994</td>
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Conclusion

- As built process results in fully dense parts (>99.9%);
- Every HT that includes Anneal at 900°C (AMS 4999a) results in low strength for Gr.23;
- Every HT that includes low temperature martensite conversion (SR or STA) results in low ductility for Gr. 5;
Conclusion

- Highest YS and UTS obtained with HT at 704°C (HIP 704°C or Anneal 704°C);
- HIP + STOA (AMS 2801B) provides with high YS and UTS but requires many steps;
- HIP (4999a) and HIP + Anneal (2801B) are the HT conditions that provides the best combination of strength and high elongation.
Conclusion

- HIP is not necessary for densification or increase in elongation;
  - However, it provides an increase in strength;
- Martensite conversion can be used as unique HT to obtain highest strength.
Questions?