Part-scale finite element thermo-mechanical modelling and validation of selective laser melting of Ti6Al4V

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AM process

- Layer by layer

- Advantages
  - Short manufacturing time
  - Low material waste
  - Capable of complex geometries

- L-PBF or SLM
  - Laser-based Powder Bed Fusion
  - Selective Laser Melting

- Common material
  - IN718, Ti6Al4V, SS 316L

- Application
  - Aerospace
  - Automotive
  - Medical

SLM machine

• Main two steps
  • Powder-laying
  • Laser scanning

• Main components
  • Powder table
  • Build table
  • Coating mechanism
  • F-Ø lens
  • Laser
Typical defects

- Lack-of-fusion voids
- Surface instabilities
- Keyhole porosity
- Deflection
- Crack

Modelling of Metal AM

- Calibrated numerical model
  - Prediction of part deflection/quality

- Major challenges
  - Multi-physics
  - Fluid dynamics
  - Metallurgical evolution
  - Heat transfer
  - Solid mechanics

- Multi-scale
  - Micro-scale: < 500 µm
  - Meso-scale: ≈ 1-3 mm
  - Part-scale: > 1 cm

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SLM process modelling

Process steps

- Powder handling
- SLM process
- Heat treatment
- Cutting from base plate
- Support removal
- Post processing
- Blowing/cleaning
- Surface finishing
- Quality control
State-of-the-art

- Existing thermo-mechanical models

1. **Inherent strain method**
   - A-priori experimental measurements are required
   - High-fidelity modelling required (alternative)
   - No information regarding thermal conditions

2. **Agglomerated laser model**
   - Extremely heavy
   - Realistic stress/strain fields

3. **Flash heating method**
   - Relatively fast
   - Insensitive to laser scanning pattern
Case study

Alloy: Ti6Al4V
Scan speed: 800 mm.s^{-1}
Laser power: 120 W
Size: 3.00 cm by 3.00 cm by 1.00 mm
Support height: 3.00 mm

Hatch size: 80 µm

E.D.M
Experimental measurements

- Optical 3D-scanning
- Fringe projection technique
Deflection map

- STL file compared with nominal CAD file
- Done in GOM Inspect
Geometry and model

- Fully coupled thermo-mechanical model
- Developed in Abaqus-CAE
Part-scale model (1 of 3)

- Heat transfer

\[ \rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) - \rho \cdot \Delta H_{sl} \cdot \frac{\partial f_{liq}}{\partial t} + \dot{Q}'''' \]

- Phase change - solidification

\[ f_{liq} = \begin{cases} 1 & T \geq T_{liq} \\ \frac{T - T_{sol}}{T_{liq} - T_{sol}} & T_{sol} < T < T_{liq} \\ 0 & T \leq T_{sol} \end{cases} \]

**Latent heat of fusion**

\[ k = f_{sol} k_{sol} + f_{liq} k_{liq} \]

**Mass-averaged**

\[ C_p = \frac{\rho_{sol} \cdot C_{p,sol} \cdot f_{liq} + \rho_{liq} \cdot C_{p,liq} \cdot f_{liq}}{\rho_{sol} \cdot f_{liq} + \rho_{liq} \cdot f_{liq}} \]

\[ \rho = f_{sol} \cdot \rho_{sol} + f_{liq} \cdot \rho_{liq} \]

**Linear relationship**

(suitable for thermo-mechanical model)

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solidus temperature</td>
<td>( T_{sol} )</td>
<td>1620</td>
<td>(K)</td>
</tr>
<tr>
<td>Liquidus temperature</td>
<td>( T_{liq} )</td>
<td>1653</td>
<td>(K)</td>
</tr>
<tr>
<td>Solid specific heat capacity</td>
<td>( C_{ps} )</td>
<td>543</td>
<td>(J.kg(^{-1}).K(^{-1}))</td>
</tr>
<tr>
<td>Liquid specific heat capacity</td>
<td>( C_{pl} )</td>
<td>750</td>
<td>(J.kg(^{-1}).K(^{-1}))</td>
</tr>
<tr>
<td>Solid thermal conductivity</td>
<td>( k_s )</td>
<td>13</td>
<td>(W.m(^{-1}).K(^{-1}))</td>
</tr>
<tr>
<td>Liquid thermal conductivity</td>
<td>( k_l )</td>
<td>33</td>
<td>(W.m(^{-1}).K(^{-1}))</td>
</tr>
<tr>
<td>Latent heat of fusion</td>
<td>( \Delta H_{fl} )</td>
<td>280000</td>
<td>(J.kg(^{-1}))</td>
</tr>
<tr>
<td>Laser absorption coefficient</td>
<td>( \alpha )</td>
<td>0.3</td>
<td>(-)</td>
</tr>
</tbody>
</table>

Part-scale model (2 of 3)

• **Flash heating method (F.H.)**
  
  • Total input energy is the same
  
  • Total melt zone is equal

\[
\begin{align*}
t_{\text{total}} &= \frac{L_x \cdot L_y}{v} \\
E_\delta &= \alpha \cdot P \cdot t_{\text{total}} \\
E_\Delta &= E_\delta \cdot \frac{\Delta}{\delta} \\
\dot{Q}'' &= \frac{E_\Delta}{\forall_\Delta \cdot \Delta t_{\text{cont}}} = \frac{\alpha \cdot P}{v \cdot h \cdot \Delta t_{\text{cont}} \cdot \delta}
\end{align*}
\]
Part-scale model (3 of 3)

- Solid mechanics

\[
\sigma_{ij,j} = 0
\]
\[
\sigma_{ij} = M_{ijkl} \varepsilon_{kl}^{e}
\]
\[
M_{ijkl} = \frac{E}{1 + v} \left[ \frac{1}{2} (\delta_{ik} \delta_{jl} + \delta_{il} \delta_{jk}) + \frac{v}{1 - 2v} \delta_{ij} \delta_{kl} \right]
\]
\[
\dot{\varepsilon}_{ij}^{total} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{pl} + \dot{\varepsilon}_{ij}^{th} + \dot{\varepsilon}_{ij}^{f}
\]
\[
\dot{\varepsilon}_{ij}^{th} = \alpha (T) \cdot \delta_{ij} \cdot (T - T_{ref})
\]
\[
\dot{\varepsilon}_{ij}^{pl} = \frac{9}{4} \left[ \frac{1}{E_{tan}} - \frac{1}{E} \right] \frac{s_{kl} \sigma_{kl}}{\sigma_{e}^2} s_{ij}
\]
\[
f = \frac{3}{2} s_{ij} s_{ij} - \sigma_{e}^2
\]

- Force equilibrium

\[
\varepsilon_{mech} = \frac{\sigma_{yield}}{E} \left[ \frac{1}{n} \left( \frac{\sigma}{\sigma_{yield}} \right) ^n - \frac{1}{n} + 1 \right] \quad \sigma > \sigma_{yield}
\]

- Strain decomposition

- J2 flow theory

- Isotropic hardening

Power-law hardening

Yield strength

Temperature (˚C)

σ_{yield} (Pa)

0,0E+00 1,0E+08 2,0E+08 3,0E+08 4,0E+08 5,0E+08 6,0E+08 7,0E+08

0 250 500 750 1000 1250 1500 1750 2000 2250

2/7/2020
Temperature field (F.H. method)

- 1 meta-layer = 10 actual layer
- All exposed surface is heated
- Total 6 meta-layer (component)
Cooling step (F.H. method)

- Cooling time per component = 10 s
- Faster cooling above support zones
- High thermal gradients in vertical direction

Support underneath
Stress contour

- Tensile S11 stress at components in x direction
- Symmetrical stress field
Temperature and stress numerical results

- Maximum temperature is reached at 1.6 ms
- Until the start of solidification, the stress is very low

Melt point

[Graph showing temperature and stress over time]
Cutting and deflections

- Stress level is highly reduced
- Sample is deflected in a symmetrical manner
- Thermal effect of EDM is not included
Cutting and deflections

- Not close to the measurements
- Not sensitive to scanning pattern
Sequential F.H. (S.F.H. method)

- Each meta-layer is heated in two steps
- Total 12 components
- More representative of the scanning pattern
S.F.H. - cooling

- Each meta-layer is heated in two steps
- More representative of the scanning pattern
S.F.H – H02 and H05

- Two different hatch sizes are used
- H02 with 1.5 cm and H05 with 0.6 cm width
- S11 in H05 is much higher than S22
**S.F.H – H10 and H20**

- H10 with 3 mm and H20 with 1.5 mm width
- Continuous stress field in x-direction

<table>
<thead>
<tr>
<th></th>
<th>Longitudinal stress</th>
<th>Transverse stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 - hatches</td>
<td><img src="image1" alt="Longitudinal Stress" /></td>
<td><img src="image2" alt="Transverse Stress" /></td>
</tr>
<tr>
<td>20 - hatches</td>
<td><img src="image3" alt="Longitudinal Stress" /></td>
<td><img src="image4" alt="Transverse Stress" /></td>
</tr>
</tbody>
</table>

2/7/2020
S.F.H. – thermal cycles

- Cooling rate increases with smaller hatch widths
- Δt between two peaks decreases with smaller hatches
S.F.H. - deflections

<table>
<thead>
<tr>
<th></th>
<th>F.H.</th>
<th>S.F.H. – H02</th>
<th>S.F.H. – H05</th>
</tr>
</thead>
<tbody>
<tr>
<td>H10</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td>H20</td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>H01</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
</tr>
</tbody>
</table>

- H10 and H20 are very close to the measurements
- H01 gives a symmetrical deflection field
- More divisions lead to better agreement

2/7/2020
<table>
<thead>
<tr>
<th>Sample</th>
<th>Long bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy</td>
<td>Ti6Al4V</td>
</tr>
<tr>
<td>Scanning strategy</td>
<td>Fully uni-directional</td>
</tr>
<tr>
<td>Scan speed</td>
<td>800 mm.s⁻¹</td>
</tr>
<tr>
<td>Laser power</td>
<td>120 W</td>
</tr>
<tr>
<td>Size</td>
<td>10.00 cm * 1.00 cm * 1.00 mm</td>
</tr>
<tr>
<td>Support height</td>
<td>3.00 mm</td>
</tr>
</tbody>
</table>

![Diagram](image-url)

- Hatch size: 80 µm
Numerical model

Experimental image
Conclusion

• A FEM-based part-scale thermo-mechanical model is developed

• Sequential Flash Heating (S.F.H.) method is proposed

• Smaller hatch widths lead to more realistic deflection field

• F.H. is not sensitive to scanning pattern or sequence
Thank you for your attention