Session 8, questions 5-8
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Honeywell Aerospace

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Sigma Labs: M. Cola
SwRI: M. Enright, J. McFarland
Stratonics: J. Craig

NAS Workshop on Predictive Theoretical and Computational Approaches for Additive Manufacturing
AM Scalability, Implementation, Readiness, and Transition
October 8, 2015
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Questions to be Addressed

• (5) What measurements of quality or systems are appropriate that correlate computational and analytical methods to practical implementation?

• (6) Software architecture and data-bases for AM model development

• (7) Careful design of validation experiments for model validation, uncertainty quantification, and in situ process monitoring

• (8) Software development, integration with precision engineering, and integration into engineering work flow
Examples of DMLS Built Components at Honeywell

Various Part Complexities were Manufactured

Functional Testing Substantiations ranging from rig to engine testing
## Exploratory EOS M280 Build Condition Outcomes

<table>
<thead>
<tr>
<th>Displacement</th>
<th>Power=370W, Speed in mm/sec</th>
<th>Disp.</th>
<th>Place- ment</th>
<th>Hatch=140μ</th>
<th>Speed=880</th>
<th>Hatch=140μ</th>
<th>Speed=2200</th>
<th>Hatch=100μ</th>
<th>Speed=2250</th>
<th>Hatch=100μ</th>
<th>Speed=1230</th>
<th>Hatch=140μ</th>
<th>Speed=1320</th>
<th>Hatch=140μ</th>
<th>Speed=3780</th>
<th>Hatch=100μ</th>
<th>Speed=3080</th>
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</thead>
<tbody>
<tr>
<td>40 μm</td>
<td></td>
<td>I</td>
<td>GED=3</td>
<td>Hatch=140μ</td>
<td>Speed=880</td>
<td>Hatch=140μ</td>
<td>Speed=2200</td>
<td>Hatch=100μ</td>
<td>Speed=2250</td>
<td>Hatch=100μ</td>
<td>Speed=1230</td>
<td>Hatch=140μ</td>
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<td>Speed=3780</td>
<td>Hatch=100μ</td>
<td>Speed=3080</td>
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<tr>
<td>30 μm</td>
<td></td>
<td>II</td>
<td>GED=1.2</td>
<td>Hatch=140μ</td>
<td>Speed=880</td>
<td>Hatch=140μ</td>
<td>Speed=2200</td>
<td>Hatch=100μ</td>
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<td>Hatch=100μ</td>
<td>Speed=1230</td>
<td>Hatch=140μ</td>
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<td>Speed=3780</td>
<td>Hatch=100μ</td>
<td>Speed=3080</td>
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<tr>
<td>20 μm</td>
<td></td>
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<td>Speed=1230</td>
<td>Hatch=140μ</td>
<td>Speed=1320</td>
<td>Hatch=140μ</td>
<td>Speed=3780</td>
<td>Hatch=100μ</td>
<td>Speed=3080</td>
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<tr>
<td></td>
<td></td>
<td>IV</td>
<td>GED=2</td>
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<td>Speed=880</td>
<td>Hatch=140μ</td>
<td>Speed=2200</td>
<td>Hatch=100μ</td>
<td>Speed=2250</td>
<td>Hatch=100μ</td>
<td>Speed=1230</td>
<td>Hatch=140μ</td>
<td>Speed=1320</td>
<td>Hatch=140μ</td>
<td>Speed=3780</td>
<td>Hatch=100μ</td>
<td>Speed=3080</td>
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<tr>
<td></td>
<td></td>
<td>V</td>
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<td>Speed=1230</td>
<td>Hatch=140μ</td>
<td>Speed=1320</td>
<td>Hatch=140μ</td>
<td>Speed=3780</td>
<td>Hatch=100μ</td>
<td>Speed=3080</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VI</td>
<td>GED=1.2</td>
<td>Hatch=140μ</td>
<td>Speed=880</td>
<td>Hatch=140μ</td>
<td>Speed=2200</td>
<td>Hatch=100μ</td>
<td>Speed=2250</td>
<td>Hatch=100μ</td>
<td>Speed=1230</td>
<td>Hatch=140μ</td>
<td>Speed=1320</td>
<td>Hatch=140μ</td>
<td>Speed=3780</td>
<td>Hatch=100μ</td>
<td>Speed=3080</td>
</tr>
</tbody>
</table>

### Porosity Level

<table>
<thead>
<tr>
<th>Displacement</th>
<th>Data Range</th>
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<tbody>
<tr>
<td>40 μm</td>
<td>0.001-0.006%</td>
</tr>
<tr>
<td>30 μm</td>
<td>0.002-0.013%</td>
</tr>
<tr>
<td>20 μm</td>
<td>0.002-0.008%</td>
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</table>

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The Powder Bed Laser AM Process Inherent Residual Stresses

1D – residual stress

2D – residual stress

Position Dependent – residual stress (3D?)
Examples of Software/Database Requirements
Possible Defects Found in Powder Bed Laser AM Builds

LOF - Large powder particle
Large powder particle not melted

Liquation micro-cracking

IN718+ DMLS Powder Distribution

Surface roughness

Types of Porosity
Lack of Fusion
Gas Porosity/ KW
AM 718Plus Yield Strength Comparison

![Graph comparing yield strength for casting, DMLS, and forging processes.](image-url)
Task 2: PrintRite3D Quality Metric Analysis

Results: New pyrometers: IMPAC IGA 740-LO

Data from a single build layer

Data from single peaks

Six Quality Metrics extracted from pyrometer data:

- QM1 & 4 are related to peak temperature (C)
- QM2 & 5 are related to heating rate (C/s)
- QM3 & 6 related to cooling rate (C/s)

Quality Metric Limit
Baseline: Build 2

Quality Metric Value
For each layer (250 layers per build)

Build 1 and Build 4 used identical build parameters

New Pyrometers Provided Data Capable Of Distinguishing Differences Between The Various Build Parameters As Well As Provide Additional Voice Of The Process Information
5. What measurements of quality or systems are appropriate that correlate computational and analytical methods to practical implementation?

- Requirements are driven by Design Intent
- Manufacturing requirements and controls need to be commensurate with the design intent
- For the most part, the requirements for components tend to be:
  - Functional
  - Dimensional
    - Accuracy of the process,
    - Distortion due to the process
    - Surface finish capabilities of the process, etc.
  - Service life related
    - Failure modes
    - Material defects
    - Material microstructure / phases
    - Grain size, etc.
Computational methods must have the capability to simulate the process:

- Replicate the process, follow the laser and simulate the melting and solidification
- Deformation during the build, to predict dimensional qualities of the process
- Surface roughness, which is a function of the build layer thickness, the powder size distribution, the randomness of the powder spreading, the laser beam diameter, the hatch spacing, the laser power, etc.
Recoating of the powder layer, 2\textsuperscript{nd} Layer
Recoating a 2nd Layer: Large particles can lead to recoater blade crashes
hermal Animation and Residual Stress Model: Hatch and Stripe Model

Maximum concave curvature location sensitive to deposit directions.

First deposit at this corner for both layers.

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6. Software architecture and data-bases for AM model development

- **Software requirements**
  - **Melt pool**
    - Model the power size distribution
    - Model the powder spreading
    - Model the laser – powder interaction
    - Model the CFD – melting and solidification, heat transfer, Marangoni forces, etc.
    - Model defect generation, i.e. porosity, micro cracking
    - Model the micro scale residual stresses, at the melt pool level
  - **Structural**
    - Model the macro scale residual stresses, at the structural level
    - Deformation, at the structural level
  - **Microstructure**
    - Model the material microstructure evolution, i.e. phases, grain growth, defects
  - **Properties**
    - Yield, Ultimate, fatigue, crack growth, creep, environmental effects
- **Location and orientation specific prediction capabilities**
- **Software may be self standing or integrated, but information shared**
6. Software architecture and data-bases for AM model development

Database requirements

Material properties needed for use in the Computational models

- From room temperature to boiling point
- For non equilibrium conditions
- At very high rates

Experiments to verify the relevant physics of the process

- Laser scribing/ melting on solid
- Laser scribing/ melting on powder
- At various processing conditions
- Build simple shapes and determine deformation – 1D i.e. beams
- Build more complex – 2D i.e. plates
- Build components – 3D i.e. airfoils,
- As build microstructure characterization
- As stress relieved microstructure
- As HIPped, as Solution, as Aged microstructures
- ...

<table>
<thead>
<tr>
<th>MatProp1P</th>
<th>Mat. Prop Liquid:</th>
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<td>Mat. Prop Solid.</td>
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<tr>
<td>• Density, ρ</td>
<td>• Density, ρ</td>
</tr>
<tr>
<td>• Thermal conductivity, k</td>
<td>• Thermal conductivity, k</td>
</tr>
<tr>
<td>• Specific heat, Cp</td>
<td>• Specific heat, Cp</td>
</tr>
<tr>
<td>• absorptivity, α</td>
<td>• absorptivity, α</td>
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<tr>
<td>• Emissivity, ε</td>
<td>• Emissivity, ε</td>
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<td>• Coeff. of thermal exp., α</td>
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<td>• Young Modulus, E</td>
<td>• Young Modulus, E</td>
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<td>• Shear Modulus, G</td>
<td>• Shear Modulus, G</td>
</tr>
<tr>
<td>• Poisson’s ratio, ν</td>
<td>• Poisson’s ratio, ν</td>
</tr>
<tr>
<td>• Melting Temp, lower and higher limits per phase</td>
<td>• Melting Temp, lower and higher limits per phase</td>
</tr>
<tr>
<td>• Melting latent heat</td>
<td>• Melting latent heat</td>
</tr>
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</table>

Powder properties

- Apparent Density, ρ
- Apparent Thermal conductivity, k
- Apparent Specific heat, Cp
- Melting Temp, lower and higher limits per phase
- Melting latent heat

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δ: 30\(\mu\)m, H: 100 \(\mu\)m, \(v\): 2250 mm/s \((10.5.3)\)
Micro-Model Defect Prediction

Gas Porosity

Lack of Fusion Porosity

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Examples of Software and Experimental databases for Materials Modeling

Phase quantity prediction

Gamma Prime size prediction

Effect of Stress relief

Grain Growth and Solidification
Final Microstructure: Phase Fraction & Compositions

Final microstructure after double step aging (varying solution temperature):

<table>
<thead>
<tr>
<th>Phase Fraction</th>
<th>1750</th>
<th>1775</th>
<th>1800</th>
<th>1950</th>
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<tr>
<td>δ-Ni3Nb</td>
<td>5.93%</td>
<td>5.39%</td>
<td>4.66%</td>
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<tr>
<td>γ'-Ni3(Al,Nb,Ti)</td>
<td>3.67%</td>
<td>1.60%</td>
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<tr>
<td>γ''-Ni3(Al,Nb,Ti)</td>
<td>20.07%</td>
<td>20.85%</td>
<td>21.16%</td>
<td>22.93%</td>
</tr>
</tbody>
</table>

Solution temperature in F

Compositions (1775F solution treatment):

<table>
<thead>
<tr>
<th>Composition in at%</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>Co</th>
<th>Mo</th>
<th>Al</th>
<th>W</th>
<th>Nb</th>
<th>Ti</th>
<th>RMS</th>
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<tr>
<td>prediction</td>
<td>45.65</td>
<td>26.92</td>
<td>12.80</td>
<td>10.79</td>
<td>2.17</td>
<td>0.92</td>
<td>0.36</td>
<td>0.35</td>
<td>0.03</td>
<td>0.66</td>
</tr>
<tr>
<td>LEAP*</td>
<td>44.30</td>
<td>26.40</td>
<td>13.20</td>
<td>11.50</td>
<td>2.10</td>
<td>0.40</td>
<td>0.40</td>
<td>1.30</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>γ'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>prediction</td>
<td>70.47</td>
<td>1.13</td>
<td>1.27</td>
<td>2.88</td>
<td>0.20</td>
<td>11.91</td>
<td>0.21</td>
<td>8.48</td>
<td>3.44</td>
<td>0.37</td>
</tr>
<tr>
<td>LEAP*</td>
<td>70.69</td>
<td>0.65</td>
<td>1.27</td>
<td>3.39</td>
<td>-</td>
<td>11.28</td>
<td>-</td>
<td>8.85</td>
<td>3.19</td>
<td></td>
</tr>
</tbody>
</table>

*L. Viskari, K. Stiller, Ultramicroscopy 111(2011) 652–658

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YS Model for 718 plus

I. Solution treated material

- Assume linear superposition of strengths of primary phases

\[
\sigma_{yield} = \sigma_{yield} \left( D_{gr}; f_\gamma; f_{\gamma'}; f_\delta \right)
\]

\[
= f_\gamma \sigma^\gamma + f_{\gamma'} \sigma^{\gamma'} + f_\delta \sigma^\delta
\]

where \( f_\gamma + f_\delta + f_{\gamma'} = 1 \).

\[
\sigma^\gamma = \sigma^{HP}(D_{gr}) + \Delta \sigma^{SS}(C_i)
\]

Strengthening in \( \gamma \) matrix due to grain size and solid solution strengthening.

\[
\sigma^{\gamma'} = \sigma_0^{Ni_3Al} + \Delta \sigma^{SS}(C_i)
\]

Strengthening in primary \( \gamma' \) due to base strength of \( Ni_3Al \) and solid solution strengthening.

Strength of \( \delta \) phase extracted from YS of soln. treated material at higher temp.
YS Model for 718 plus

II. Aged material

- Includes effect of secondary $\gamma'$ precipitates.

$$\sigma_{\text{yield}} = \sigma_{\text{yield}}\left(D_{gr}; f_\gamma, f_{\gamma'p}, f_\delta, f_{\gamma's}, r; \gamma_{APB}\right)$$

$$= f_{(\gamma+\gamma's)}\sigma^{(\gamma+\gamma's)} + f_{\gamma'p}\sigma_{\gamma'p} + f_\delta\sigma_\delta$$

where

$$f_{(\gamma+\gamma's)} + f_\delta + f_{\gamma'p} = 1.$$  

$$\sigma_{\gamma'p} = \sigma_{0^{Ni_3Al}} + \sigma^{SS}(C_i)$$

$$\sigma^{(\gamma+\gamma's)} = \sigma^{HP}(D_{gr}) + \sigma^{SS}(C_i) + \sigma^{precip}(f_{\gamma's}, r; \gamma_{APB})$$

Strength of $\delta$ phase extracted from YS of soln. treated material at higher temp.

In addition to grain size and solid solution strengthening, secondary $\gamma'$ precipitates' effect on dislocation motion mechanisms contributes to strength.

$$r$$: Radius of secondary $\gamma'$ precipitates.
7. Careful design of validation experiments for model validation, uncertainty quantification, and *in situ* process monitoring

- Example Experiments Follow, prior examples also fit as examples or this question
Laser Power and Size Calibration

Camera based Beam Profiler is set to re-coater height
Beam sampled at center and each corner of platform

Laser Burn Images indicate laser beam maintains a circular shape within the build platform
0912 pyro2 segment 4 baseline 1.95 vs 0912 pyro2 segment 7 candidate 1.63

Plot QMpro; 95% Confidence

The resultant QualityMetric value for each layer …

… is compared to the critical value. Red indicates it exceeds this value.
Melt Pool Shape and Temperature “Measurement”

Low Power

High Power

Stripline Width

Fast Speed
Pyrometer Temperature Measurements

**Melt Pool Thermal Cycle, aka, instantaneous thermal cycle**

<table>
<thead>
<tr>
<th></th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT (C)</td>
<td>1,797</td>
</tr>
<tr>
<td>HR (C/s)</td>
<td>1,876,300</td>
</tr>
<tr>
<td>CR (C/s)</td>
<td>-691,340</td>
</tr>
</tbody>
</table>
Digital Camera Temperature Measurements

Peak Heating Rate: 183 °C / pixel
8.3 M °C / sec

Peak Cooling Rate: -86 °C / pixel
-3.9 M °C / sec

Conversion: spatial to temporal
- 22 microns / pixel
- 880 mm / sec
- 40 K pixels / sec

Camera calibrated to 2500 °C source
$$\delta: 20\mu m, H: 140 \mu m, v: 880 \text{ mm/s} \quad (10.4.2)$$

Model / Simulation Temperature Predictions

Top: Bead
Middle: Pool
Bottom: Pool deep

$$\Delta T_{\text{Heating}} = 5 \text{ M K/s}$$
$$\Delta T_{\text{Cooling}} = 1.5 \text{ M K/s}$$
ROM Predictions Build Optimization and Rearranging the columns

<table>
<thead>
<tr>
<th>Displacement</th>
<th>I</th>
<th>IV</th>
<th>V</th>
<th>II</th>
<th>III</th>
<th>VII</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>GED=3</td>
<td>GED=3</td>
<td>GED=2</td>
<td>GED=1.2</td>
<td>GED=1.6</td>
<td>GED=1.2</td>
<td>GED=0.7</td>
<td></td>
</tr>
<tr>
<td>Hatch=140μm</td>
<td>Hatch=100μm</td>
<td>Hatch=140μm</td>
<td>Hatch=100μm</td>
<td>Hatch=140μm</td>
<td>Hatch=100μm</td>
<td>Hatch=140μm</td>
<td></td>
</tr>
<tr>
<td>Speed = 880</td>
<td>Speed = 1230</td>
<td>Speed = 1320</td>
<td>Speed = 2200</td>
<td>Speed = 2250</td>
<td>Speed = 3080</td>
<td>Speed = 3780</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Porosity Level</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 um</td>
<td>0.001-0.006%</td>
<td>0.002-0.018%</td>
<td>0.13-0.45%</td>
<td>3.03-4.83%</td>
<td>0.03-0.42%</td>
<td>7.20-12.28%</td>
<td>30.13-30.86%</td>
</tr>
<tr>
<td>30 um</td>
<td>0.002-0.013%</td>
<td>0.01-0.02%</td>
<td>0.12-0.31%</td>
<td>2.65-3.48%</td>
<td>0.04-0.43%</td>
<td>2.59-4.79%</td>
<td>20.2-23.9%</td>
</tr>
<tr>
<td>20 um</td>
<td>0.002-0.008%</td>
<td>0.003-0.012%</td>
<td>0.05-0.56%</td>
<td>0.95-1.19%</td>
<td>0.10-0.21%</td>
<td>0.68-8.99%</td>
<td>11.1-11.6%</td>
</tr>
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**Objective:** Understand the effect of Power, Speed, and Hatch Spacing on Residual Stress.

<table>
<thead>
<tr>
<th>No</th>
<th>Power Watts</th>
<th>Hatch Spacing mm</th>
<th>Speed mm/s</th>
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<tbody>
<tr>
<td>A1</td>
<td>370</td>
<td>0.09</td>
<td>1000</td>
</tr>
<tr>
<td>A2</td>
<td>300</td>
<td>0.09</td>
<td>1000</td>
</tr>
<tr>
<td>A3</td>
<td>250</td>
<td>0.09</td>
<td>1000</td>
</tr>
<tr>
<td>A4</td>
<td>200</td>
<td>0.09</td>
<td>1000</td>
</tr>
<tr>
<td>A5</td>
<td>150</td>
<td>0.09</td>
<td>1000</td>
</tr>
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<td>A6</td>
<td>370</td>
<td>0.09</td>
<td>1250</td>
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<td>A7</td>
<td>300</td>
<td>0.09</td>
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<td>A8</td>
<td>250</td>
<td>0.09</td>
<td>1250</td>
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<td>A9</td>
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<td>0.09</td>
<td>1250</td>
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<td>0.09</td>
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**Method:** Printing 90 beams with varying power, speed, and hatch spacing. Then measuring deflections using our CMM to calculate stress.

\[
\sigma_{Max} = -EK \frac{t}{2}
\]

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**Specimens are being measured**
Deformed Beam Data: Same Build Conditions

Curvature vs Thickness

\[ y = 0.0011x^{-1.028} \]
\[ y = 0.001x^{-0.947} \]

Displacement vs. Thickness

\[ y = 0.0012x^{-1.011} \]
\[ y = 0.0011x^{-0.958} \]

\[ \sigma_{\text{Max}} = -E \kappa \frac{t}{2} \Rightarrow \kappa = \frac{-2\sigma_{\text{Max}}}{Et} \propto t^{-1} \]

\[ y = \frac{ML^2}{2EI} = \frac{EI \kappa L^2}{2EI} = \frac{\kappa L^2}{2} \propto t^{-1} \]

Plots confirm, an assumed constant max stress independent of thickness
Deformed Beam Data: Different Build Conditions

Sensitivities show speed and power are most important.

Surface plot as function of two most important variables.

Speed and Power are most important variables, not hatch spacing.
$\sigma_{true} - \varepsilon_{true}$ Curve and UTS Analysis

- Elastic modulus $E$ is determined by linear fitting of elastic part of the curve.
  
  \[ E = 470 \text{GPa} \]

- Standard power-law equation is used to calculate $K_1$ and $n$ by fitting of UTS and FS points
  \[ K_1 = 2518 \quad n = 4.21 \]

- Low-strain part of the curve is fitted by using Ramberg-Osgood model with drag stress $K$. (Manually)
  \[ K_2 = 2900 \quad m = 220 \]

- UTS is calculated by the intercept point of $\sigma - \varepsilon$ and $d\sigma/d\varepsilon - \varepsilon$ curves.
  \[ UTS = 1788 \text{MPa} \]
Residual Stress UQ Model

Identified 5 key input variables and uncertainty ranges

Generated set of 21 cases to run based on a Latin Hypercube design

Fit Sysweld residual stress results to Gaussian Process (GP) response surfaces

Used response surfaces for:
- UQ of residual stress contours (mean/stdev.)
- Sensitivity analysis at select locations
Residual Stress UQ Results – 25% Location
8. Software development, integration with precision engineering, and integration into engineering work flow

• Develop software for realm of interest

  1) High fidelity, physics-based simulations to simulate the process at the micro scale and understand differences between build conditions and between geometrical differences

  2) Computationally faster engineering simulations for component / structural simulation based on high fidelity models

Location specific material properties need to be integrated into current FE codes
ICME need to be moved over to the Analysis and Manufacturing Groups, maybe a concurrent engineering philosophy is needed.
Thank You!

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