The Air Force Research Laboratory, Additive Manufacturing (AM) Modeling Challenge Series

Challenge Problem 3: Macroscale Structure-to-Properties

Released August 2019
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General Problem Statement

Predict aspects of stress-strain curve(s) for AM material printed in different orientations and geometries and post-processed under different conditions (heat-treatment and surface machining)

- Report elastic modulus (E), yield strength ($\sigma_{ys}$), ultimate tensile strength ($\sigma_{uts}$), uniform elongation ($\varepsilon_{uts}$) and stress @ 5 strain values during hardening (1%, 2%, 4%, 8% & 16%) for each unique microstructure + environment condition
- Microstructure information (grains, void, precipitates, surface roughness) will be provided for each condition.

Fig. 1: Schematic of stress-strain curve with desired predictions
General Process Overview

- Samples were printed on an EOS M280 in 2017.
  - EOS M280 is a Laser Powder Bed Fusion system (LPBF)
- Commercially available IN625 gas atomized powder was used as stock (slide 20 for material data provided by supplier)
- Calibration and challenge articles were printed using nominal parameters
- All build plates went through a stress relief (SR) heat treatment and specific samples were put through an additional hot isostatic press (HIP) and heat treatment (HT)
- Calibration cylinders/bars and milli-tensile blanks/walls were separated from the build plate by electrical discharge machining (EDM).
- Calibration tensile bars, designed using ASTM E8 guidance, were all machined with a low-stress ground surface.
- Milli-tensile samples (challenge samples) were precision machined
  - The Z’ X’ face of the milli-tensile samples were either left ‘as- printed’ or ‘surface ground’ (low-stress ground)

Fig. 2: Photograph of a (a) full build plate, (b) milli-tensile sample blank (c) schematic of sample location in blank and (d) photograph of an example milli-tensile sample
Background Information
The nominal geometry of all items being printed is provided in a .stl file. The coordinates used in these files are described in the machine centered reference frame (X,Y,Z). The coordinate directions are consistent with those described in ISO/ASTM 52921: Z is orthogonal to the build plate, pointed upward, X is parallel to the front of the machine with positive X pointed to the right as viewed from the front of the machine. Finally, Y is orthogonal to X and Z, forming a right handed coordinate system. The origin of the coordinate system is the front, left corner of the build plate, as viewed by a user standing in front of the machine (not the center, as denoted in ISO/ASTM 52921).

Each tensile specimen also has a specimen centered coordinate system denoted as X',Y',Z'. For all specimens, X' is rotated 10 degrees in the counter-clockwise or positive sense about the Z axis from the machine centered X direction. Z' varies from being parallel to Z to being inclined 40° from Z by rotating about the X' axis. Y' is orthogonal to X' and Z', and forms a right handed set. Furthermore, Z' is parallel to the tensile axis of the specimen. Y' is parallel to the thickness direction as shown in the next slide.

All characterization images/scans provided in this document/challenge will be referenced in the tensile specimen coordinate system (i.e. X'-Y' plane or X'-Z' plane). In the file names for the raw data however, the primes have been removed, but still correspond to the tensile specimen coordinate system.

See schematic on next slide
Coordinate Systems & Sample Geometries

Tensile bar (calibration):

Milli-tensile sample:

Fig. 3: Drawings of milli-tensile and calibration tensile sample (units in mm)

Fig. 4: Schematic showing extraction of tensile samples

- Drawing of calibration tensile sample dimensions located in \Challenge3\Calibration Data\Sample Geometry Details
- Drawing of milli-tensile sample dimensions located in \Challenge3\InputData\Sample Geometry Details
- .stp files of 2 unique tensile geometries located in \Challenge3\InputData\Sample Geometry Details
Powder Chemistry

Table 1: Chemical Analysis of IN625 Powder (prior to build)

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<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
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<th>CbTa</th>
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<td></td>
<td>0.03</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.004</td>
<td>0.002</td>
<td>21.20</td>
<td>Bal</td>
<td>8.91</td>
<td>3.56</td>
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<td>0.01</td>
<td>0.05</td>
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<td>&lt;0.01</td>
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<td>Ti</td>
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<td>0.001</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>3.09</td>
<td>0.008</td>
<td>0.015</td>
<td>&lt;0.01</td>
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<td>0.02</td>
<td>0.04</td>
<td>0.001</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>2.12</td>
<td>0.005</td>
<td>0.035</td>
<td>&lt;0.02</td>
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</table>

- Chemical analysis of powder lot used for challenges
- Chemical analysis performed by powder supplier
- Gas atomized powder
- No post-build chemical analysis performed
Calibration Data
Calibration Samples

- Cylinders for calibration samples were printed and processed as described in the general process overview.
  - All cylinders were printed parallel to the build direction (θ=0)
- Tensile samples were machined from the printed calibration cylinders using ASTM E8 as guidance and the surfaces were low-stress ground.
- One cylinder from each build/post HT condition was reserved and used for material characterization.
  - Free surfaces depicted in the microstructural characterization of the calibration samples’ section of this document and referenced raw images are either from rough cuts or are as-printed surfaces.

NOTE: Calibration tensile samples were low stress ground & as-printed surface features were removed.

Fig. 5: Schematic showing locations of characterization material extracted from a calibration cylinder build and post processed with cylinders that were machined into tensile samples.
Mechanical Tests

Calibration tensile test data from calibration tensile bars AM IN625

Fig. 6: Stress-strain curves for calibration tensile bars in SR Only (black=RT, blue=ET) and SR+HIP+HT (red=RT, green=ET) conditions

Fig. 7: Fracture surface images for calibration tensile bars (A) SR Only @ RT, (B) SR Only @ ET, (C) SR+HIP+HT @ RT and (D) SR+HIP+HT @ ET

<table>
<thead>
<tr>
<th>Post Build Treatment</th>
<th>Build Angle</th>
<th>Sample Diameter [mm]</th>
<th>Test Temperature [°F]</th>
<th>Elastic Modulus [GPa]</th>
<th>0.2% Yield Strength [MPa]</th>
<th>Stress @ 1%, 2%, 4%, 8%, 16% Strain [MPa]</th>
<th>Ultimate Tensile Strength [MPa]</th>
<th>Uniform Elongation</th>
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<tbody>
<tr>
<td>SR+HIP+HT</td>
<td>0</td>
<td>15</td>
<td>75</td>
<td>210.9</td>
<td>381.8</td>
<td>420.2, 470.1, 539.6, 629.5, 748.7</td>
<td>918.2</td>
<td>0.453</td>
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<td>SR</td>
<td>0</td>
<td>15</td>
<td>75</td>
<td>197.8</td>
<td>676.7</td>
<td>697.0, 728.6, 792.2, 893.6, 998.5</td>
<td>1060.1</td>
<td>0.309</td>
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<tr>
<td>SR+HIP+HT</td>
<td>0</td>
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<td>1600</td>
<td>128.6</td>
<td>247.3</td>
<td>235.8, 217.2, 216.3, 206.1, 5.6</td>
<td>252.1</td>
<td>0.0053</td>
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<tr>
<td>SR</td>
<td>0</td>
<td>15</td>
<td>1600</td>
<td>101.0</td>
<td>228.7</td>
<td>240.8, 236.8, 227.2, 211.7, 188.4</td>
<td>242.6</td>
<td>0.01</td>
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</table>

Table 2: Extracted mechanical properties for calibration tensile bars in SR Only and SR+HIP+HT conditions at room temperature (RT) and elevated temperature (ET)

- Raw stress-strain data for calibration tensile tests located in \\
  |Challenge3\CalibrationData\MechanicalTestData
Microstructural Characterization

Fig. 8: EBSD scans of the SR+HIP+HT calibration cylinder. Each IPFZ map has a 1mm x 1mm field of view.

Fig. 9: EBSD scans of the SR Only calibration cylinder. Each IPFZ map has a 1mm x 1mm field of view.

<table>
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<tr>
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<tbody>
<tr>
<td>No</td>
<td>17.1, 15.9</td>
<td>0.49, 0.20</td>
<td>15.6, 14.1</td>
<td>0.49, 0.19</td>
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<td>Yes</td>
<td>22.5, 29.1</td>
<td>0.58, 0.18</td>
<td>18.4, 17.2</td>
<td>0.50, 0.19</td>
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Table 3: Grain statistics for cin SR+HIP+HT condition

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>15.2, 12.7</td>
<td>0.56, 0.18</td>
<td>16.1, 15.7</td>
<td>0.41, 0.20</td>
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</table>

Table 4: Grain statistics for milli-tensile sample in SR Only condition

- Tabulated grain statistics for calibration cylinder located in \Challenge3\CalibrationData\MicrostructureData
- Raw EBSD scans located in \Challenge3\CalibrationData\MicrostructureData\EBSD
- EBSD analysis pipelines are located in \Challenge3\Pipelines
Microstructural Characterization

Fig. 8: EBSD scans of the SR+HIP+HT calibration cylinder. Each IPFZ map has a 1mm x 1mm field of view

Fig. 9: EBSD scans of the SR Only calibration cylinder. Each IPFZ map has a 1mm x 1mm field of view

Table 5: Crystallographic orientation data for calibration cylinder in SR+HIP+HT condition

Table 6: Crystallographic orientation data for calibration cylinder in SR Only condition

- Discrete list of orientations can be extracted from the raw .ctf files in \Challenge3\CalibrationData\MicrostructureData\EBSD
Microstructural Characterization
Optical Microscopy

Fig. 10: OM images of SR+HIP+HT calibration cylinder.

Fig. 11: OM images of SR Only calibration cylinder

* Note: Calibration tensile bars were turned down from larger cylinders, so roughness is for standard low-stress ground surfaces *

<table>
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<tbody>
<tr>
<td>2.87, 3.79</td>
<td>0.016</td>
<td>&lt; 1</td>
<td>2.79, 2.82</td>
<td>0.0159</td>
<td>&lt; 1</td>
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Table 7: Void statistics for calibration cylinder & roughness statistics for the tensile bar in SR+HIP+HT condition

<table>
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<tbody>
<tr>
<td>1.58, 1.36</td>
<td>0.018</td>
<td>&lt; 1</td>
<td>1.65, 2.1</td>
<td>0.019</td>
<td>&lt; 1</td>
<td></td>
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</table>

Table 8: Void statistics for calibration cylinder & roughness statistics for the tensile bar in SR Only condition

- Tabulated void and surface roughness statistics located in \Challenge3\CalibrationData\MicrostructureData
- Raw OM images located in \Challenge3\CalibrationData\MicrostructureData\OM
- Analysis pipelines located in \Challenge3\Pipelines
Details of Methodology
Optical Microscopy

Fig. 12: Example of pores in an OM image with annotations showing bulk void classification and particle contrast

* Note: area shown is approx. 1/10th of area used to calculate statistics for a given sample on a given plane *

- Some samples appeared to show increased ‘fine’ voids near surface, but that is not captured in the measurement of ‘bulk’ voids *

* Raw OM images located in \Challenge3\CalibrationData\MicrostructureData\OM *
* Analysis pipelines located in \Challenge3\Pipelines *
Microstructural Characterization
Backscattered Electron Microscopy

Table 9: Precipitate statistics for calibration cylinder in SR+HIP+HT condition

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<th></th>
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<tbody>
<tr>
<td>N/A</td>
<td>0.94, 0.48</td>
<td>1.22</td>
<td>0.96, 0.53</td>
<td>1.19</td>
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</table>

Table 10: Precipitate statistics for calibration cylinder in SR Only condition

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 13: BSE images of SR+HIP+HT calibration cylinder. Each image has approximately a 600x600µm field of view.

Fig. 14: BSE images of SR Only calibration cylinder. Each image has approximately a 600x600µm field of view.

• Tabulated precipitate statistics located in \Challenge3\CalibrationData\MicrostructureData
• Raw BSE images located in \Challenge3\CalibrationData\MicrostructureData\BSE
• Analysis pipelines located in \Challenge3\Pipelines
Fig. 15: Example segmentation of precipitates in BSE images of calibration cylinder with annotations showing missed particles.

* Note: area shown is approx. 1/10th of area used to calculate statistics for a given sample on a given plane *

- Raw BSE images located in \Challenge3\CalibrationData\MicrostructureData\BSE
- Analysis pipelines located in \Challenge3\Pipelines
Input for Challenge Questions
Characterization Details

Characterization was performed on material extracted from milli-tensile blanks, adjacent to the material that was mechanically tested. Free surfaces seen in microscopy images used to characterize material are either as-printed surfaces or machined ‘rough cuts' used to extract material from the blanks. None of the free surface depicted are in the Surface Ground condition.

Fig. 16: Schematic showing locations of characterization material extracted from milli-tensile blanks showing illustrating characterization performed adjacent to milli-tensile samples.

- 2 EBSD scans performed on each orthogonal face (one at corner & on at center)
- BSE montages performed across each orthogonal face
- Optical montages performed along perimeter of each orthogonal face
- * Some samples also imaged/scanned third orthogonal face *

Characterization Details

Characterization was performed on material extracted from milli-tensile blanks, adjacent to the material that was mechanically tested. Free surfaces seen in microscopy images used to characterize material are either as-printed surfaces or machined ‘rough cuts' used to extract material from the blanks. None of the free surface depicted are in the Surface Ground condition.

Fig. 16: Schematic showing locations of characterization material extracted from milli-tensile blanks showing illustrating characterization performed adjacent to milli-tensile samples.

- 2 EBSD scans performed on each orthogonal face (one at corner & on at center)
- BSE montages performed across each orthogonal face
- Optical montages performed along perimeter of each orthogonal face
- * Some samples also imaged/scanned third orthogonal face *
Microstructural “Zones”

Near surface “zones” of microstructure appear to exist near each of 6 faces of the rectangular, printed ‘blank’, but only the +/- Y’ face are present in the gauge section of extracted samples. Grain zones appear in the SR Only samples and precipitate zones appear in the SR+HIP+HT samples.

Fig. 17: Schematic of milli-tensile sample with potential ‘zones’ annotated to display ‘pseudo-laminate’ nature of microstructure

Fig. 18: IPFX EBSD scan of SR Only sample showing apparent microstructure “zones”.

Fig. 19: BSE scan of SR+HIP+HT sample showing precipitate denuded region.
Microstructural “Zones”

Roughness makes quantifying near surfaces “zones” difficult – can’t isolate zone with single cropped region; most features are biased by intersecting cropped boundary

Some samples showed less visual evidence of presence of second, ‘columnar’ zone

Grain statistics not quantified by “zone” – all grains contributed to single family for distributions

Generally, the fine equiaxed zone $\approx 50$-$70$ $\mu$m and the ‘columnar’ zone $\approx 100$-$120$ $\mu$m

Fig. 20: IPFX EBSD scans of SR Only sample showing/not-showing apparent microstructure “zones” along with complicating roughness. Both scans are of an X'-Y' face with a 1mm x 1mm field of view.
Details of Methodology

$R_a$ measurements

Fig. 21: Example of surface segmentation and $R_a$ calculation method using BSE images. Each image has a field of view of 185µm x 105µm

* Note: length shown is approx. 1/20th of length used to calculate $R_a$ for a given sample on a given plane *

- Raw BSE images located in \Challenge3\InputData\Sample Condition\BSE
- Analysis pipelines located in \Challenge3\Pipelines
• All characterization and analysis was performed on ‘as-printed’ material, not surface ground.
• The following slides provide summary statistics and example images of material used in the challenge questions (input data).
• Note:
  • Top Rₐ is the roughness measured from the sample surface commonly referred to as top skin, the surface facing toward the +Z direction.
  • Bottom Rₐ is the roughness measured form the sample surface commonly referred to as bottom skin, the surface facing toward the -Z direction.
  • Voids and precipitates were characterized using the methodologies outlined on slides 15 and 17.

• ‘Surface ground’ (low-stress ground) samples referred to in challenge questions were over built by 500µm of total thickness and ~250µm were removed from each side during grinding. The contour scan effected material was removed and low-stress ground surface finish was produced.
### Microstructural Input Data

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<th>1mm thickness</th>
<th>5mm thickness</th>
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<tr>
<td></td>
<td>0°</td>
<td>40°</td>
</tr>
<tr>
<td><strong>X’Y’</strong></td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
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<tr>
<td><strong>Y’Z’</strong></td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
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**SR+HIP+HT**

- **Corner**
  - 1mm thickness: ![Image](image13)
  - 5mm thickness: ![Image](image14)

- **Middle**
  - 1mm thickness: ![Image](image15)
  - 5mm thickness: ![Image](image16)

**SR Only**

- **Corner**
  - 1mm thickness: ![Image](image17)
  - 5mm thickness: ![Image](image18)

- **Middle**
  - 1mm thickness: ![Image](image19)
  - 5mm thickness: ![Image](image20)

---

**Fig. 22:** EBSD Inverse Pole Figure (Z) scans for all microstructure conditions. Each image has a field of view of 1mm x 1mm.
<table>
<thead>
<tr>
<th>Location</th>
<th>View</th>
<th>Twins Merged</th>
<th>Grain Size – Mean [µm]</th>
<th>Grain Size – StdDev [µm]</th>
<th>Aspect Ratio Mean</th>
<th>Aspect Ratio StdDev</th>
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</thead>
<tbody>
<tr>
<td>corner</td>
<td>X‘Y’</td>
<td>No</td>
<td>17.292</td>
<td>14.930</td>
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<td>0.203</td>
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<tr>
<td>corner</td>
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<td>32.614</td>
<td>36.650</td>
<td>0.592</td>
<td>0.186</td>
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<td>X‘Y’</td>
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<td>X‘Z’</td>
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<td>34.743</td>
<td>43.480</td>
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<td>0.183</td>
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<table>
<thead>
<tr>
<th>X‘-Y’ Void Size [µm] μ, σ</th>
<th>X‘-Y’ Void Vf [%]</th>
<th>Top Rₐ [µm]</th>
<th>X‘-Z’ Void Size [µm] μ, σ</th>
<th>X‘-Z’ Void Vf [%]</th>
<th>Bottom Rₐ [µm]</th>
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<tr>
<td>1.17, 0.68</td>
<td>0.021</td>
<td>10.9</td>
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<td>0.02</td>
<td>8.6</td>
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<table>
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<tr>
<th>Denuded Zone Thickness [µm]</th>
<th>X‘-Y’ Precipitate Size [µm] μ, σ</th>
<th>X‘-Y’ Precipitate Vf [%]</th>
<th>X‘-Z’ Precipitate Size [µm] μ, σ</th>
<th>X‘-Z’ Precipitate Vf [%]</th>
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<tr>
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<td>1.51</td>
<td>0.95, 0.50</td>
<td>1.19</td>
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</table>

Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px. Original Data at: Challenge3\Input Data\1mm - 0deg - SR+HIP+HT\.
1mm - 40deg - SR+HIP+HT (C09)

<table>
<thead>
<tr>
<th>Location</th>
<th>View</th>
<th>Twins Merged</th>
<th>Grain Size – Mean [µm]</th>
<th>Grain Size – StdDev [µm]</th>
<th>Aspect Ratio Mean</th>
<th>Aspect Ratio StdDev</th>
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</thead>
<tbody>
<tr>
<td>corner</td>
<td>X'Y'</td>
<td>No</td>
<td>17.413</td>
<td>14.346</td>
<td>0.487</td>
<td>0.195</td>
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<td>X'Y'</td>
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<td>13.813</td>
<td>0.486</td>
<td>0.194</td>
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<td>X'Y'</td>
<td>Yes</td>
<td>25.749</td>
<td>28.279</td>
<td>0.558</td>
<td>0.186</td>
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<tr>
<td>corner</td>
<td>Y'Z'</td>
<td>No</td>
<td>16.749</td>
<td>14.521</td>
<td>0.470</td>
<td>0.200</td>
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<td>corner</td>
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<td>Yes</td>
<td>29.200</td>
<td>33.011</td>
<td>0.565</td>
<td>0.192</td>
</tr>
<tr>
<td>middle</td>
<td>Y'Z'</td>
<td>No</td>
<td>17.768</td>
<td>15.860</td>
<td>0.474</td>
<td>0.195</td>
</tr>
<tr>
<td>middle</td>
<td>Y'Z'</td>
<td>Yes</td>
<td>28.942</td>
<td>31.006</td>
<td>0.532</td>
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</table>

Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px. Original Data at: [Challenge3\Input Data\1mm - 40deg - SR+HIP+HT](#)

**X’-Y’ Void Size [µm] μ, σ**
- X’-Y’ Void Vf %
- Top Rₐ [µm]
- Y’-Z’ Void Size [µm] μ, σ
- Y’-Z’ Void Vf %
- Bottom Rₐ [µm]

<table>
<thead>
<tr>
<th>X’-Y’ Void Size [µm] μ, σ</th>
<th>X’-Y’ Void Vf %</th>
<th>Top Rₐ [µm]</th>
<th>Y’-Z’ Void Size [µm] μ, σ</th>
<th>Y’-Z’ Void Vf %</th>
<th>Bottom Rₐ [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.67, 0.82</td>
<td>0.033</td>
<td>11.8</td>
<td>1.69, 0.92</td>
<td>0.021</td>
<td>25.4</td>
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**Denuded Zone Thickness [µm]**
- X’-Y’ Precipitate Size [µm] μ, σ
- X’-Y’ Precipitate Vf
- Y’-Z’ Precipitate Size [µm] μ, σ
- Y’-Z’ Precipitate Vf

<table>
<thead>
<tr>
<th>Denuded Zone Thickness [µm]</th>
<th>X’-Y’ Precipitate Size [µm] μ, σ</th>
<th>X’-Y’ Precipitate Vf</th>
<th>Y’-Z’ Precipitate Size [µm] μ, σ</th>
<th>Y’-Z’ Precipitate Vf</th>
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</thead>
<tbody>
<tr>
<td>60</td>
<td>1.03, 0.57</td>
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<td>1.25, 0.69</td>
<td>1.72</td>
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5mm - 0deg - SR+HIP+HT   (C0B)

<table>
<thead>
<tr>
<th>Location</th>
<th>View</th>
<th>Twins Merged</th>
<th>Grain Size – Mean [µm]</th>
<th>Grain Size – StdDev [µm]</th>
<th>Aspect Ratio Mean</th>
<th>Aspect Ratio StdDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>corner</td>
<td>X'Y'</td>
<td>No</td>
<td>19.721</td>
<td>15.987</td>
<td>0.543</td>
<td>0.181</td>
</tr>
<tr>
<td>corner</td>
<td>X'Y'</td>
<td>Yes</td>
<td>25.999</td>
<td>28.554</td>
<td>0.584</td>
<td>0.162</td>
</tr>
<tr>
<td>middle</td>
<td>X'Y'</td>
<td>No</td>
<td>18.783</td>
<td>15.079</td>
<td>0.509</td>
<td>0.189</td>
</tr>
<tr>
<td>middle</td>
<td>X'Y'</td>
<td>Yes</td>
<td>36.297</td>
<td>39.262</td>
<td>0.592</td>
<td>0.182</td>
</tr>
<tr>
<td>corner</td>
<td>X'Z'</td>
<td>No</td>
<td>16.726</td>
<td>15.032</td>
<td>0.471</td>
<td>0.198</td>
</tr>
<tr>
<td>corner</td>
<td>X'Z'</td>
<td>Yes</td>
<td>26.782</td>
<td>34.689</td>
<td>0.546</td>
<td>0.179</td>
</tr>
<tr>
<td>middle</td>
<td>X'Z'</td>
<td>No</td>
<td>17.651</td>
<td>16.228</td>
<td>0.464</td>
<td>0.199</td>
</tr>
<tr>
<td>middle</td>
<td>X'Z'</td>
<td>Yes</td>
<td>34.363</td>
<td>44.660</td>
<td>0.524</td>
<td>0.184</td>
</tr>
</tbody>
</table>

X'Y' Void Size [µm] μ, σ | X'Y' Void Vf % | Top Rₐ [µm] | X'Z' Void Size [µm] μ, σ | X'Z' Void Vf % | Bottom Rₐ [µm] |
<table>
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<tr>
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</thead>
<tbody>
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Denuded Zone Thickness [µm] X'Y' Precipitate Size [µm] μ, σ | X'Y' Precipitate Vf | X'Z' Precipitate Size [µm] μ, σ | X'Z' Precipitate Vf |
<table>
<thead>
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</thead>
<tbody>
<tr>
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</table>

Corner X'Y' View Twins Merged

<table>
<thead>
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<th>Location</th>
<th>View</th>
<th>Twins Merged</th>
<th>Grain Size – Mean [µm]</th>
<th>Grain Size – StdDev [µm]</th>
<th>Aspect Ratio Mean</th>
<th>Aspect Ratio StdDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>corner</td>
<td>X'Z'</td>
<td>No</td>
<td>16.726</td>
<td>15.032</td>
<td>0.471</td>
<td>0.198</td>
</tr>
<tr>
<td>corner</td>
<td>X'Z'</td>
<td>Yes</td>
<td>26.782</td>
<td>34.689</td>
<td>0.546</td>
<td>0.179</td>
</tr>
<tr>
<td>middle</td>
<td>X'Z'</td>
<td>No</td>
<td>17.651</td>
<td>16.228</td>
<td>0.464</td>
<td>0.199</td>
</tr>
<tr>
<td>middle</td>
<td>X'Z'</td>
<td>Yes</td>
<td>34.363</td>
<td>44.660</td>
<td>0.524</td>
<td>0.184</td>
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</table>

Corner X'Z' View Twins Merged

<table>
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<th>Grain Size – StdDev [µm]</th>
<th>Aspect Ratio Mean</th>
<th>Aspect Ratio StdDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>corner</td>
<td>X'Y'</td>
<td>No</td>
<td>19.721</td>
<td>15.987</td>
<td>0.543</td>
<td>0.181</td>
</tr>
<tr>
<td>corner</td>
<td>X'Y'</td>
<td>Yes</td>
<td>25.999</td>
<td>28.554</td>
<td>0.584</td>
<td>0.162</td>
</tr>
<tr>
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<td>No</td>
<td>18.783</td>
<td>15.079</td>
<td>0.509</td>
<td>0.189</td>
</tr>
<tr>
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<td>36.297</td>
<td>39.262</td>
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<td>0.182</td>
</tr>
<tr>
<td>corner</td>
<td>X'Z'</td>
<td>No</td>
<td>16.726</td>
<td>15.032</td>
<td>0.471</td>
<td>0.198</td>
</tr>
<tr>
<td>corner</td>
<td>X'Z'</td>
<td>Yes</td>
<td>26.782</td>
<td>34.689</td>
<td>0.546</td>
<td>0.179</td>
</tr>
<tr>
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<td>0.464</td>
<td>0.199</td>
</tr>
<tr>
<td>middle</td>
<td>X'Z'</td>
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<td>44.660</td>
<td>0.524</td>
<td>0.184</td>
</tr>
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</table>

Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px. Original Data at: \Challenge3\Input Data\5mm - 0deg - SR+HIP+HT
5mm - 40deg - SR+HIP+HT (C13)

<table>
<thead>
<tr>
<th>Location</th>
<th>View</th>
<th>Twins Merged</th>
<th>Grain Size – Mean [µm]</th>
<th>Grain Size – StdDev [µm]</th>
<th>Aspect Ratio Mean</th>
<th>Aspect Ratio StdDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>corner</td>
<td>X'Y'</td>
<td>No</td>
<td>16.705</td>
<td>14.465</td>
<td>0.480</td>
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<td>Y'Z'</td>
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<td>0.183</td>
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</table>

<table>
<thead>
<tr>
<th>X'-Y' Void Size [µm]</th>
<th>X'-Y' Void Vf %</th>
<th>Top $R_a$ [µm]</th>
<th>Y'-Z’ Void Size [µm]</th>
<th>Y'-Z’ Void Vf %</th>
<th>Bottom $R_a$ [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.74, 1.97</td>
<td>0.019</td>
<td>11.3</td>
<td>1.43, 1.54</td>
<td>0.021</td>
<td>29.7</td>
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</table>

<table>
<thead>
<tr>
<th>Denuded Zone Thickness [µm]</th>
<th>X'-Y' Precipitate Size [µm]</th>
<th>X'-Y' Precipitate Vf</th>
<th>Y'-Z’ Precipitate Size [µm]</th>
<th>Y'-Z’ Precipitate Vf</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>1.01, 0.53</td>
<td>0.96</td>
<td>1.00, 0.52</td>
<td>1.13</td>
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</table>

Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: IChallenge3\Input Data\5mm - 40deg - SR+HIP+HT
### 1mm - 0deg - SR (G33)

<table>
<thead>
<tr>
<th>Location</th>
<th>View</th>
<th>Twins</th>
<th>Grain Size – Mean [µm]</th>
<th>Grain Size – StdDev [µm]</th>
<th>Aspect Ratio Mean</th>
<th>Aspect Ratio StdDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>corner</td>
<td>X'Y'</td>
<td>No</td>
<td>15.810</td>
<td>16.966</td>
<td>0.563</td>
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<tr>
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<td>X'Y'</td>
<td>No</td>
<td>16.695</td>
<td>15.529</td>
<td>0.554</td>
<td>0.175</td>
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<tr>
<td>corner</td>
<td>X'Z'</td>
<td>No</td>
<td>28.144</td>
<td>26.822</td>
<td>0.368</td>
<td>0.177</td>
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<tr>
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<td>No</td>
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<td>No</td>
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<tr>
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<td>26.460</td>
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<td>0.177</td>
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<tr>
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<td>No</td>
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<td>20.572</td>
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<td>No</td>
<td>27.828</td>
<td>24.798</td>
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<td>0.177</td>
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</table>

#### X'-Y' Void Size
- **μ, σ**: 6.02, 8.42
- **Vf %**: 0.087
- **Top R:a [µm]**: 8
- **X'-Z' Void Size [µm]**: 1.69, 1.57
- **X'-Z' Void Vf %**: 0.015
- **Bottom R:a [µm]**: 7.6

#### Denuded Zone Thickness [µm]
- **X'-Y' Precipitate Size [µm]**: N/A
- **X'-Y' Precipitate Vf**: 0
- **X'-Z' Precipitate Size [µm]**: N/A
- **X'-Z' Precipitate Vf**: 0

---

Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: iChallenge 3 Fixes\Input Data\1mm - 0deg - SR only
### 1mm - 40deg - SR  (H50)

<table>
<thead>
<tr>
<th>Location</th>
<th>View</th>
<th>Twins Merged</th>
<th>Grain Size – Mean [µm]</th>
<th>Grain Size – StdDev [µm]</th>
<th>Aspect Ratio Mean</th>
<th>Aspect Ratio StdDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>corner</td>
<td>X’Y’</td>
<td>No</td>
<td>15.623</td>
<td>15.390</td>
<td>0.522</td>
<td>0.179</td>
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<tr>
<td>middle</td>
<td>X’Y’</td>
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<td>14.544</td>
<td>13.769</td>
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<tr>
<td>corner</td>
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<td>16.397</td>
<td>16.647</td>
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<td>No</td>
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<tr>
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### X’-Y’ Void

<table>
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<th>X’-Y’ Void Size [µm]</th>
<th>X’-Y’ Void Vf %</th>
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### X’-Z’ Void

<table>
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<th>X’-Z’ Void Vf %</th>
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### Bottom Ra [µm]

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### Denuded Zone Thickness [µm]

<table>
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<tr>
<th>Denuded Zone Thickness [µm]</th>
<th>X’-Y’ Precipitate Size [µm]</th>
<th>X’-Y’ Precipitate Vf</th>
<th>X’-Z’ Precipitate Size [µm]</th>
<th>X’-Z’ Precipitate Vf</th>
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<td>N/A</td>
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<td>N/A</td>
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</tbody>
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Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.  
Original Data at: \\Challenge 3 \_Fixes\_Input Data\_1mm - 40deg - SR only
5mm - 0deg - SR (H0B)

<table>
<thead>
<tr>
<th>Location</th>
<th>View</th>
<th>Twins Merged</th>
<th>Grain Size – Mean [µm]</th>
<th>Grain Size – StdDev [µm]</th>
<th>Aspect Ratio Mean</th>
<th>Aspect Ratio StdDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>corner</td>
<td>X″Y′</td>
<td>No</td>
<td>15.328</td>
<td>12.838</td>
<td>0.559</td>
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</tr>
<tr>
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<td>X″Y′</td>
<td>No</td>
<td>16.270</td>
<td>13.939</td>
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<td>0.175</td>
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<td>X″Z′</td>
<td>No</td>
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<td>28.677</td>
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<td>0.177</td>
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<tr>
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Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: Challenge3\Input Data\5mm - 0deg - SR only
5mm - 40deg - SR (G70)

<table>
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<th>Grain Size – StdDev [µm]</th>
<th>Aspect Ratio Mean</th>
<th>Aspect Ratio StdDev</th>
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</thead>
<tbody>
<tr>
<td>corner</td>
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<td>14.235</td>
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<td>18.766</td>
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X'Y' Void Size [µm], σ
2.59, 3.56 0.036 16.2
X'Z' Void Size [µm], σ
2.66, 4.29 0.045 30.5

X'-Y' Void Vf
0
X'-Z' Void Vf
0

X'-Y' Precipitate Size [µm], σ
N/A
X'-Z' Precipitate Size [µm], σ
N/A

Denuded Zone Thickness [µm]
N/A
X'-Y' Precipitate Vf
0
X'-Z' Precipitate Vf
0

Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: [Challenge3]Input Data/5mm - 40deg - SR only
Challenge Question and Scoring
Description of Desired Predictions

- **Elastic Modulus (E):** slope of the linear fit to data points from 25 MPa to 50 MPa below the visually determined proportional limit for each sample

- **Yield Strength (σ_{YS}):** stress value at the intersection of the line with slope E and x-intercept of 0.002 with the polynomial fit (order = 2) through the data points from strain 0.002 to 0.01

- **Ultimate Tensile Strength (σ_{UTS}):** maximum of the polynomial fit (order = 2) through data points +/- 0.005 strain around the strain of the maximum stress raw data point (*note: maximum stress used should be at a significant strain value, > 0.05, not at an upper yield point if one exists)

- **Uniform Elongation (ε_{UTS}):** strain value at determined σ_{UTS}

- **Stress Profile During Hardening (σ_{1,2,4,8,16}):** stress value at each discrete strain, evaluated on the polynomial fit (order = 2) through data points +/- 0.0025 around each discrete strain

Fig. 23: Schematic of stress-strain curve with desired predictions
**Answer Format**

### As-Printed Samples

<table>
<thead>
<tr>
<th>Post Build Treatment</th>
<th>Build Angle</th>
<th>Thickness [μm]</th>
<th>Test Temperature [°F]</th>
<th>Elastic Modulus [GPa]</th>
<th>0.2% Yield Strength [Mpa]</th>
<th>Stress @ 1%, 2%, 4%, 8%, 16%** Strain [MPa]</th>
<th>Ultimate Tensile Strength [MPa]</th>
<th>Uniform Elongation</th>
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** For 1600°F results, stress @ 16% strain will not be utilized for scoring, only report stress at 1%, 2%, 4%, 8% strain

- Answer sheet template located in \Challenge3\Challenge 3Answer Template.xls
# Surface Ground (low-stress ground) Samples

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<tr>
<th>Post Build Treatment</th>
<th>Build Angle</th>
<th>Thickness [μm]</th>
<th>Test Temperature [°F]</th>
<th>Elastic Modulus [GPa]</th>
<th>0.2% Yield Strength [Mpa]</th>
<th>Stress @ 1%, 2%, 4%, 8%, 16%** Strain [MPa]</th>
<th>Ultimate Tensile Strength [MPa]</th>
<th>Uniform Elongation</th>
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</table>

** For 1600°F results, stress @ 16% strain will not be utilized for scoring, only report stress at 1%, 2%, 4% & 8% strain

- Answer sheet template located in \Challenge3\Challenge 3 AnswerTemplate.xlsx
Scoring

• Predictions for each geometry + microstructure + environment condition are worth same value

• Grades will consist of accumulating points based on accuracy of predictions. For example:
  • For Elastic Modulus (E):
    +/- 3 GPa = 9 pts;
    +/- 6 GPa = 3 pts;
    +/- 15 GPa = 1 pt
  • For 0.2% Yield Stress (\(\sigma_{YS}\)):
    +/- 10 MPa = 9 pts;
    +/- 20 MPa = 3 pts;
    +/- 40 MPa = 1 pt
  • For Stress @ Fixed Strain (x5):
    +/- 10 MPa = 7 pts;
    +/- 20 MPa = 3 pts;
    +/- 40 MPa = 1 pt
  • For Ultimate Tensile Stress (\(\sigma_{UTS}\)):
    +/- 10 MPa = 5 pts;
    +/- 20 MPa = 2 pts;
    +/- 40 MPa = 1 pt
  • For Uniform Elongation (\(\varepsilon_{UTS}\)):
    +/- 0.02 = 3 pts;
    +/- 0.04 = 2 pts;
    +/- 0.08 = 1 pt

• Scoring ranges will vary based on experimental variability and uncertainty.
• Responses must be returned within the document “Challenge 3 Answer Template.xlsx”.

**Answers returned in any other format will not be scored.**

• Answer sheet template located in \Challenge3\Challenge 3 Answer Template.xls
Supplemental Data (non-AFRL data)
Supplemental Data

Table 11: Mechanical properties of AM IN625 at select temperatures

<table>
<thead>
<tr>
<th>Test direction</th>
<th>Temperature (F)</th>
<th>Elastic Modulus (msi)</th>
<th>Yield Stress (0.2%) (ksi)</th>
<th>Ultimate Tensile Stress (ksi)</th>
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- Data not collected by AFRL and from different AM machine platform (SLM 250) with different lot of powder.
- Additional information about properties as function of strain rate and build orientation located in supplemental information document.

- Tabulated mechanical property data & plots located in \Challenge3\SupplementalData\Supplemental AM IN625 Data.pdf
Supplemental Data

- Powder size distribution measured by laser particle size analysis (Beckman Coulter LS230)
- BSE image of representative powder morphology

- Raw data for powder size analysis located in \Challenge3\CalibrationData\Powder Size.xlsx
- Powder morphology images located in \Challenge3\CalibrationData\Powder Images

Fig. 24: Powder particle size distribution after build was completed

Fig. 25: BSE image of powder particles after build was completed