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

Challenge Problem 3:

Macroscale Structure-to-Properties

Released August 2019

Integrity ★ Service ★ Excellence

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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 (σ_{ys}), ultimate tensile strength (σ_{uts}), uniform elongation (ε_{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

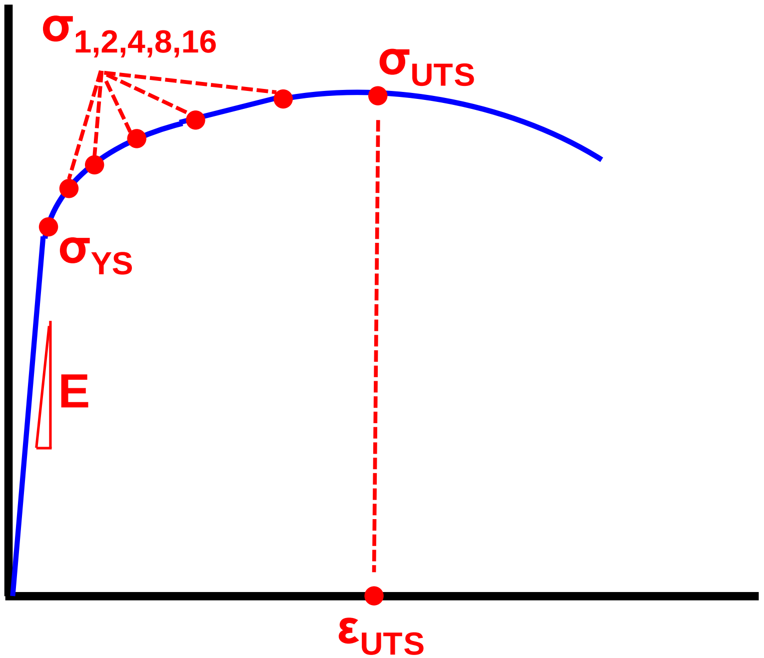


Fig. 1: Schematic of stress-strain curve with desired predictions

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 suppler)
- 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)

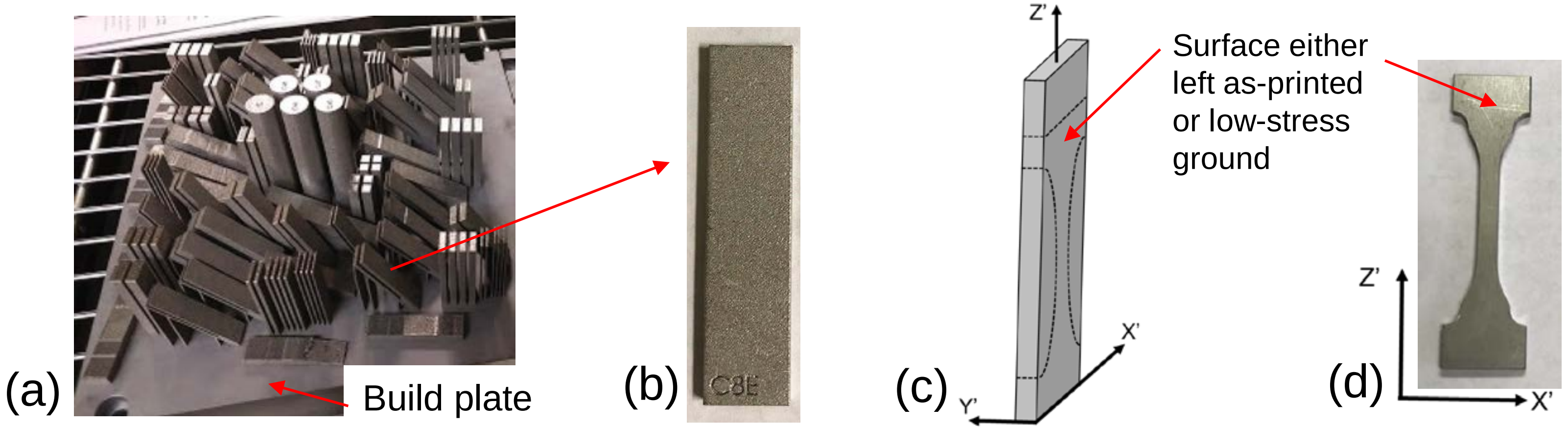


Fig. 2: Photograph of a (a) full build plate, (b) milli-tensile sample blank (c) schematic of sample location in blank and (d) photograph of an example milli-tensile sample

Background Information

Coordinate Systems

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 40º 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.

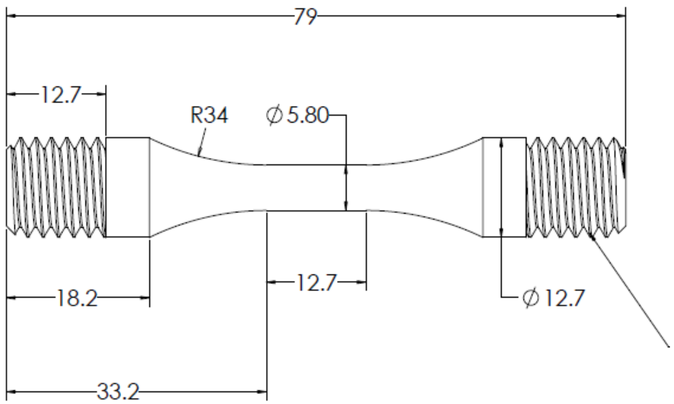
All characterization images/scans provided in this document/challenge will be referenced in the tensile specimen coordinate system (i.e. X'-Y' plane or X'-Z' plane). In the file names for the raw data however, the primes have been removed, but still correspond to the tensile specimen coordinate system.

See schematic on next slide

- Full build .stl file located in \Challenge3\Calibration Data\Build Layout Details\

Coordinate Systems & Sample Geometries

Tensile bar (calibration):



Milli-tensile sample:

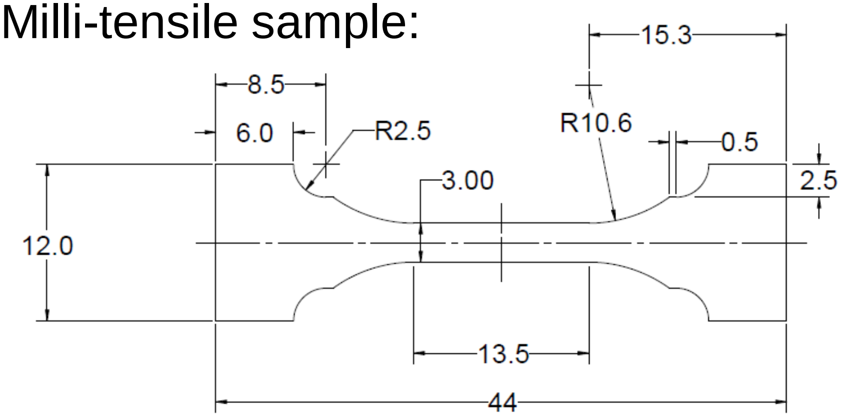


Fig. 3: Drawings of milli-tensile and calibration tensile sample (units in mm)

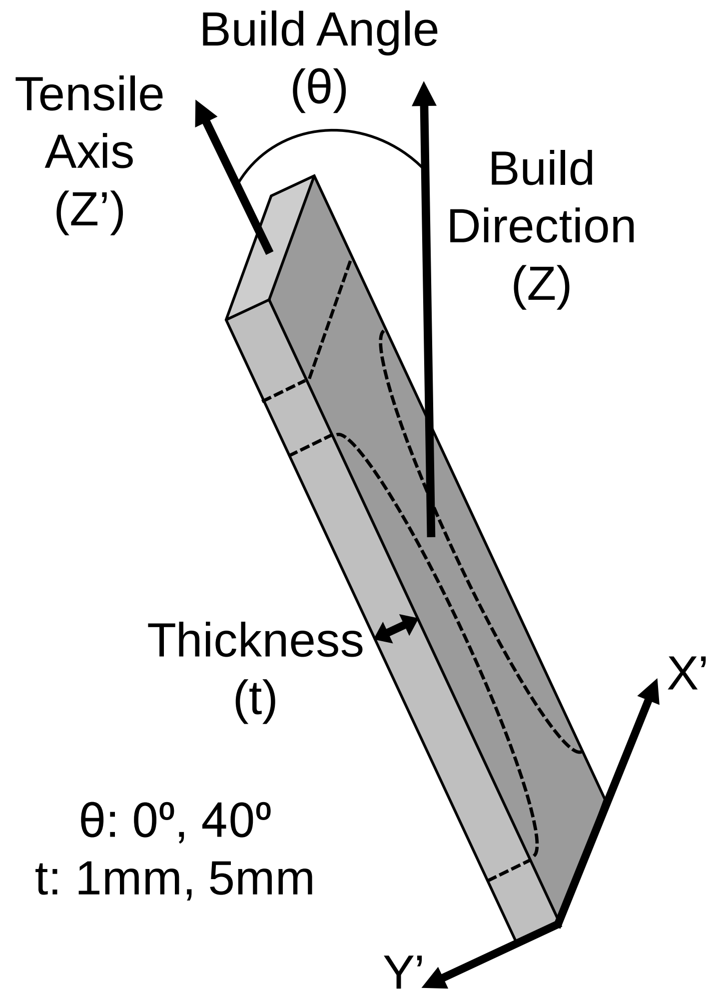


Fig. 4: Schematic showing extraction of tensile samples

- 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

Chemical Analysis (% wt)								
C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**CbTa**
0.03 0.01	<0.01 0.05	<0.01 <0.01	<0.004 <0.001	0.002 <0.01	21.20 21.69	Bal Bal	8.91 9.06	3.56 3.75
Ti	**Al**	**B**	**Co**	**Cu**	**Fe**	**N**	**O**	**Ta**
0.01 0.02	0.05 0.04	0.001 0.001	<0.01 <0.01	0.01 0.01	3.09 2.12	0.008 0.005	0.015 0.035	<0.01 <0.02
Mg								
<0.001 <0.001								

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

- 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.

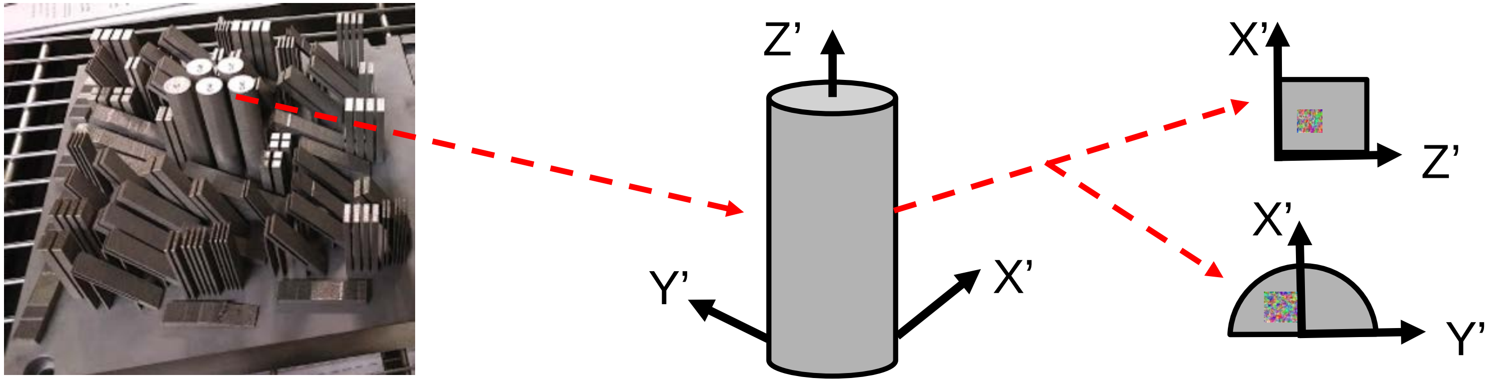


Fig. 5: Schematic showing locations of characterization material extracted from a calibration cylinder build and post processed with cylinders that were machined into tensile samples

Mechanical Tests

Calibration tensile test data from calibration tensile bars AM IN625

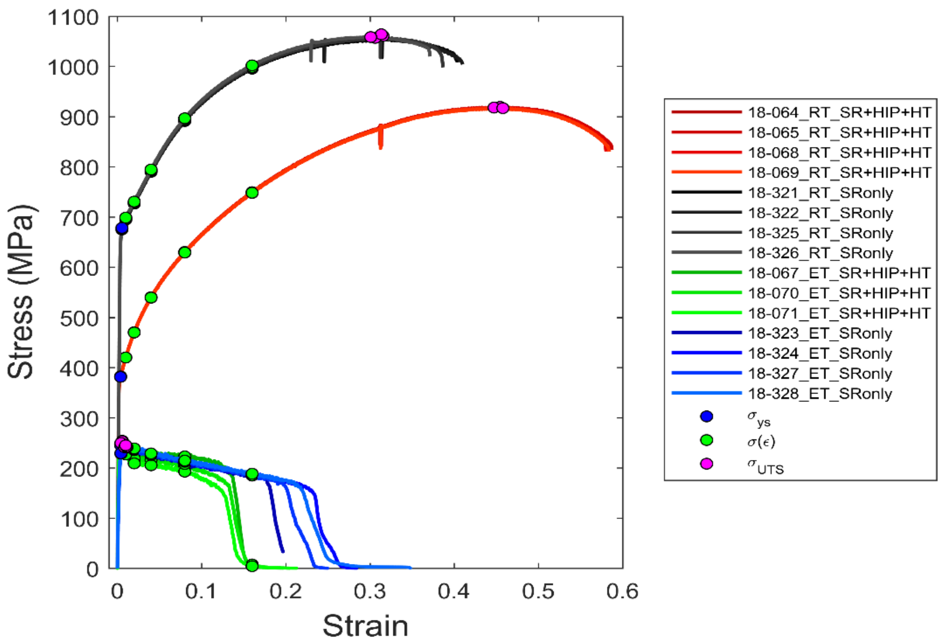


Fig. 6: Stress-strain curves for calibration tensile bars in SR Only (black=RT, blue=ET) and SR+HIP+HT (red=RT, green=ET) conditions

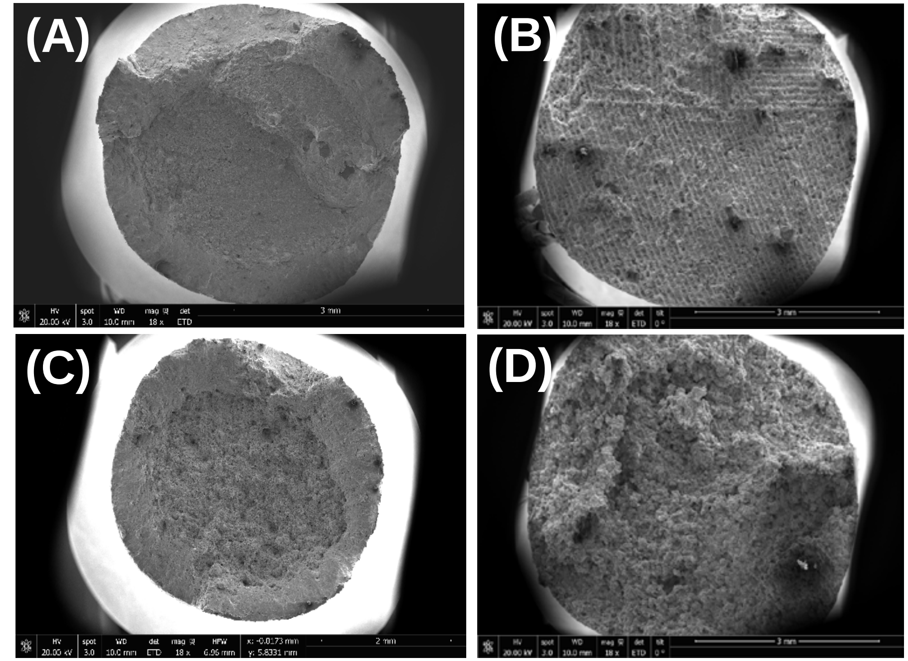


Fig. 7: Fracture surface images for calibration tensile bars (A) SR Only @ RT, (B) SR Only @ ET, (C) SR+HIP+HT @ RT and (D) SR+HIP+HT @ ET

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

Table 2: Extracted mechanical properties for calibration tensile bars 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

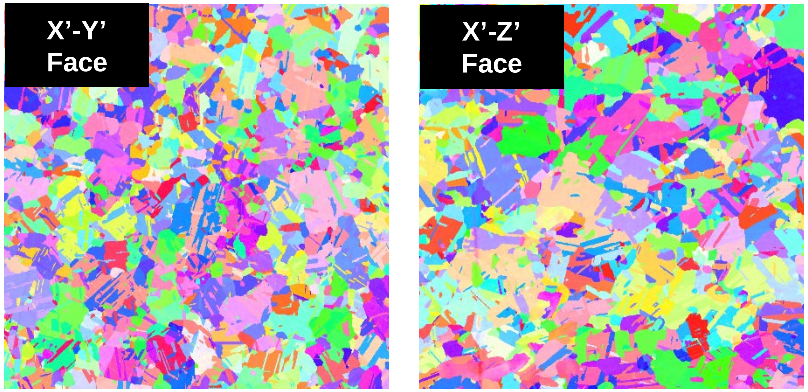


Fig. 8: EBSD scans of the SR+HIP+HT calibration cylinder. Each IPFZ map has a 1mm x 1mm field of view.

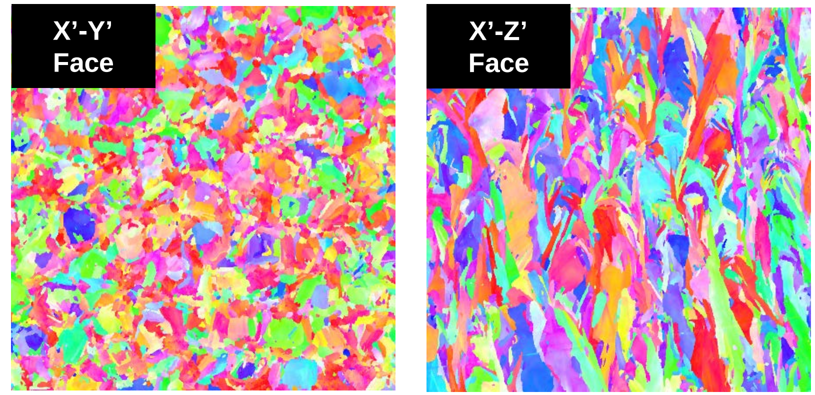
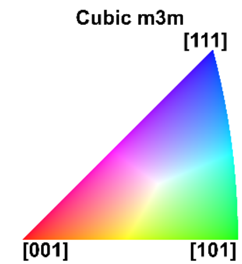


Fig. 9: EBSD scans of the SR Only calibration cylinder. Each IPFZ map has a 1mm x 1mm field of view.



SR+HIP+HT

Twins Merged	X-Y Grain Size [μm] μ, σ	X-Y Aspect Ratio [μm] μ, σ	X-Z Grain Size [μm] μ, σ	X-Z Aspect Ratio [μm] μ, σ
No	17.1, 15.9	0.49, 0.20	15.6, 14.1	0.49, 0.19
Yes	22.5, 29.1	0.58, 0.18	18.4, 17.2	0.50, 0.19

Table 3: Grain statistics for cin SR+HIP+HT condition

SR Only

X-Y Grain Size [μm] μ, σ	X-Y Aspect Ratio [μm] μ, σ	X-Z Grain Size [μm] μ, σ	X-Z Aspect Ratio [μm] μ, σ
15.2, 12.7	0.56, 0.18	16.1, 15.7	0.41, 0.20

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

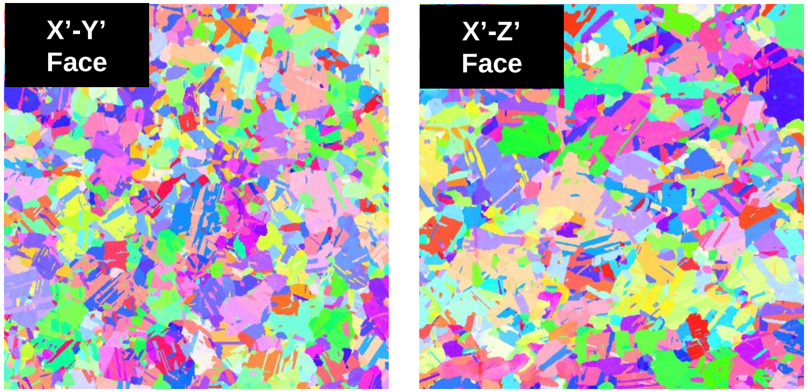


Fig. 8: EBSD scans of the SR+HIP+HT calibration cylinder. Each IPFZ map has a 1mm x 1mm field of view

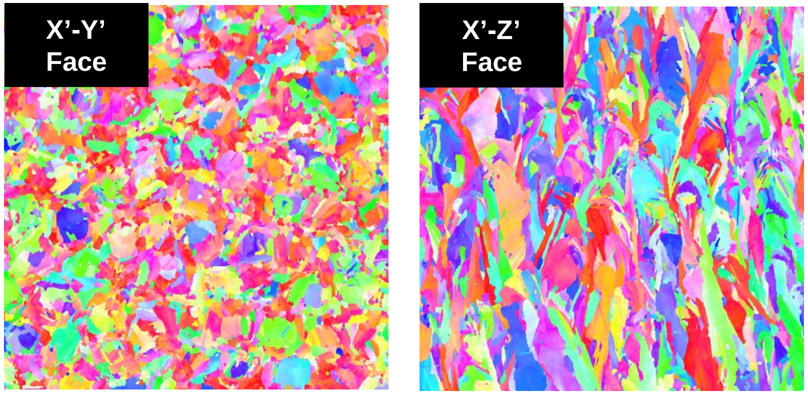


Fig. 9: EBSD scans of the SR Only calibration cylinder. Each IPFZ map has a 1mm x 1mm field of view

SR+HIP+HT

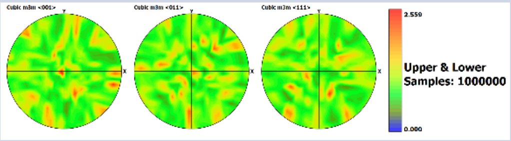
Build Angle	Thickness [µm]	Pole Figures
0	15	

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

SR Only

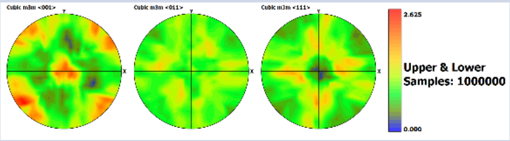
Build Angle	Thickness [µm]	Pole Figures
0	15	

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

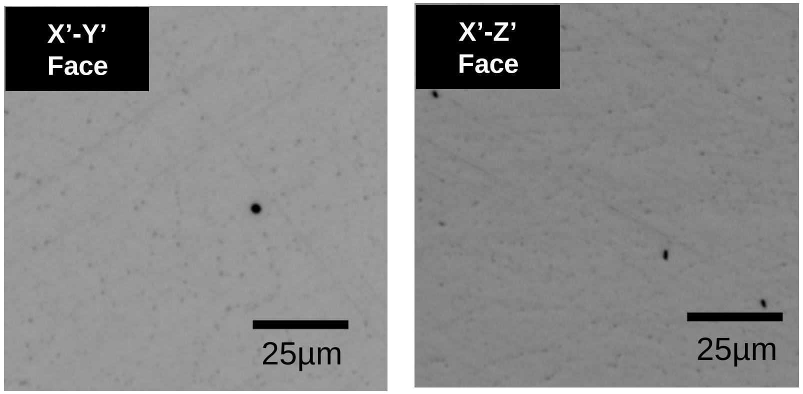


Fig. 10: OM images of SR+HIP+HT calibration cylinder.

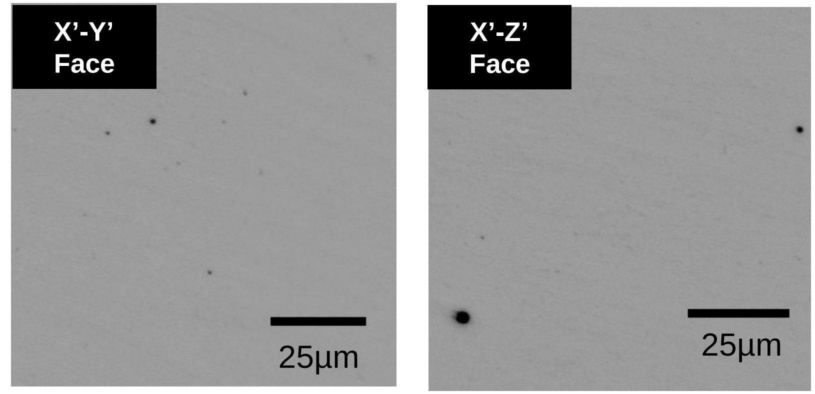


Fig. 11: OM images of SR Only calibration cylinder

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

SR+HIP+HT

X-Y Void Size [µm] µ, σ	X-Y Void V_f %	X-Y R_a [µm]	X-Z Void Size [µm] µ, σ	X-Z Void V_f %	X-Z R_a [µm]
2.87, 3.79	0.016	< 1	2.79, 2.82	0.0159	< 1

Table 7: Void statistics for calibration cylinder & roughness statistics for the tensile bar in SR+HIP+HT condition

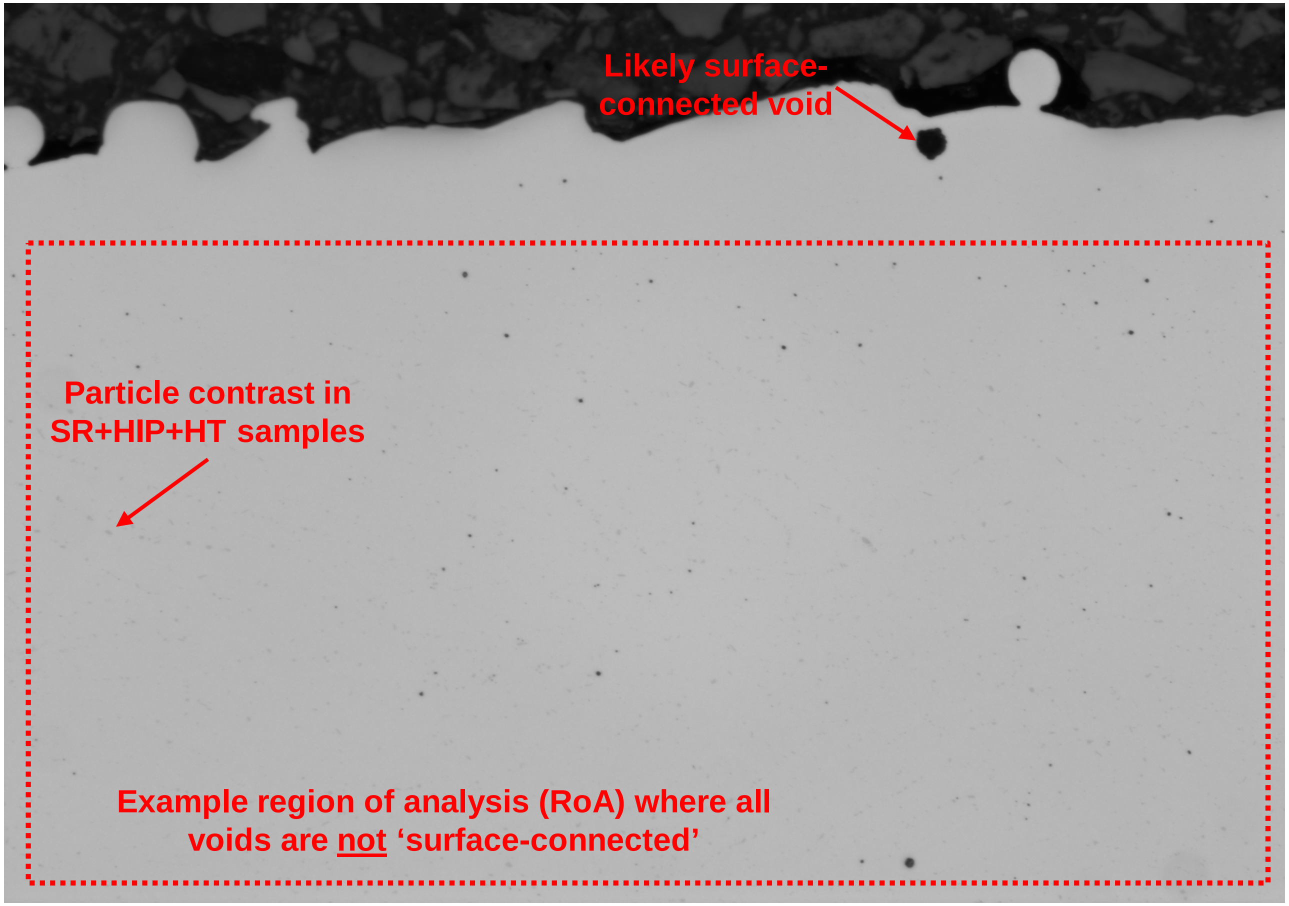
SR Only

X-Y Void Size [µm] µ, σ	X-Y Void V_f %	X-Y R_a [µm]	X-Z Void Size [µm] µ, σ	X-Z Void V_f %	X-Z R_a [µm]
1.58, 1.36	0.018	< 1	1.65, 2.1	0.019	< 1

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



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

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

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

- Raw OM images located in \Challenge3\CalibrationData\MicrostructureData\OM
- Analysis pipelines located in \Challenge3\Pipelines

Microstructural Characterization
Backscattered Electron Microscopy

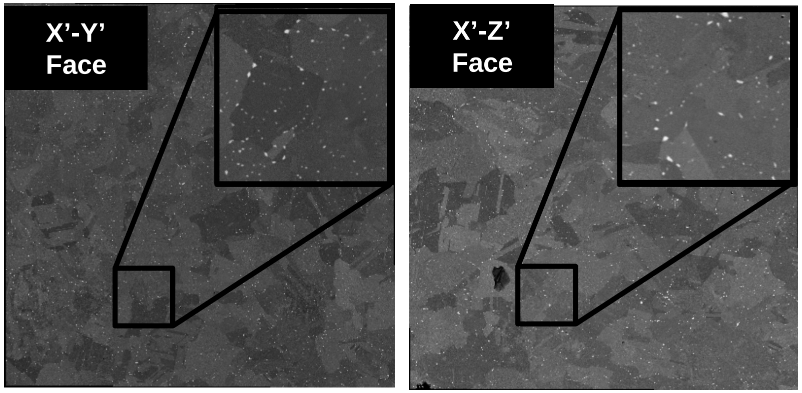


Fig. 13: BSE images of SR+HIP+HT calibration cylinder. Each image has approximately a 600x600μm field of view.

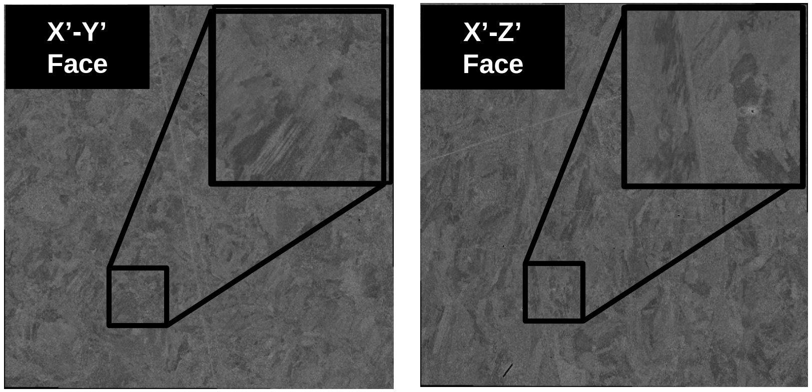


Fig. 14: BSE images of SR Only calibration cylinder. Each image has approximately a 600x600μm field of view.

SR+HIP+HT

Denuded Zone Thickness [μm]	X-Y Precipitate Size [μm] μ, σ	X-Y Precipitate V_f [%]	X-Z Precipitate Size [μm] μ, σ	X-Z Precipitate V_f [%]
N/A	0.94, 0.48	1.22	0.96, 0.53	1.19

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

SR Only

X-Y Precipitate Size [μm] μ, σ	X-Y Precipitate V_f [%]	X-Z Precipitate Size [μm] μ, σ	X-Z Precipitate V_f [%]
N/A	0	N/A	0

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

- Tabulated precipitate statistics located in \Challenge3\CalibrationData\MicrostructureData
- Raw BSE images located in \Challenge3\CalibrationData\MicrostructureData\BSE
- Analysis pipelines located in \Challenge3\Pipelines

Details of Methodology
Backscattered Electron Microscopy

Volume fraction is likely underestimated slightly and average size is likely overestimated

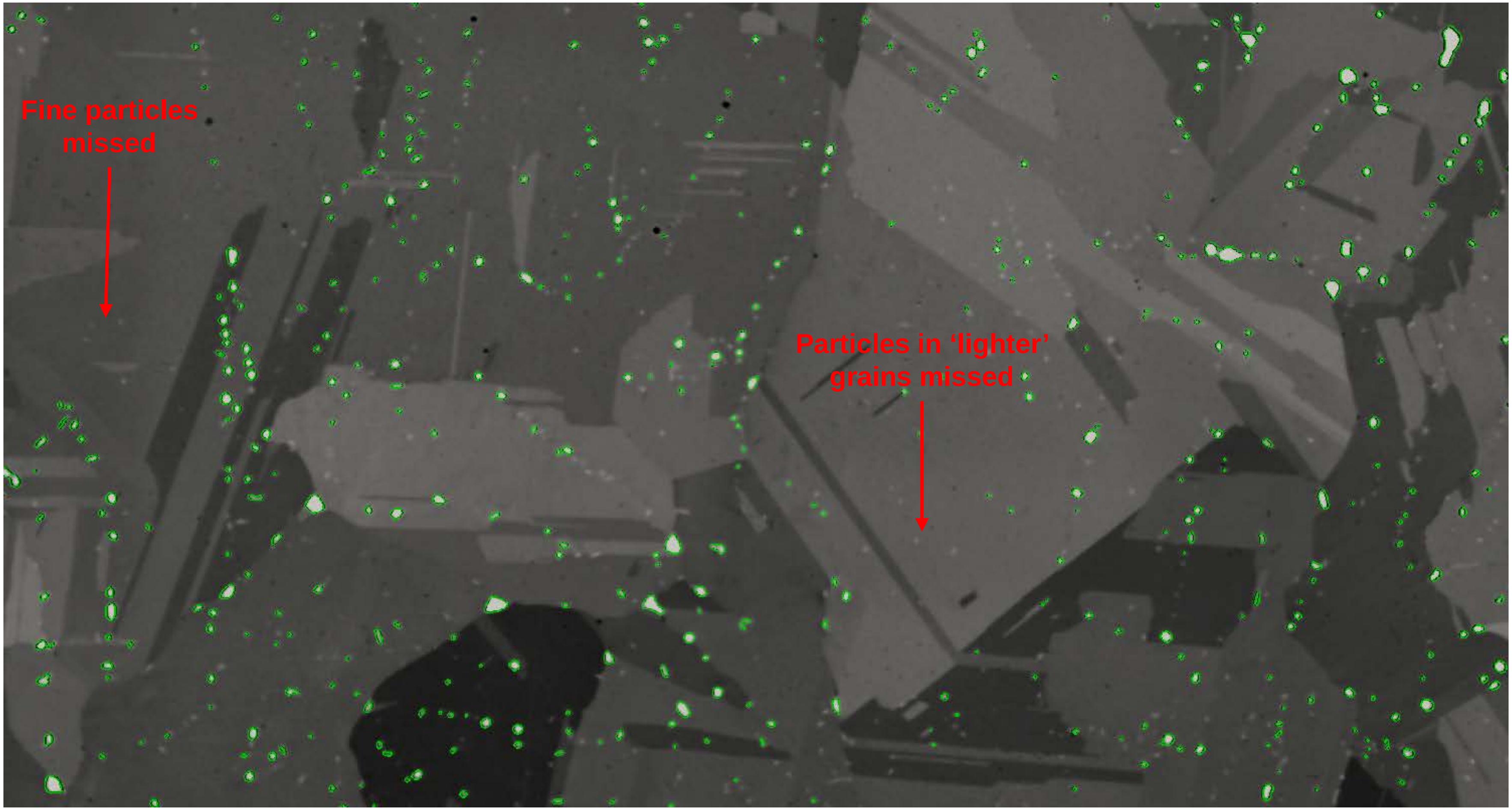


Fig. 15: Example segmentation of precipitates in BSE images of calibration cylinder with annotations showing missed particles.

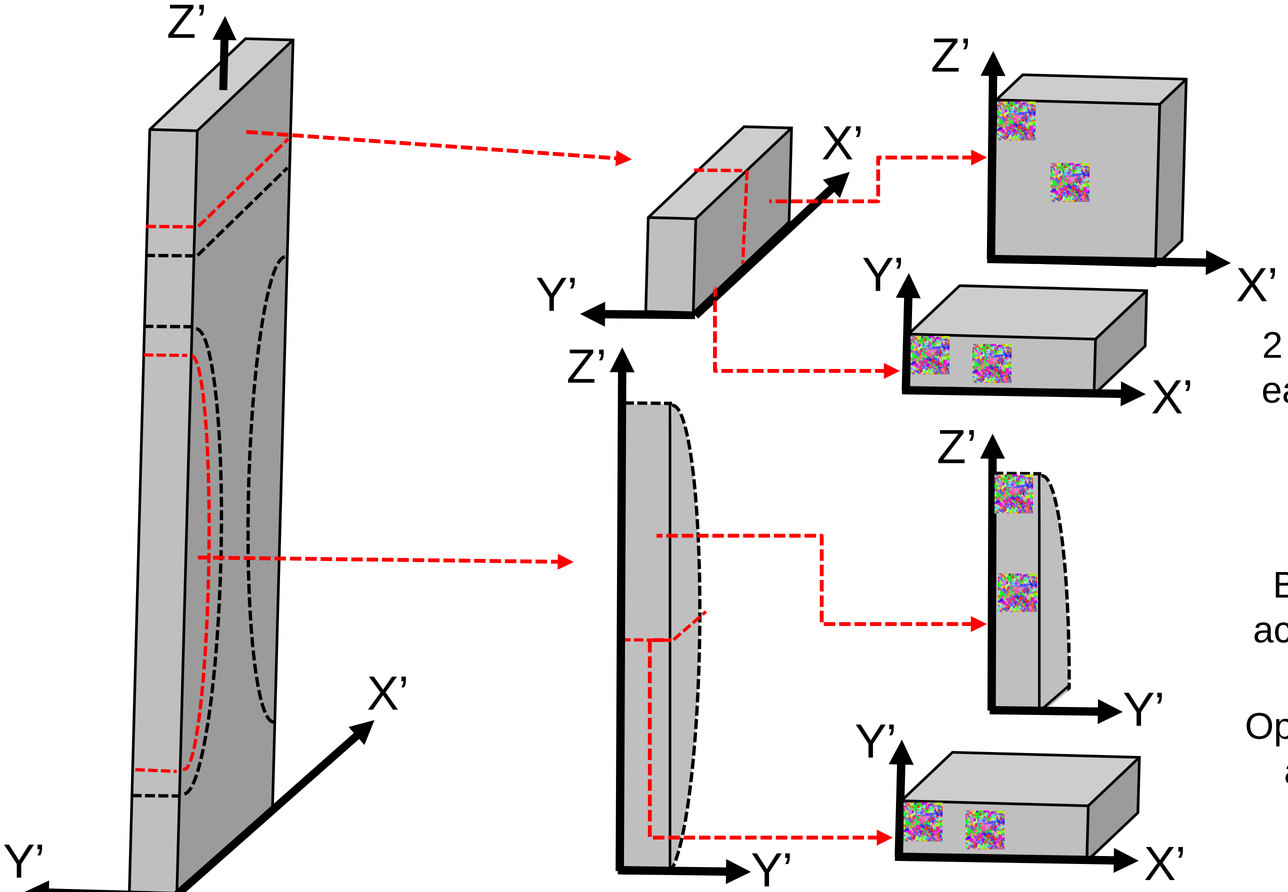
* Note: area shown is approx. 1/10th of area used to calculate statistics for a given sample on a given plane *

- 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.



* Some samples also imaged/scanned third orthogonal face *

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

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

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.

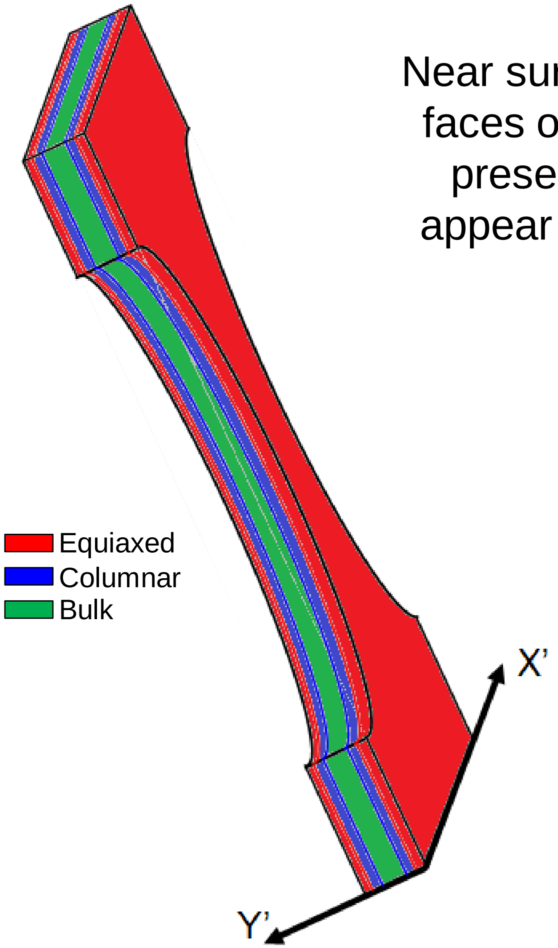


Fig. 17: Schematic of milli-tensile sample with potential 'zones' annotated to display 'pseudo-laminate' nature of microstructure

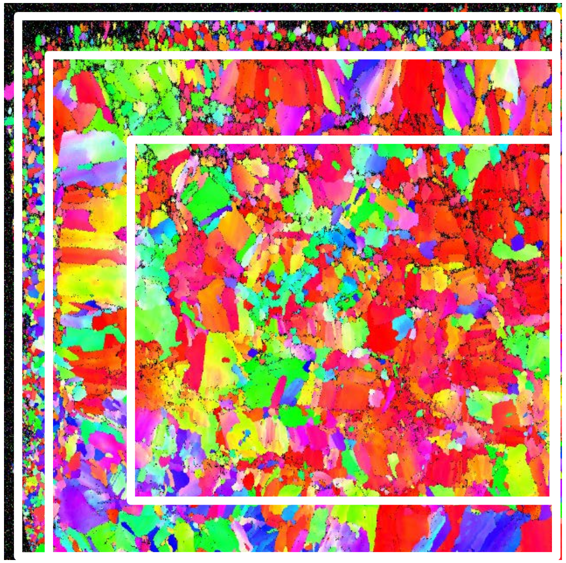


Fig. 18: IPFX EBSD scan of SR Only sample showing apparent microstructure "zones".

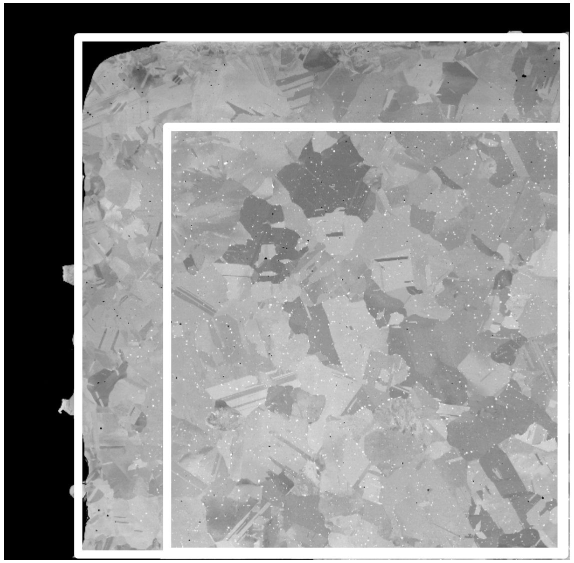


Fig. 19: BSE scan of SR+HIP+HT sample showing precipitate denuded region.

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 ≈ 50-70 μm and the 'columnar' zone ≈ 100-120 μm

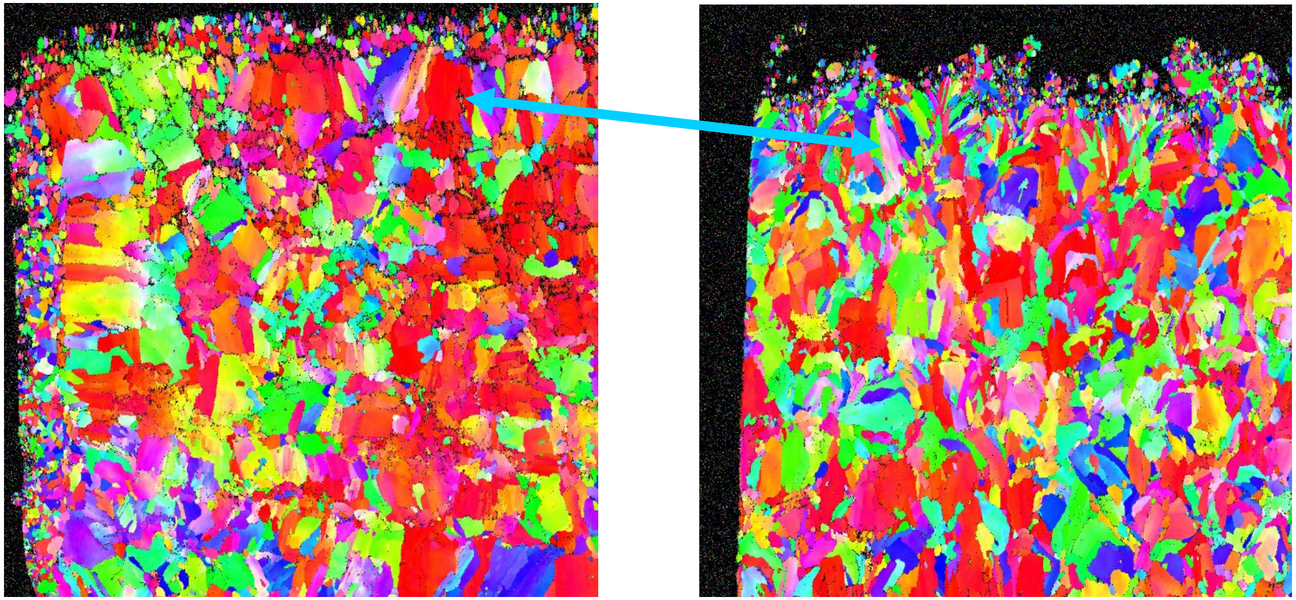


Fig. 20: IPFX EBSD scans of SR Only sample showing/not-showing apparent microstructure "zones" along with complicating roughness. Both scans are of an X'-Y' face with a 1mm x 1mm field of view.

Details of Methodology
R_a measurements

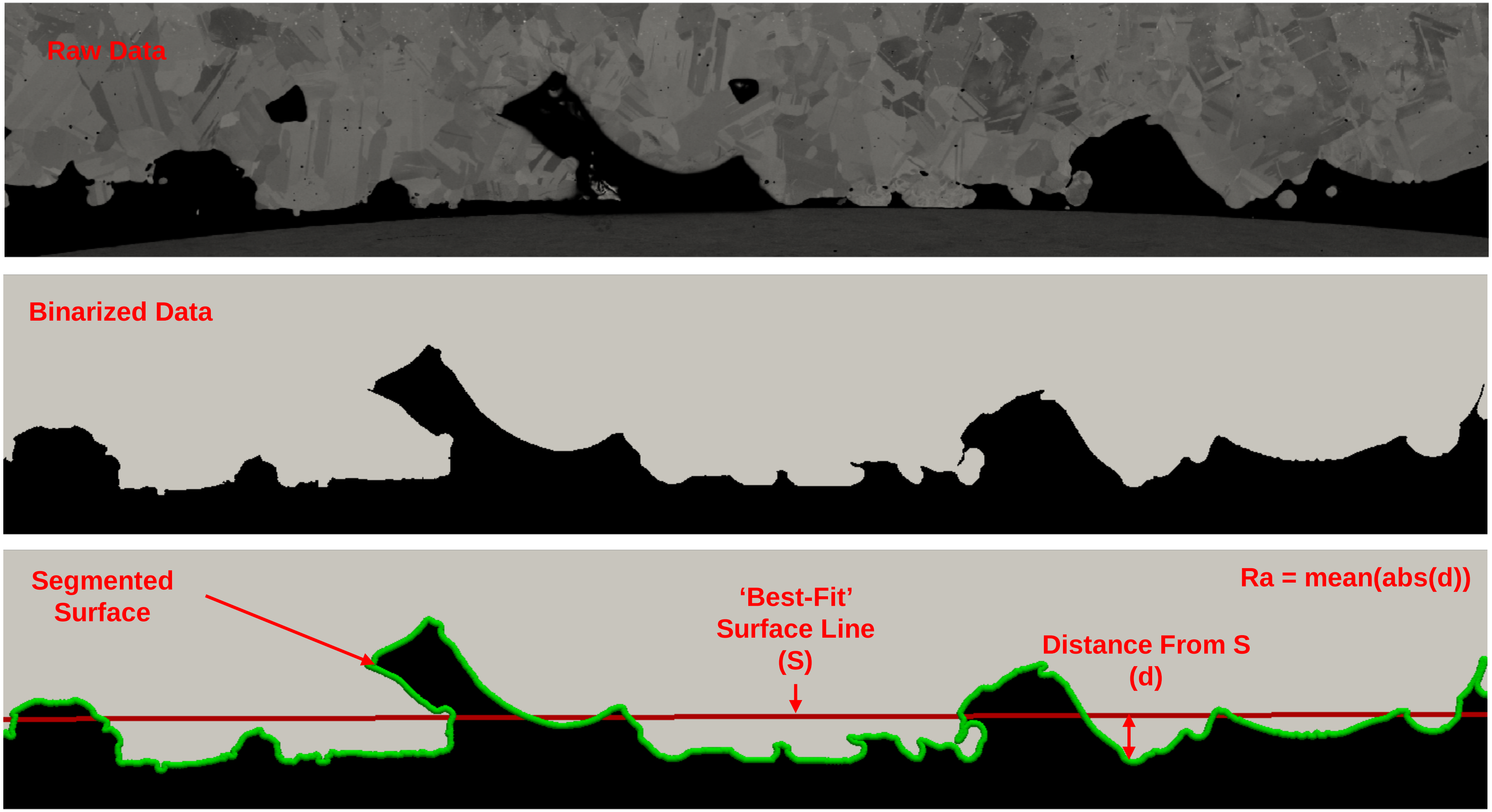


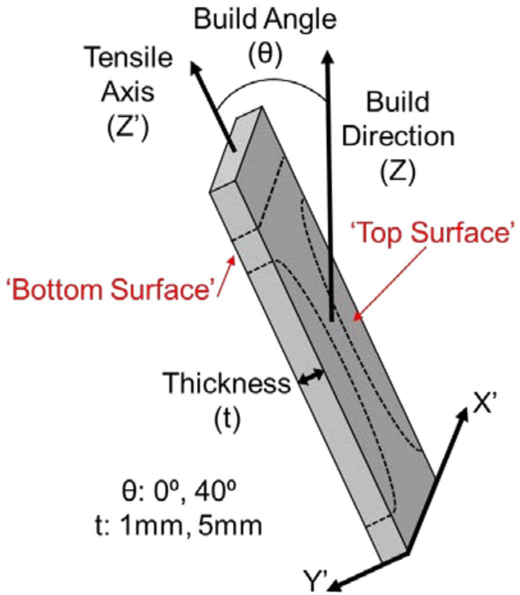
Fig. 21: Example of surface segmentation and R_a calculation method using BSE images. Each image has a field of view of 185µm x 105µm

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

- Raw BSE images located in \Challenge3\InputData*Sample Condition*\BSE
- Analysis pipelines located in \Challenge3\Pipelines

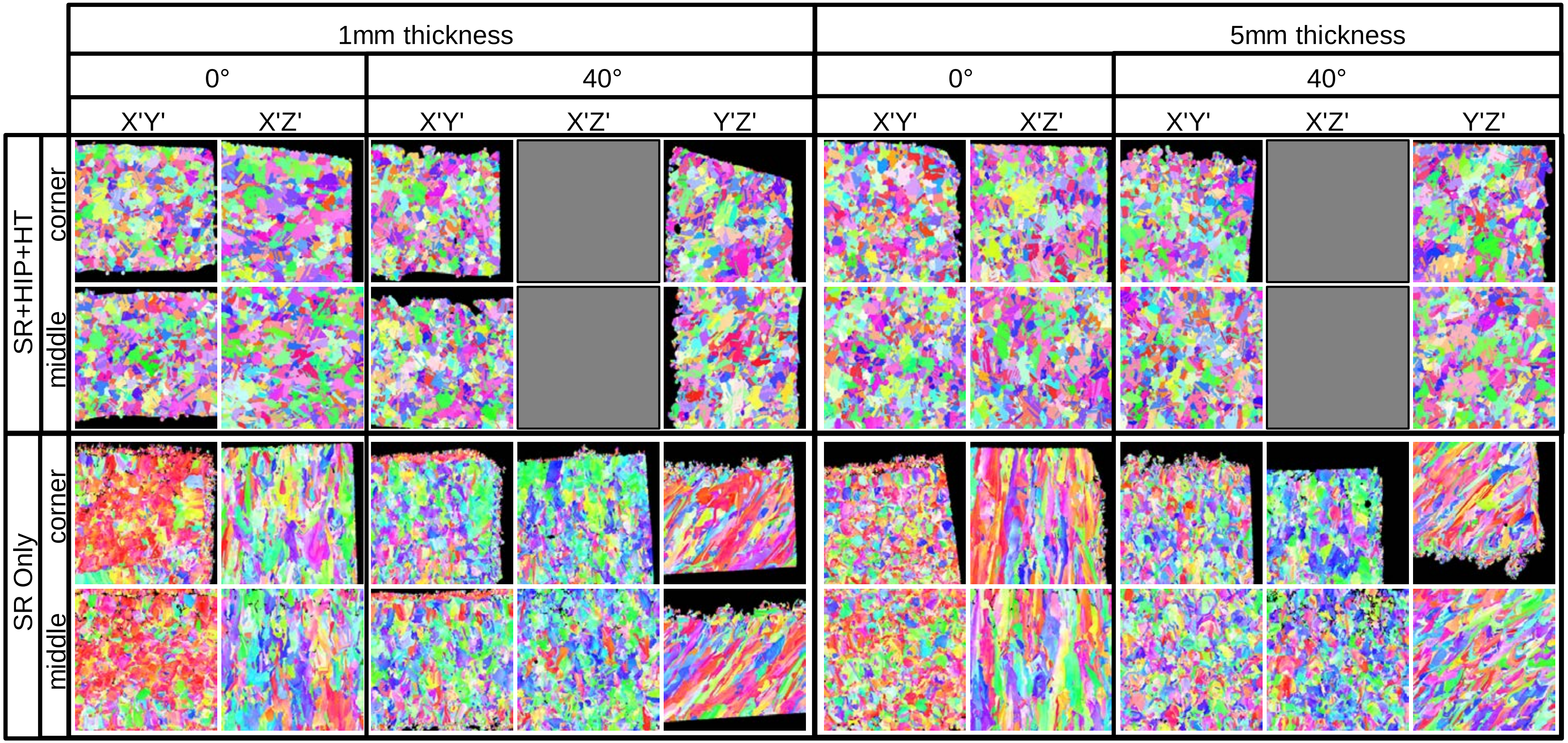
Other Characterization Notes
Input Data

- 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 R_a is the roughness measured from the sample surface commonly referred to as top skin, the surface facing toward the +Z direction.
  - Bottom R_a 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



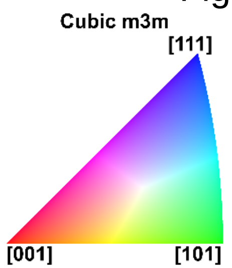
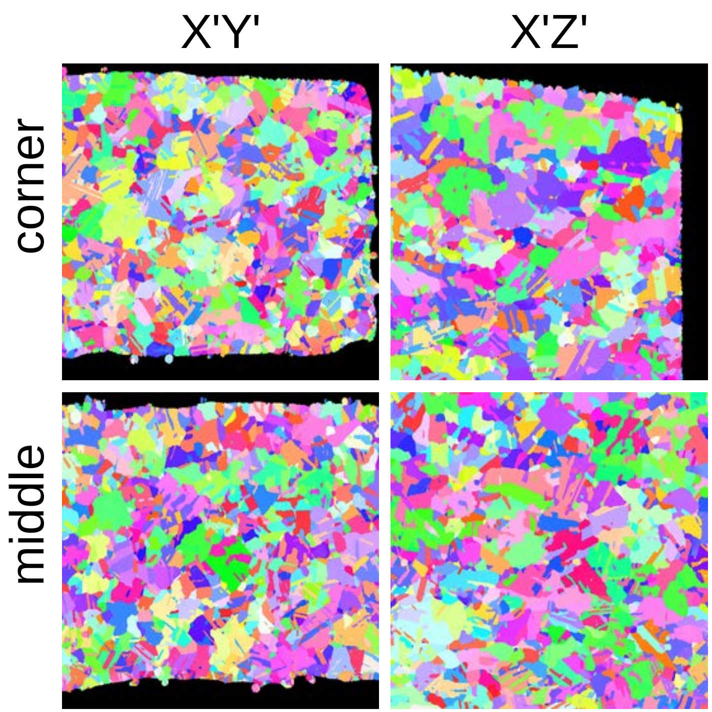


Fig. 22: EBSD Inverse Pole Figure (Z) scans for all microstructure conditions. Each image has a field of view of 1mm x 1mm

1mm - 0deg - SR+HIP+HT (C31)

	1 mm Thickness		5 mm Thickness	
	0°	40°	0°	40°
SR + HIP + HT	X			
SR Only				

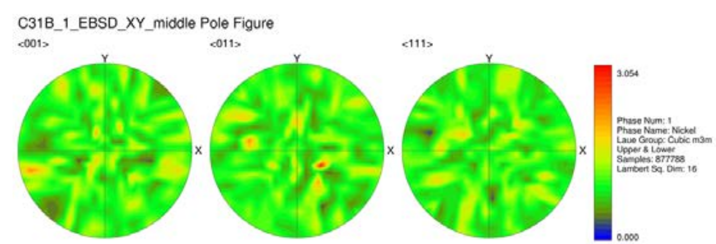
Location	View	Twins Merged	Grain Size – Mean [µm]	Grain Size – StdDev [µm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No	17.292	14.930	0.496	0.203
corner	X'Y'	Yes	32.614	36.650	0.592	0.186
middle	X'Y'	No	18.526	15.639	0.508	0.194
middle	X'Y'	Yes	37.223	37.580	0.586	0.170
corner	X'Z'	No	20.753	18.427	0.527	0.184
corner	X'Z'	Yes	37.496	42.908	0.603	0.175
middle	X'Z'	No	20.647	17.753	0.511	0.191
middle	X'Z'	Yes	34.743	43.480	0.569	0.183



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

X'-Y' Void Size [µm] µ, σ	X'-Y' Void V_f %	Top R_a [µm]	X'-Z' Void Size [µm] µ, σ	X'-Z' Void V_f %	Bottom R_a [µm]
1.17, 0.68	0.021	10.9	2.04, 2.08	0.02	8.6

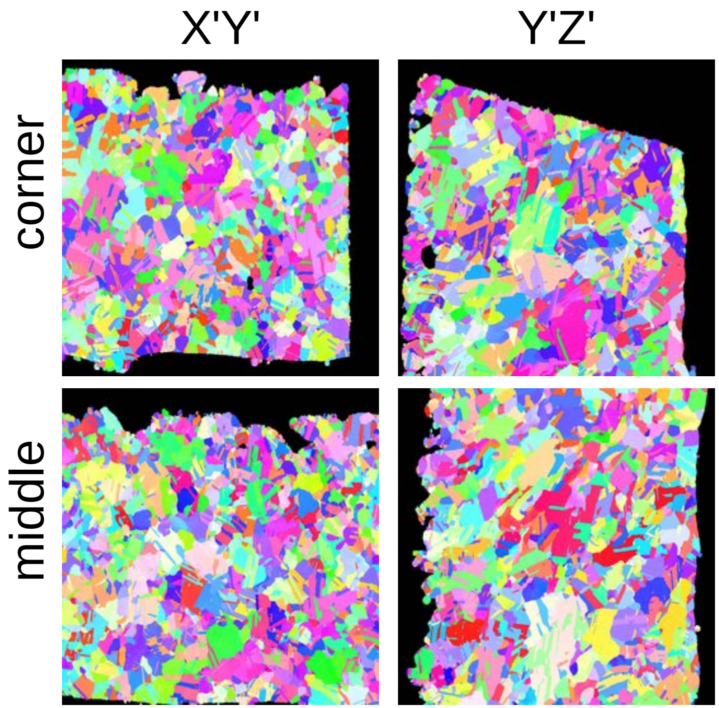
Denuded Zone Thickness [µm]	X'-Y' Precipitate Size [µm] µ, σ	X'-Y' Precipitate V_f [%]	X'-Z' Precipitate Size [µm] µ, σ	X'-Z' Precipitate V_f [%]
75	1.04, 0.55	1.51	0.95, 0.50	1.19



1mm - 40deg - SR+HIP+HT (C09)

	1 mm Thickness		5 mm Thickness	
	0°	40°	0°	40°
SR + HIP + HT		X		
SR Only				

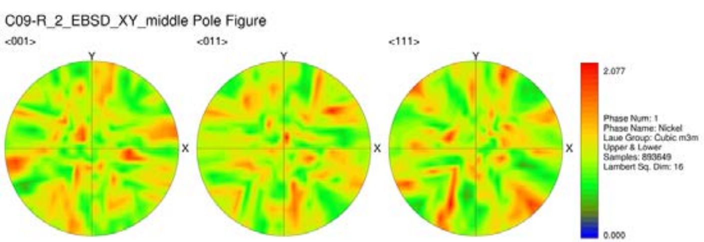
Location	View	Twins Merged	Grain Size – Mean [μm]	Grain Size – StdDev [μm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No	17.413	14.346	0.487	0.195
corner	X'Y'	Yes	30.612	30.262	0.583	0.182
middle	X'Y'	No	16.636	13.813	0.486	0.194
middle	X'Y'	Yes	25.749	28.279	0.558	0.186
corner	Y'Z'	No	16.749	14.521	0.470	0.200
corner	Y'Z'	Yes	29.200	33.011	0.565	0.192
middle	Y'Z'	No	17.768	15.860	0.474	0.195
middle	Y'Z'	Yes	28.942	31.006	0.532	0.188



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 V_f %	Top R_a [μm]	Y'-Z' Void Size [μm] μ, σ	Y'-Z' Void V_f %	Bottom R_a [μm]
1.67, 0.82	0.033	11.8	1.69, 0.92	0.021	25.4

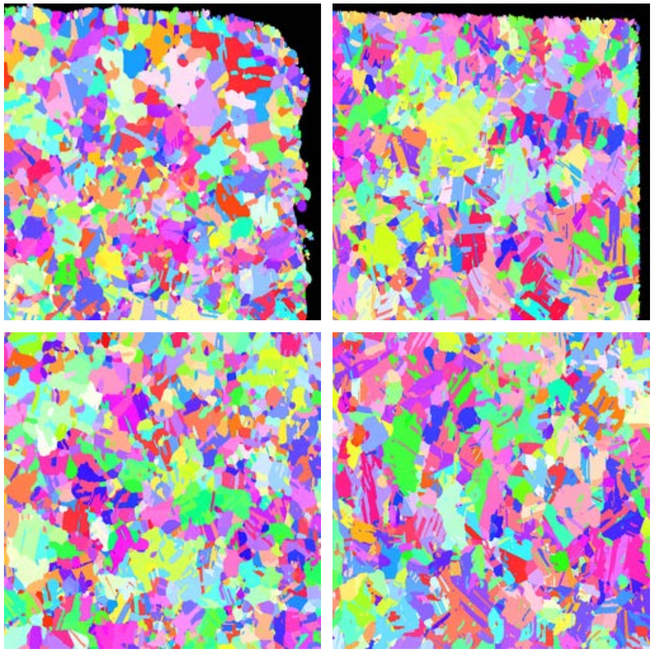
Denuded Zone Thickness [μm]	X'-Y' Precipitate Size [μm] μ, σ	X'-Y' Precipitate V_f	Y'-Z' Precipitate Size [μm] μ, σ	Y'-Z' Precipitate V_f
60	1.03, 0.57	1.85	1.25, 0.69	1.72



5mm - 0deg - SR+HIP+HT (C0B)

	1 mm Thickness		5 mm Thickness	
	0°	40°	0°	40°
SR + HIP + HT			X	
SR Only				

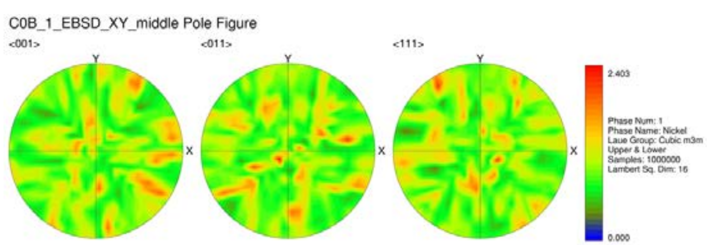
Location	View	Twins Merged	Grain Size – Mean [μm]	Grain Size – StdDev [μm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No	19.721	15.987	0.543	0.181
corner	X'Y'	Yes	25.999	28.554	0.584	0.162
middle	X'Y'	No	18.783	15.079	0.509	0.189
middle	X'Y'	Yes	36.297	39.262	0.592	0.182
corner	X'Z'	No	16.726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



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

X'-Y' Void Size [μm] μ, σ	X'-Y' Void V_f %	Top R_a [μm]	X'-Z' Void Size [μm] μ, σ	X'-Z' Void V_f %	Bottom R_a [μm]
1.69, 1.28	0.017	10.2	1.73, 1.16	0.015	8.8

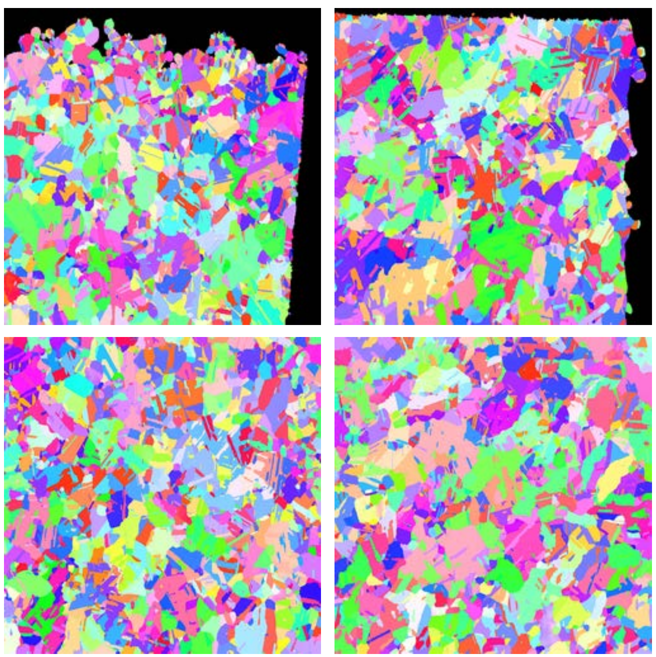
Denuded Zone Thickness [μm]	X'-Y' Precipitate Size [μm] μ, σ	X'-Y' Precipitate V_f	X'-Z' Precipitate Size [μm] μ, σ	X'-Z' Precipitate V_f
80	1.08, 0.53	0.93	1.04, 0.56	1.58



5mm - 40deg - SR+HIP+HT (C13)

	1 mm Thickness		5 mm Thickness	
	0°	40°	0°	40°
SR + HIP + HT				X
SR Only				

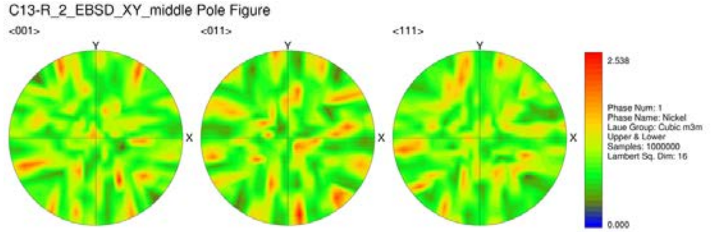
Location	View	Twins Merged	Grain Size – Mean [μm]	Grain Size – StdDev [μm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No	16.705	14.465	0.480	0.194
corner	X'Y'	Yes	28.541	32.570	0.575	0.170
middle	X'Y'	No	17.105	14.761	0.474	0.195
middle	X'Y'	Yes	31.676	38.433	0.568	0.185
corner	Y'Z'	No	17.610	15.704	0.472	0.197
corner	Y'Z'	Yes	32.167	38.955	0.538	0.178
middle	Y'Z'	No	17.317	16.136	0.474	0.201
middle	Y'Z'	Yes	30.224	41.523	0.550	0.183



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

X'-Y' Void Size [μm] μ, σ	X'-Y' Void V_f %	Top R_a [μm]	Y'-Z' Void Size [μm] μ, σ	Y'-Z' Void V_f %	Bottom R_a [μm]
1.74, 1.97	0.019	11.3	1.43, 1.54	0.021	29.7

Denuded Zone Thickness [μm]	X'-Y' Precipitate Size [μm] μ, σ	X'-Y' Precipitate V_f	Y'-Z' Precipitate Size [μm] μ, σ	Y'-Z' Precipitate V_f
65	1.01, 0.53	0.96	1.00, 0.52	1.13



1mm - 0deg - SR (G33)

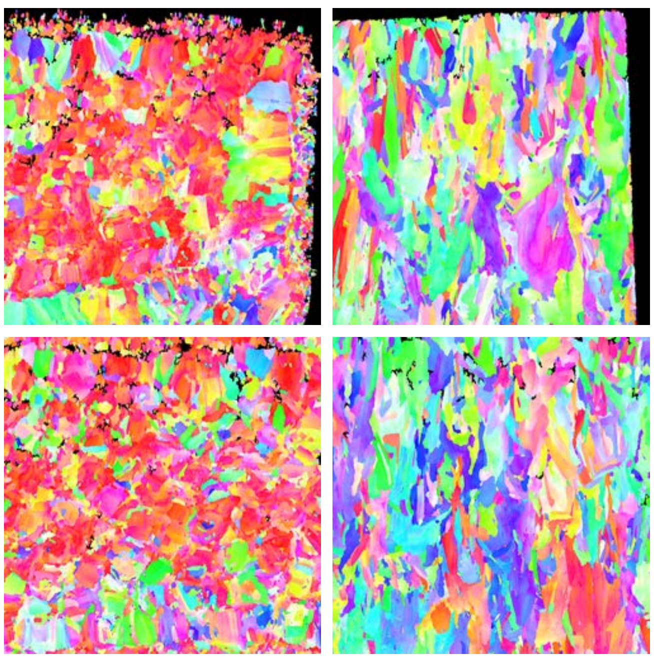
	1 mm Thickness		5 mm Thickness	
	0°	40°	0°	40°
SR + HIP + HT				
SR Only	X			

Location	View	Twins Merged	Grain Size – Mean [μm]	Grain Size – StdDev [μm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No	15.810	16.966	0.563	0.177
middle	X'Y'	No	16.695	15.529	0.554	0.175
corner	X'Z'	No	28.144	26.822	0.368	0.177
corner	X'Z'	No	20.764	23.298	0.399	0.185
corner	X'Z'	No	26.758	24.925	0.403	0.181
middle	X'Z'	No	28.086	26.460	0.371	0.177
middle	X'Z'	No	20.772	20.572	0.391	0.179
middle	X'Z'	No	27.828	24.798	0.399	0.177

X'Y' X'Z'

corner

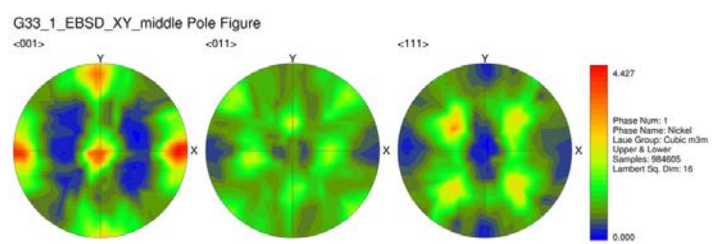
middle



Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: \Challenge 3 Fixes\Input Data\1mm - 0deg - SR only

X'-Y' Void Size [μm] μ, σ	X'-Y' Void V_f %	Top R_a [μm]	X'-Z' Void Size [μm] μ, σ	X'-Z' Void V_f %	Bottom R_a [μm]
6.02, 8.42	0.087	8	1.69, 1.57	0.015	7.6

Denuded Zone Thickness [μm]	X'-Y' Precipitate Size [μm] μ, σ	X'-Y' Precipitate V_f	X'-Z' Precipitate Size [μm] μ, σ	X'-Z' Precipitate V_f
N/A	N/A	0	N/A	0



1mm - 40deg - SR (H50)

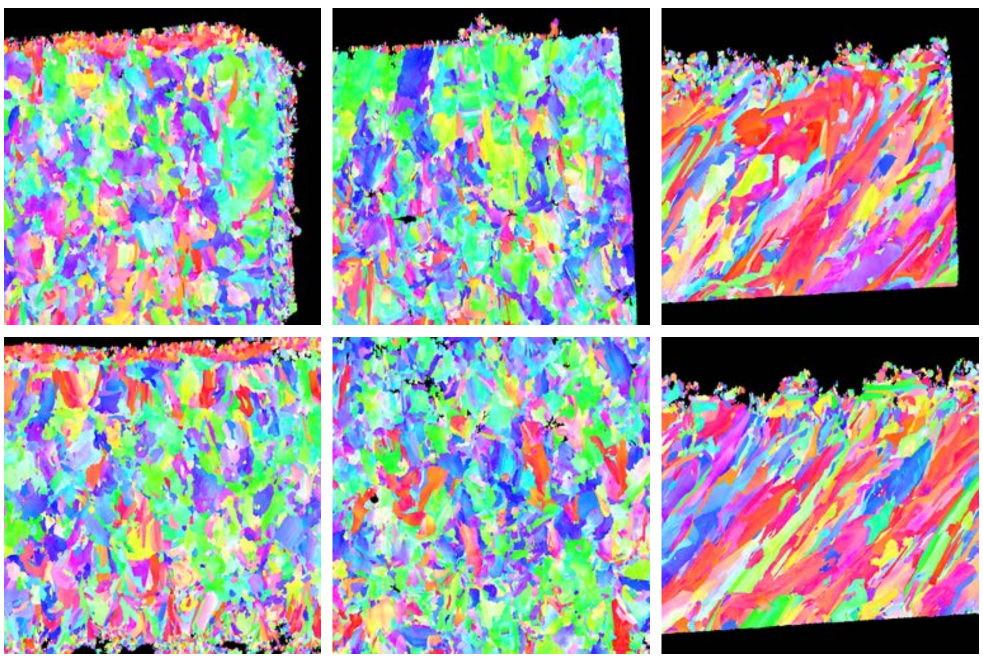
		1 mm Thickness		5 mm Thickness	
		0°	40°	0°	40°
SR + HIP + HT					
SR Only			X		

Location	View	Twins Merged	Grain Size – Mean [µm]	Grain Size – StdDev [µm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No	15.623	15.390	0.522	0.179
middle	X'Y'	No	14.544	13.769	0.515	0.184
corner	X'Z'	No	16.397	16.647	0.498	0.187
middle	X'Z'	No	16.851	16.271	0.513	0.182
corner	Y'Z'	No	16.858	17.833	0.430	0.194
middle	Y'Z'	No	16.377	17.323	0.415	0.193

X'Y' X'Z' Y'Z'

corner

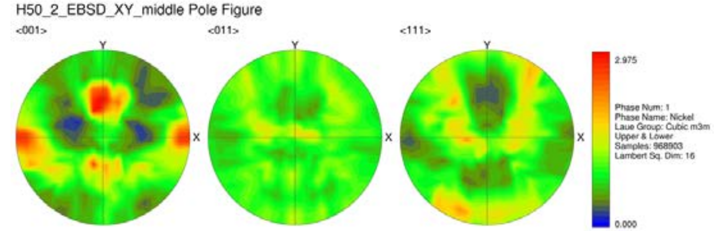
middle



Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: \Challenge 3 Fixes\Input Data\1mm - 40deg - SR only

X'-Y' Void Size [µm] µ, σ	X'-Y' Void V_f %	Top R_a [µm]	X'-Z' Void Size [µm] µ, σ	X'-Z' Void V_f %	Bottom R_a [µm]
1.64, 1.19	0.014	10.2	3.94, 6.1	0.047	25.3

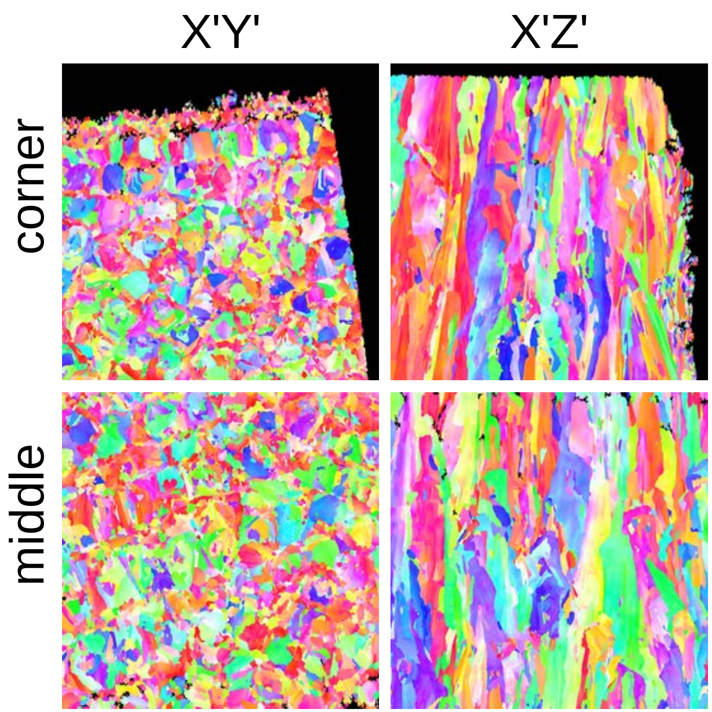
Denuded Zone Thickness [µm]	X'-Y' Precipitate Size [µm] µ, σ	X'-Y' Precipitate V_f	X'-Z' Precipitate Size [µm] µ, σ	X'-Z' Precipitate V_f
N/A	N/A	0	N/A	0



5mm - 0deg - SR (H0B)

		1 mm Thickness		5 mm Thickness	
		0°	40°	0°	40°
SR + HIP + HT					
SR Only				X	

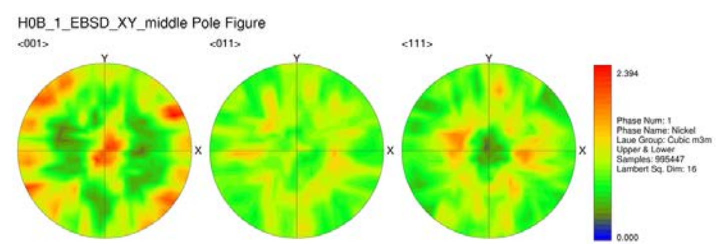
Location	View	Twins Merged	Grain Size – Mean [μm]	Grain Size – StdDev [μm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No	15.328	12.838	0.559	0.179
middle	X'Y'	No	16.270	13.939	0.553	0.175
corner	X'Z'	No	27.611	28.677	0.347	0.177
corner	X'Z'	No	17.015	18.611	0.363	0.180
corner	X'Z'	No	27.403	29.159	0.340	0.173
middle	X'Z'	No	27.524	27.164	0.363	0.182
middle	X'Z'	No	18.785	20.089	0.385	0.191
middle	X'Z'	No	28.462	26.825	0.366	0.180



Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: \Challenge3\Input Data\5mm - 0deg - SR only

X'-Y' Void Size [μm] μ, σ	X'-Y' Void V_f %	Top R_a [μm]	X'-Z' Void Size [μm] μ, σ	X'-Z' Void V_f %	Bottom R_a [μm]
2.7, 4.48	0.064	7.1	3.11, 6.02	0.079	10.2

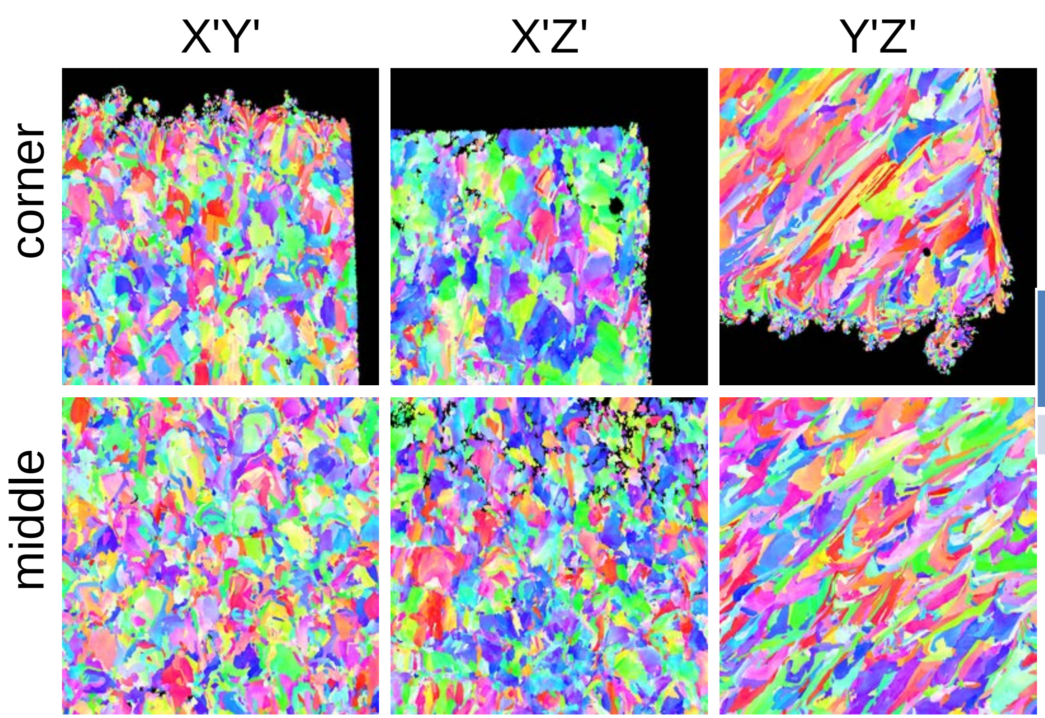
Denuded Zone Thickness [μm]	X'-Y' Precipitate Size [μm] μ, σ	X'-Y' Precipitate V_f	X'-Z' Precipitate Size [μm] μ, σ	X'-Z' Precipitate V_f
N/A	N/A	0	N/A	0



5mm - 40deg - SR (G70)

		1 mm Thickness		5 mm Thickness	
		0°	40°	0°	40°
SR + HIP + HT					
SR Only					X

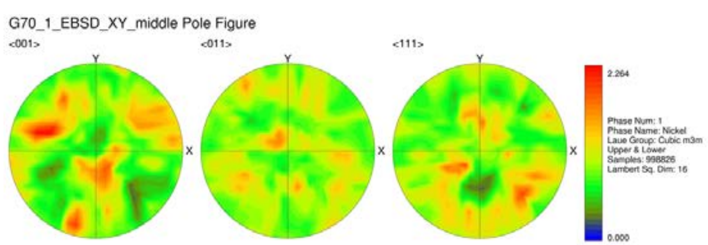
Location	View	Twins Merged	Grain Size – Mean [µm]	Grain Size – StdDev [µm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No	14.972	13.358	0.500	0.185
middle	X'Y'	No	16.651	14.235	0.506	0.182
corner	X'Z'	No	15.407	16.846	0.505	0.181
middle	X'Z'	No	16.925	14.918	0.515	0.183
corner	Y'Z'	No	13.865	14.728	0.449	0.201
middle	Y'Z'	No	18.516	18.766	0.414	0.194



Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: \Challenge3\Input Data\5mm - 40deg - SR only

X'-Y' Void Size [µm] µ, σ	X'-Y' Void V_f %	Top R_a [µm]	X'-Z' Void Size [µm] µ, σ	X'-Z' Void V_f %	Bottom R_a [µm]
2.59, 3.56	0.036	16.2	2.66, 4.29	0.045	30.5

Denuded Zone Thickness [µm]	X'-Y' Precipitate Size [µm] µ, σ	X'-Y' Precipitate V_f	X'-Z' Precipitate Size [µm] µ, σ	X'-Z' Precipitate V_f
N/A	N/A	0	N/A	0



Challenge Question and Scoring

Description of Desired Predictions

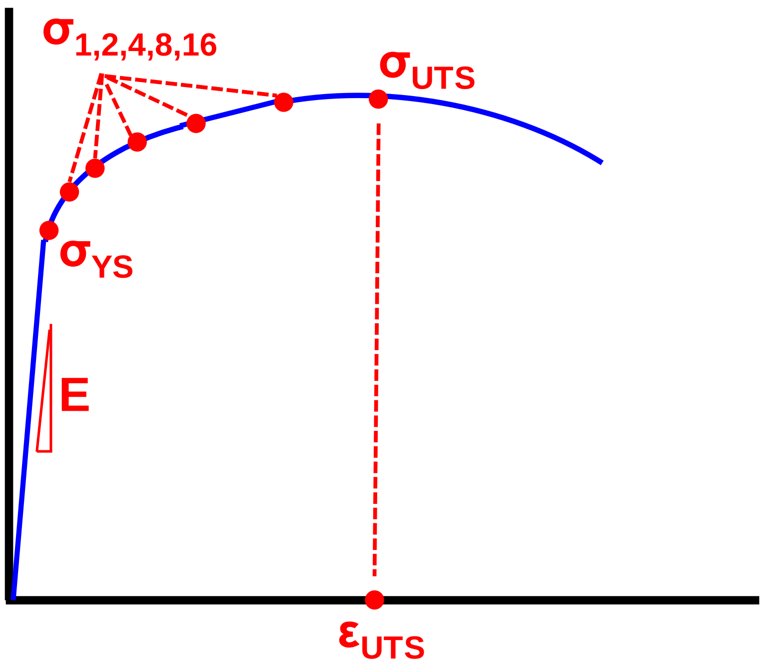


Fig. 23: Schematic of stress-strain curve with desired predictions

- 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 ($\sigma_{1,2,4,8,16}$): stress value at each discrete strain, evaluated on the polynomial fit (order = 2) through data points +/- 0.0025 around each discrete strain

Answer Format

As-Printed Samples

Post Build Treatment	Build Angle	Thickness [µm]	Test Temperature [ºF]	Elastic Modulus [GPa]	0.2% Yield Strength [Mpa]	Stress @ 1%, 2%, 4%, 8%, 16%** Strain [MPa]	Ultimate Tensile Strength [MPa]	Uniform Elongation
SR+HIP+HT	0	1	75					
SR+HIP+HT	40	1	75					
SR+HIP+HT	0	5	75					
SR+HIP+HT	40	5	75					
SR	0	1	75					
SR	40	1	75					
SR	0	5	75					
SR	40	5	75					
SR+HIP+HT	0	1	1600			**		NA
SR+HIP+HT	40	1	1600			**		NA
SR+HIP+HT	0	5	1600			**		NA
SR+HIP+HT	40	5	1600			**		NA
SR	0	1	1600			**		NA
SR	40	1	1600			**		NA
SR	0	5	1600			**		NA
SR	40	5	1600			**		NA

** For 1600ºF 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

Answer Format

Surface Ground (low-stress ground) Samples

Post Build Treatment	Build Angle	Thickness [µm]	Test Temperature [ºF]	Elastic Modulus [GPa]	0.2% Yield Strength [Mpa]	Stress @ 1%, 2%, 4%, 8%, 16%** Strain [MPa]	Ultimate Tensile Strength [MPa]	Uniform Elongation
SR+HIP+HT	0	1	75					
SR+HIP+HT	40	1	75					
SR+HIP+HT	0	5	75					
SR+HIP+HT	40	5	75					
SR	0	1	75					
SR	40	1	75					
SR	0	5	75					
SR	40	5	75					
SR+HIP+HT	0	1	1600			**		NA
SR+HIP+HT	40	1	1600			**		NA
SR	0	1	1600			**		NA
SR	40	1	1600			**		NA
SR	40	5	1600			**		NA

** For 1600ºF 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.xls

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 (σ_{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 (σ_{UTS}): +/- 10 MPa = 5 pts; +/- 20 MPa = 2 pts; +/- 40 MPa = 1 pt
  - For Uniform Elongation (ε_{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

Test direction	Temperature (F)	Elastic Modulus (msi)		Yield Stress (0.2%) (ksi)		Ultimate Tensile Stress (ksi)	
		IN625	std dev	IN625	std dev	IN625	std dev
Z	76	21.73	0.62	87.67	0.24	132.09	1.03
Z	1000	16.56	2.12	77.17	0.24	110.86	0.80
Z	1500	8.57	0.77	37.67	0.62	40.50	0.98
Z	1800	6.10	1.96	15.17	0.24	16.47	0.40
Z	2000	3.18	1.75	8.33	0.62	9.01	0.53

Table 11: Mechanical properties of AM IN625 at select temperatures

- 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

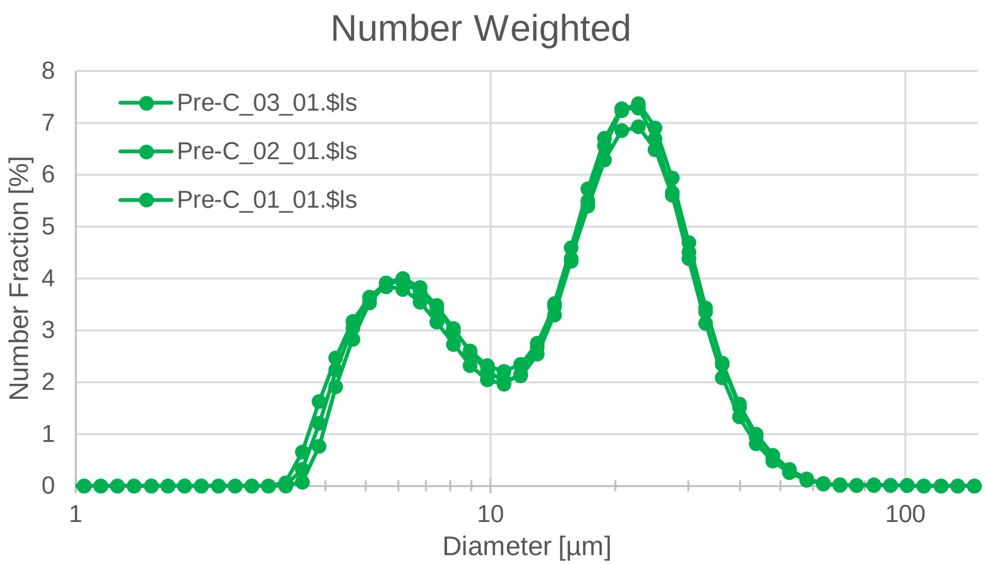


Fig. 24: Powder particle size distribution after build was completed

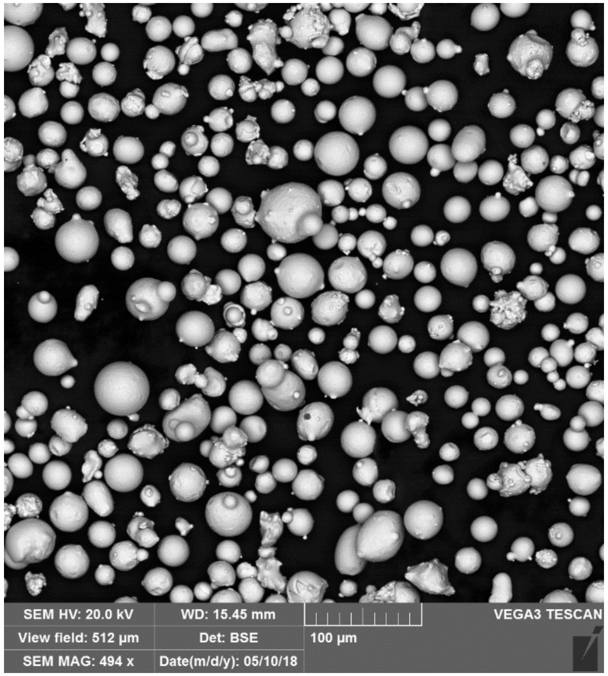


Fig. 25: BSE image of powder particles after build was completed

- 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