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

Challenge Problem 3:
Macroscale Structure-to-Properties

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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

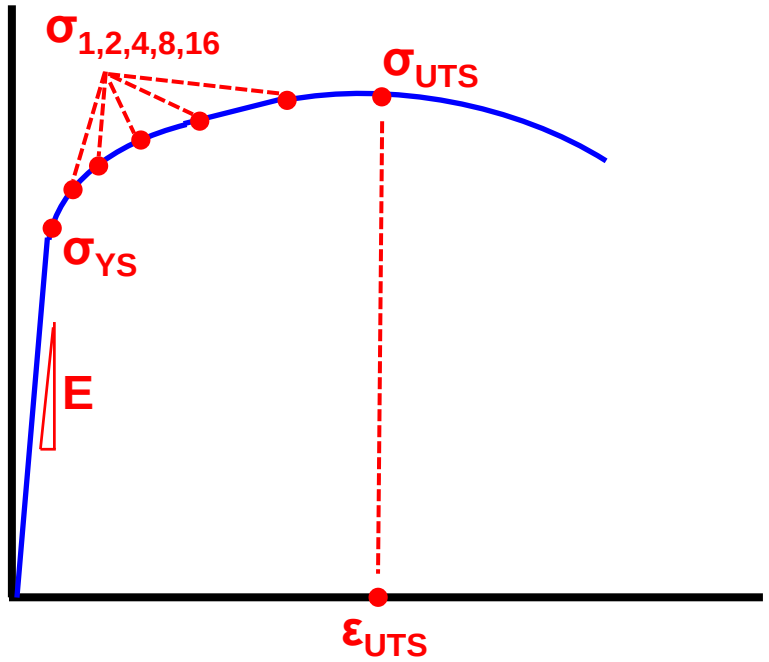


Fig. 1: Schematic of stress-strain curve with desired predictions

Coordinate Systems

The nominal geometry of all items being printed is provided in a .stl file, described in the machine centered reference frame (*X,Y,Z)*, which is consistent with that described in ASTM F2921: *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.

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\
- Tensile specimen geometries listed in Input Data section of this document

Coordinate Systems & Specimen Geometries

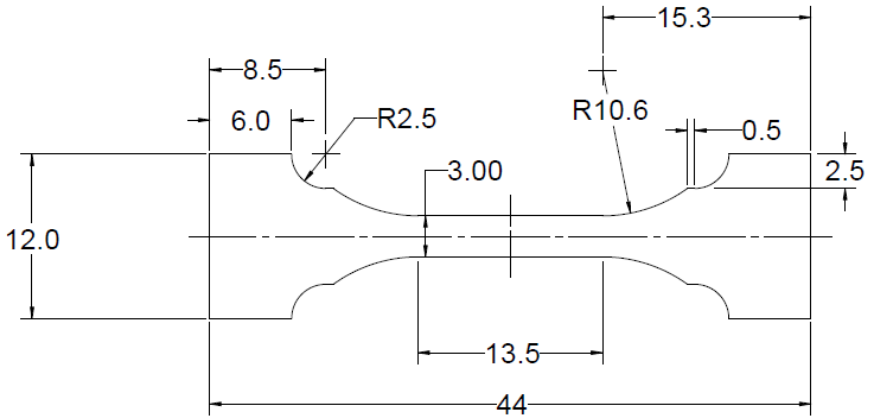


Fig. 2: Drawing of milli-scale tensile specimen (units in mm)

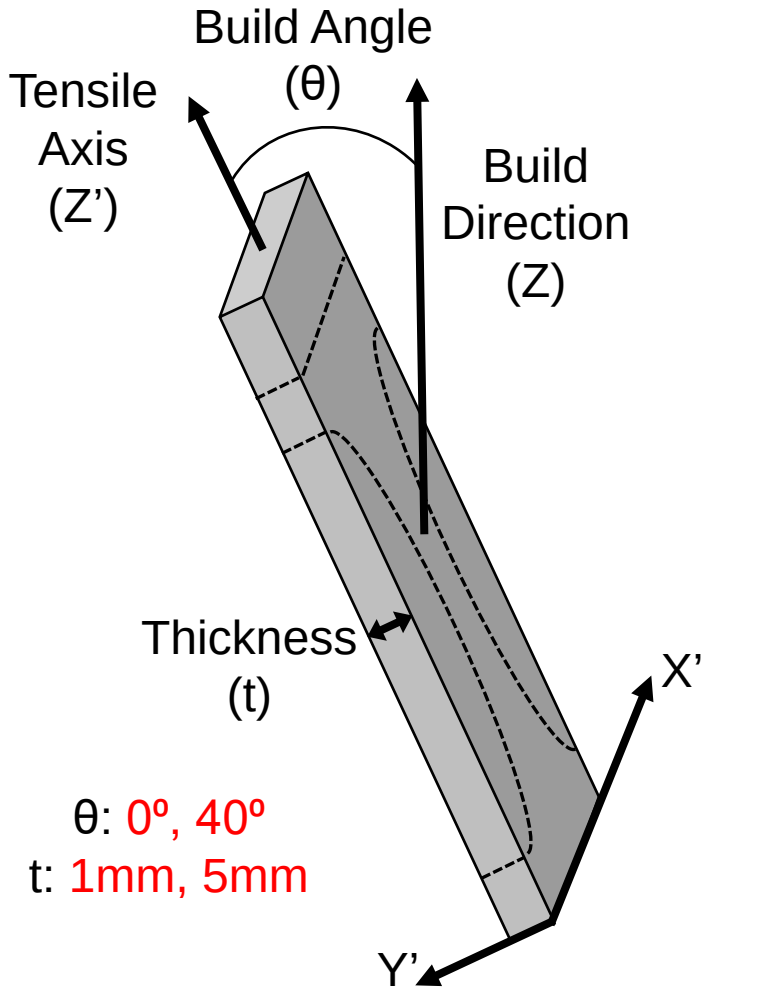


Fig. 3: Schematic showing extraction of tensile samples

- Drawing of tensile sample dimensions located in \Challenge3\InputData
- .stp files of 2 unique tensile geometries located in \Challenge3\InputData

Description of Requested Metrics

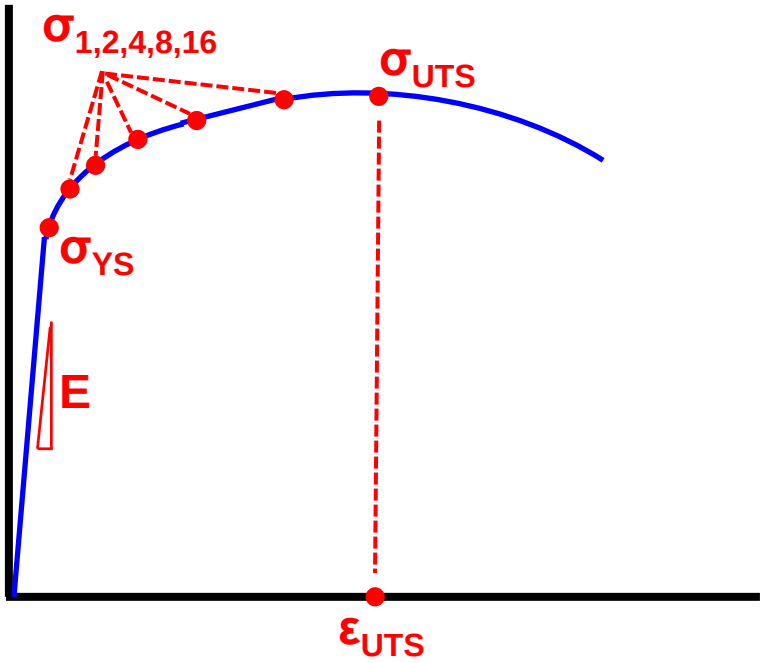


Fig. 4: Schematic of stress-strain curve with desired predictions

- 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

Microstructural “Zones”

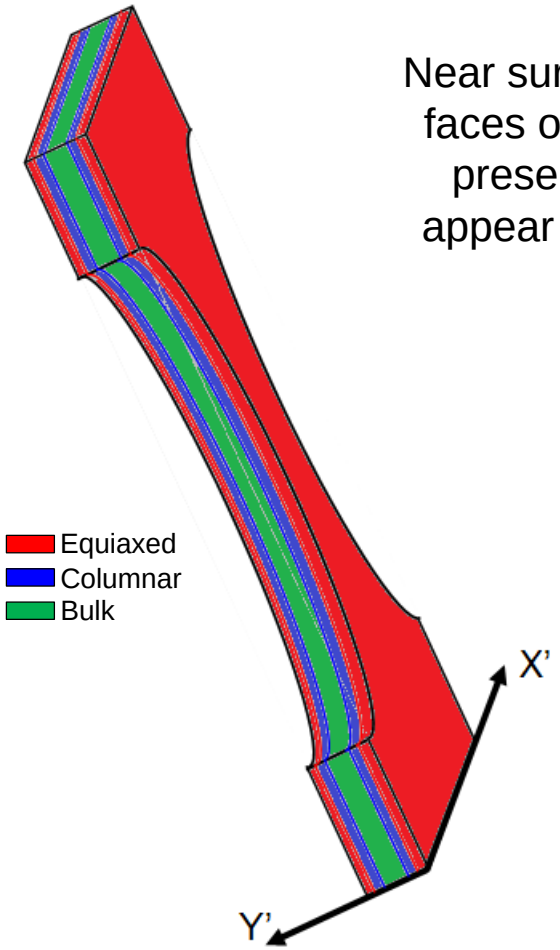


Fig. 5: Schematic of milli-scale tensile sample with potential ‘zones’ annotated to display ‘pseudo-laminate’ nature of microstructure

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.

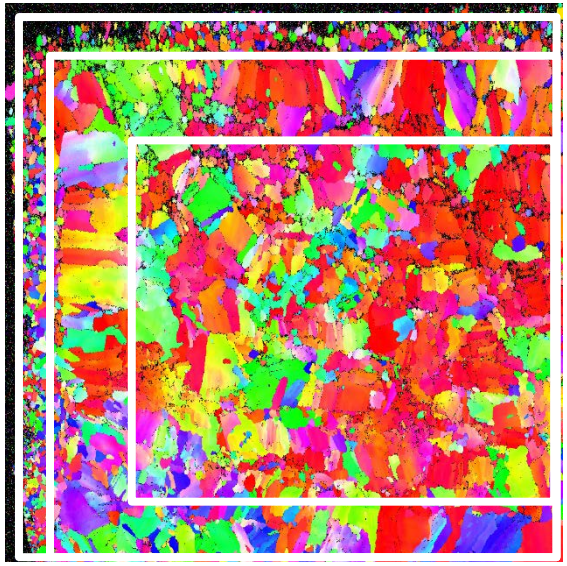


Fig. 6: EBSD scan of SR Only specimen showing apparent microstructure “zones”

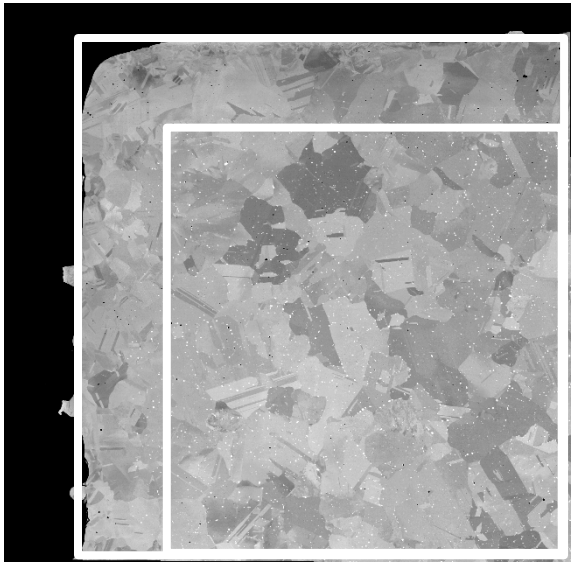


Fig. 7: BSE scan of SR+HIP+HT specimen showing precipitate denuded region

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

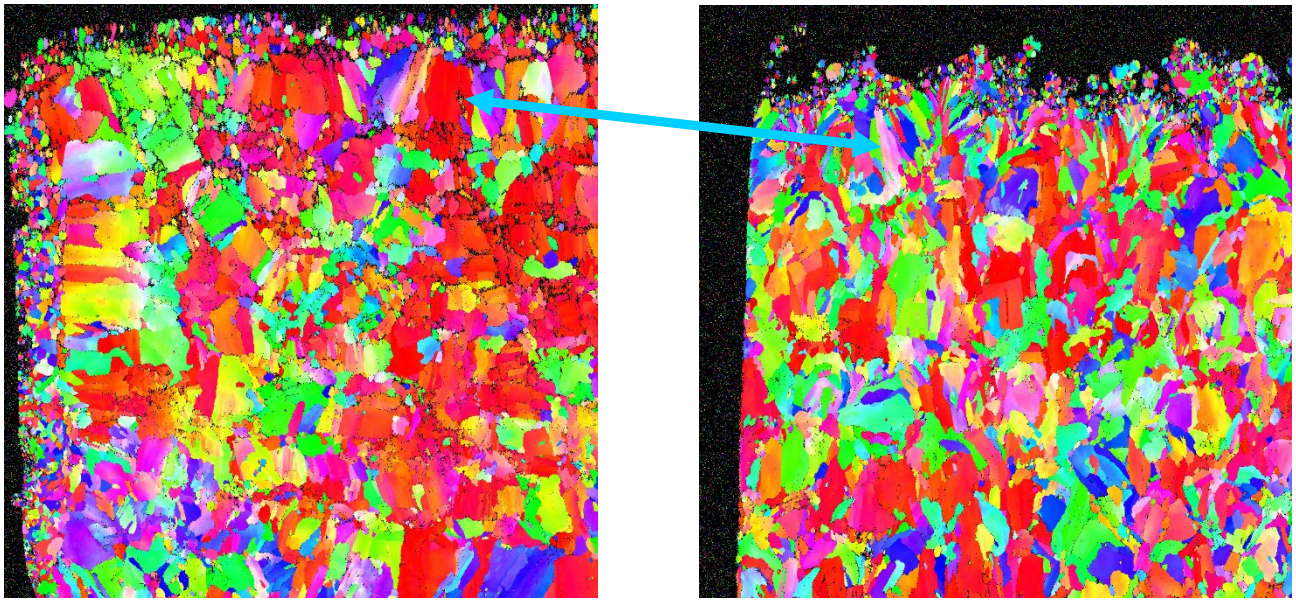


Fig. 8: EBSD scans of SR Only specimen showing/not-showing apparent microstructure “zones” along with complicating roughness. Both scans are of an X’-Y’ face.

Data for Model Calibration

Tensile test data from ASTM E8 bars of AM IN625

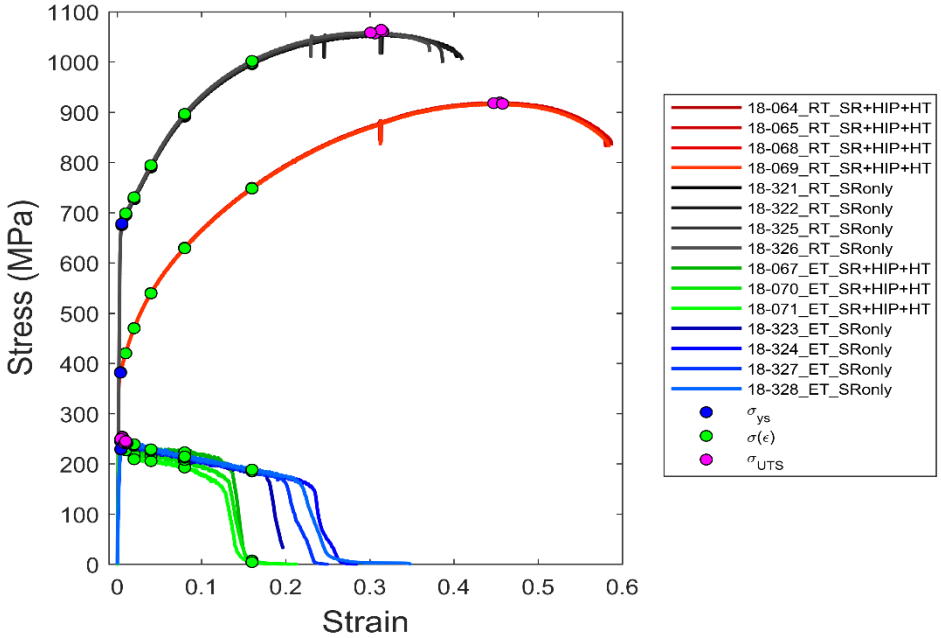


Fig. 9: Stress-strain curves for ASTM E8 tensile bars in SR Only (black=RT, blue=ET) and SR+HIP+HT (red=RT, green=ET) conditions

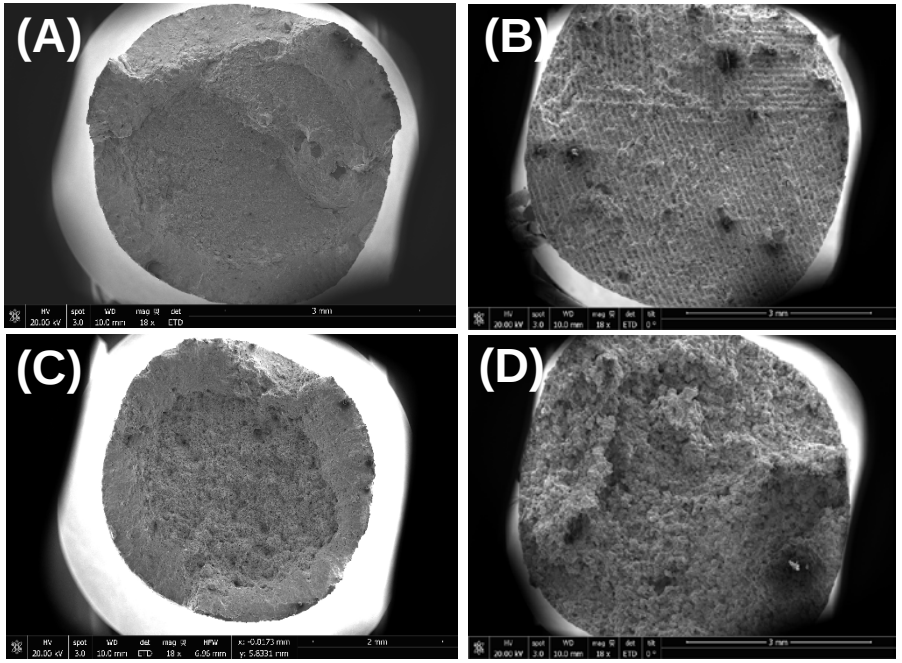


Fig. 10: Fracture surface images for ASTM E8 tensile bars (A) SR Only @ RT, (B) SR Only @ ET, (C) SR+HIP+HT @ RT and (D) SR+HIP+HT @ ET

Post Build Treatment	Build Angle	Sample Diameter [mm]	Test Temperature [°F]	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					
SR	0	15	75					
SR+HIP+HT	0	15	1600					
SR	0	15	1600					

Download Data Package for Calibration Values

Table 1: Extracted mechanical properties for ASTM E8 tensile bars in SR Only and SR+HIP+HT conditions at RT & ET

- Raw stress-strain data for ASTM E8 tests located in \Challenge3\CalibrationData\MechanicalTestData

Data for Model Calibration

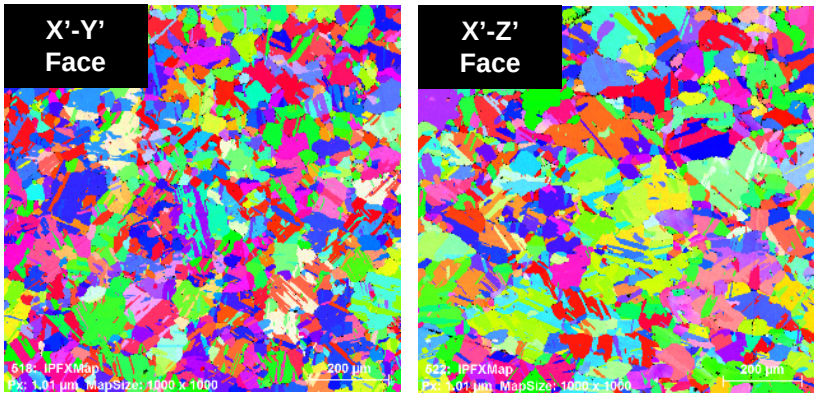


Fig. 11: EBSD scans of SR+HIP+HT ASTM E8 bar

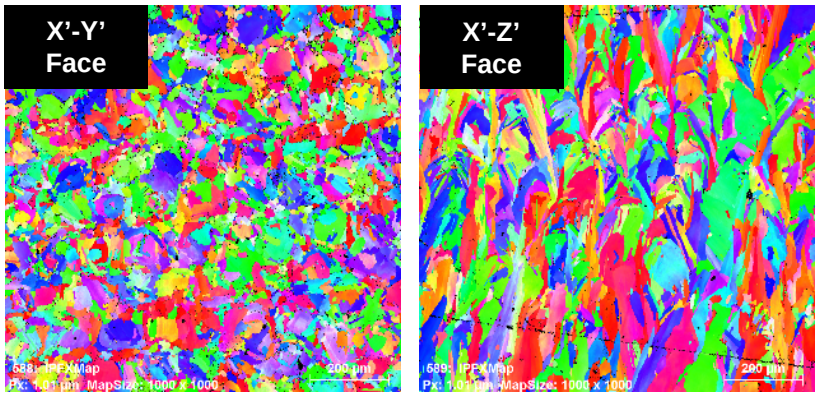


Fig. 12: EBSD scans of SR Only ASTM E8 bar

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				
Yes				

Download Data Package for Calibration Values

Table 2: Grain statistics for ASTM E8 tensile bar in 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

Download Data Package for Calibration Values

Table 3: Grain statistics for ASTM E8 tensile bar in SR Only condition

- Tabulated grain statistics for ASTM E8 bars located in \Challenge3\CalibrationData\MicrostructureData
- Raw EBSD scans & analysis pipelines located in \Challenge3\CalibrationData\MicrostructureData\EBSD
- EBSD Analysis pipelines are located in \Challenge3\Pipelines

Data for Model Calibration

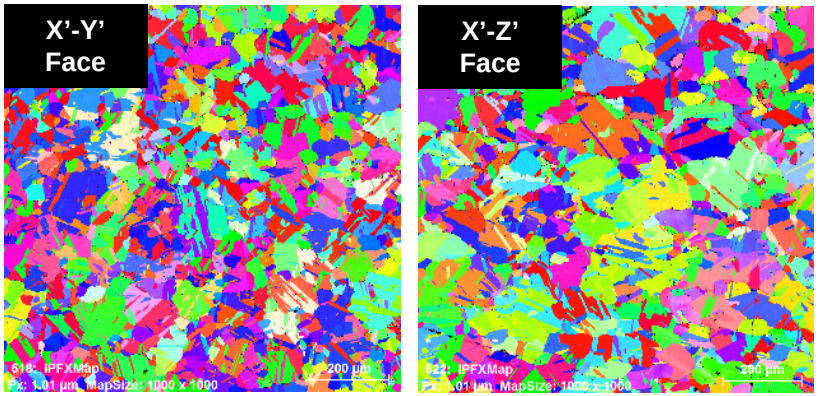


Fig. 11: EBSD scans of SR+HIP+HT ASTM E8 bar

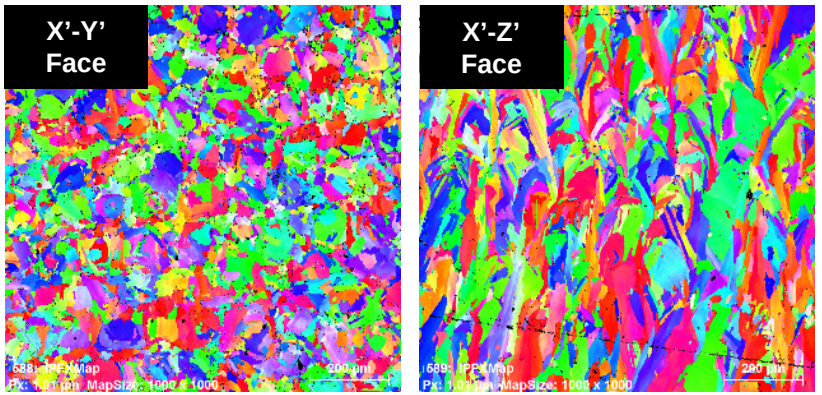


Fig. 12: EBSD scans of SR Only ASTM E8 bar

SR+HIP+HT

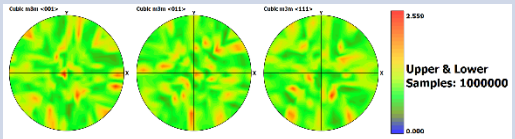
Build Angle	Thickness [µm]	Pole Figures
0	15	

Table 4: Crystallographic orientation data for ASTM E8 tensile bar in SR+HIP+HT condition

SR Only

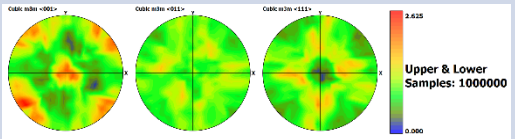
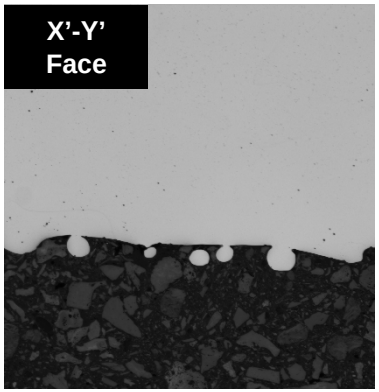
Build Angle	Thickness [µm]	Pole Figures
0	15	

Table 5: Crystallographic orientation data for ASTM E8 tensile bar in SR Only condition

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

Data for Model Calibration



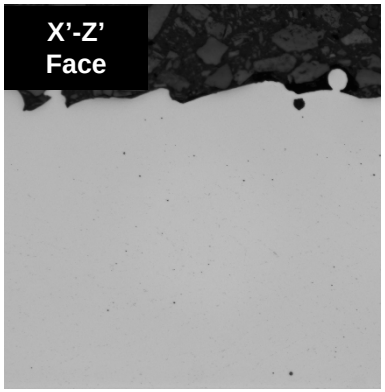
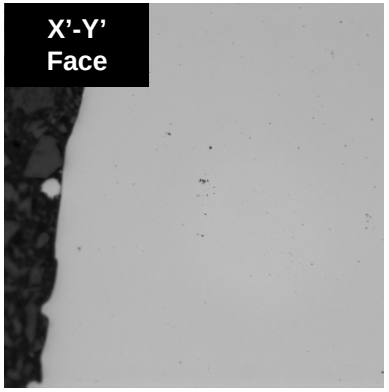


Fig. 13: OM images of SR+HIP+HT ASTM E8 bar



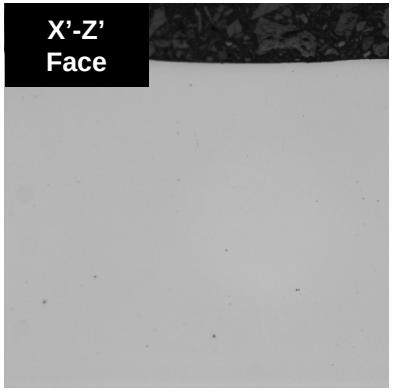


Fig. 14: OM images of SR Only ASTM E8 bar

* Note: E8 bars were turned down from larger cylinders, so roughness is for 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]
Download Data Package for Calibration Values					

Table 6: Void & Roughness statistics for ASTM E8 tensile bar in SR+HIP+HT condition

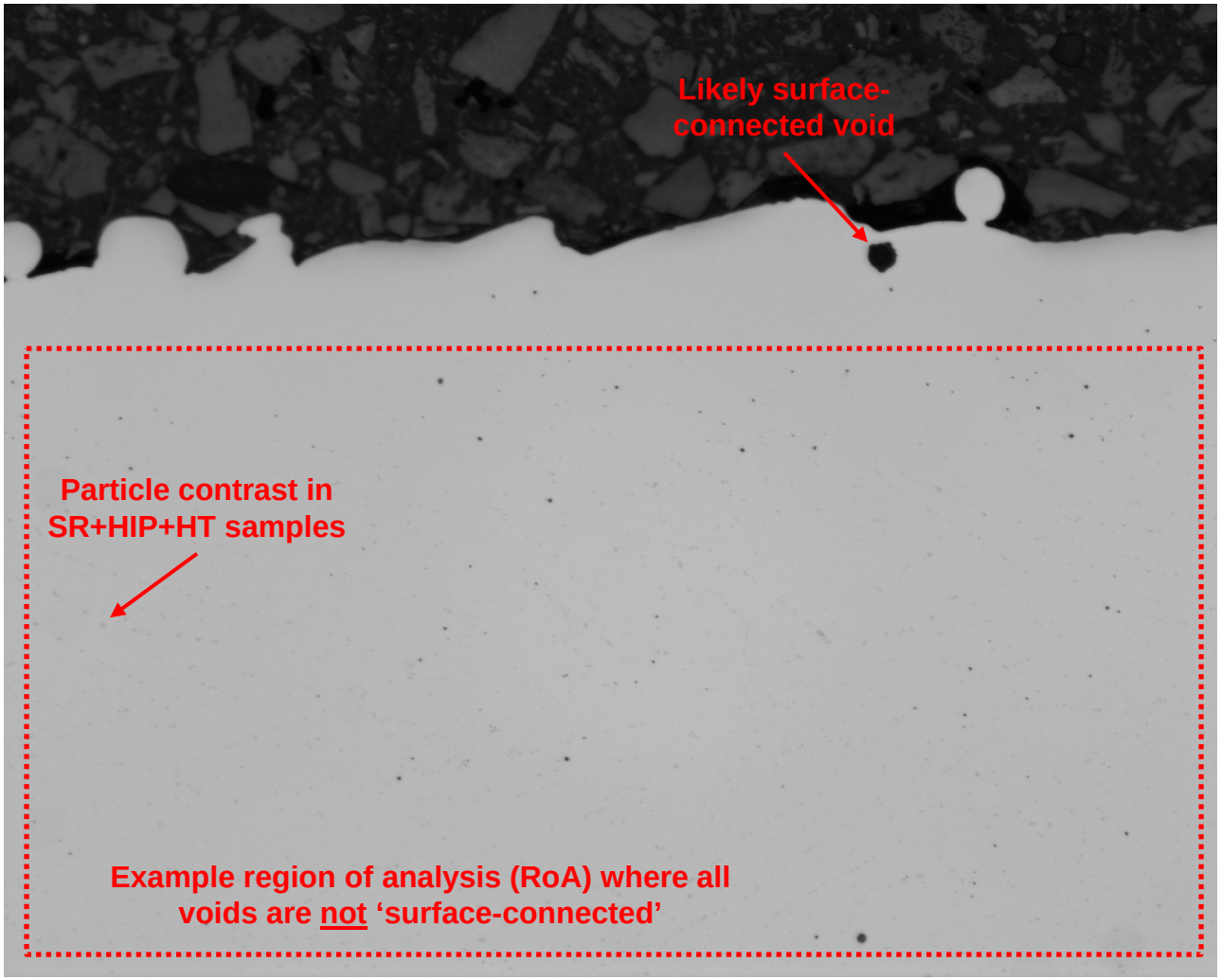
SR Only

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]
Download Data Package for Calibration Values					

Table 7: Void & Roughness statistics for ASTM E8 tensile bar in SR Only condition

- Tabulated void and surface roughness statistics located in \Challenge3\CalibrationData\MicrostructureData
- Raw OM images & analysis pipelines located in \Challenge3\CalibrationData\MicrostructureData\OM

Details of Methodology



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

Fig. 15: 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 *

- Raw OM images & analysis pipelines located in \Challenge3\CalibrationData\MicrostructureData\OM

Details of Methodology

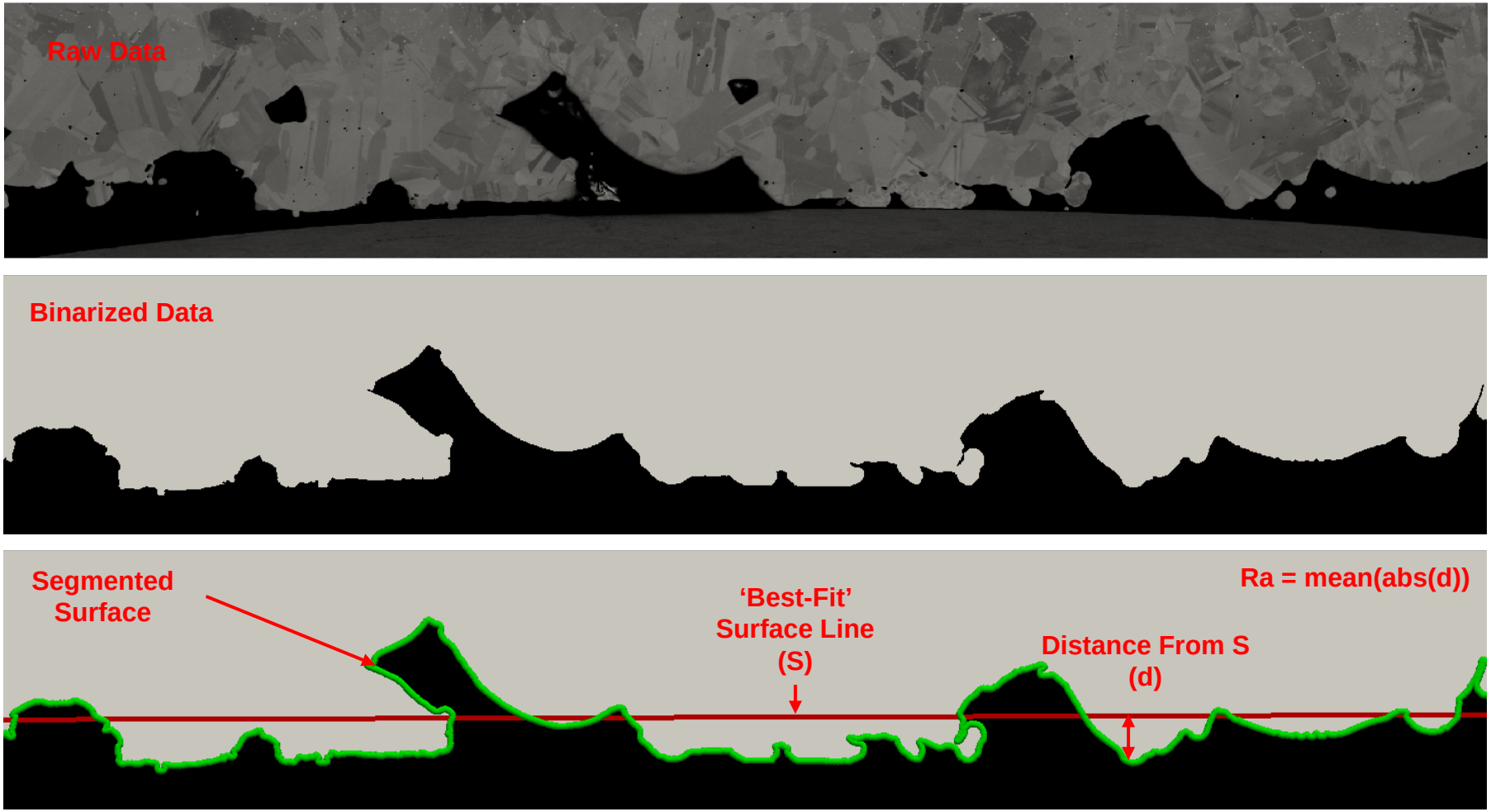


Fig. 16: Example of surface segmentation and Ra calculation method using BSE images

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

- Raw BSE images & analysis pipelines located in \Challenge3\CalibrationData\MicrostructureData\BSE

Data for Model Calibration

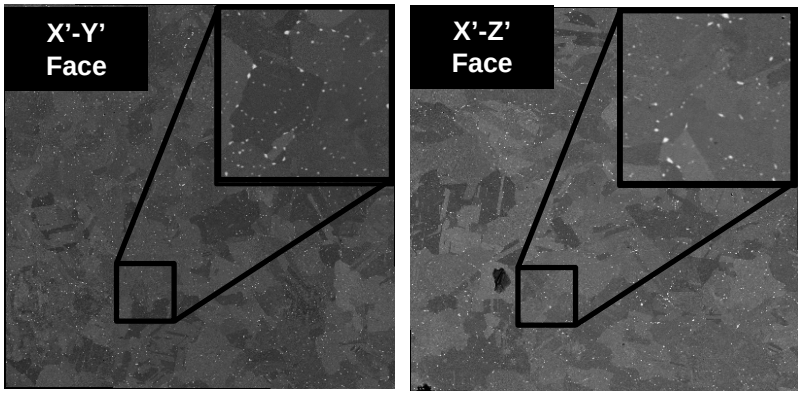


Fig. 17: BSE images of SR+HIP+HT ASTM E8 bar

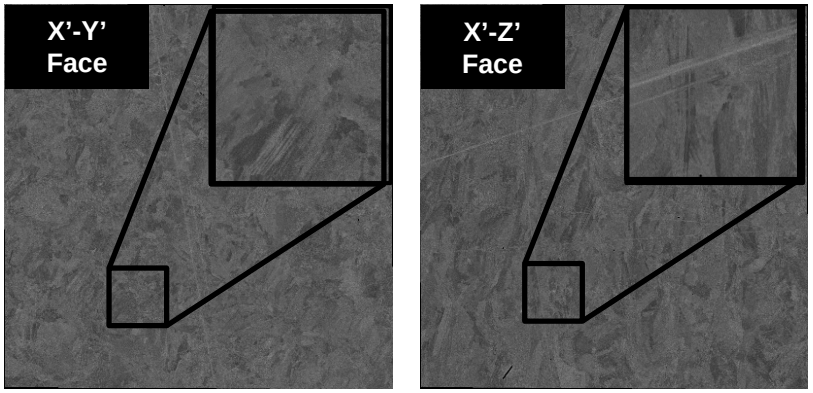


Fig. 18: BSE images of SR Only ASTM E8 bar

	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 [%]
SR+HIP+HT	Download Data Package for Calibration Values				

Table 8: Precipitate statistics for ASTM E8 tensile bar in SR+HIP+HT condition

	X-Y Precipitate Size [µm] µ, σ	X-Y Precipitate V_f [%]	X-Z Precipitate Size [µm] µ, σ	X-Z Precipitate V_f [%]
SR Only	Download Data Package for Calibration Values			

Table 9: Precipitate statistics for ASTM E8 tensile bar in SR Only condition

- Tabulated precipitate statistics located in \Challenge3\CalibrationData\MicrostructureData
- Raw BSE images & analysis pipelines located in \Challenge3\CalibrationData\MicrostructureData\BSE

Data for Model Calibration

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

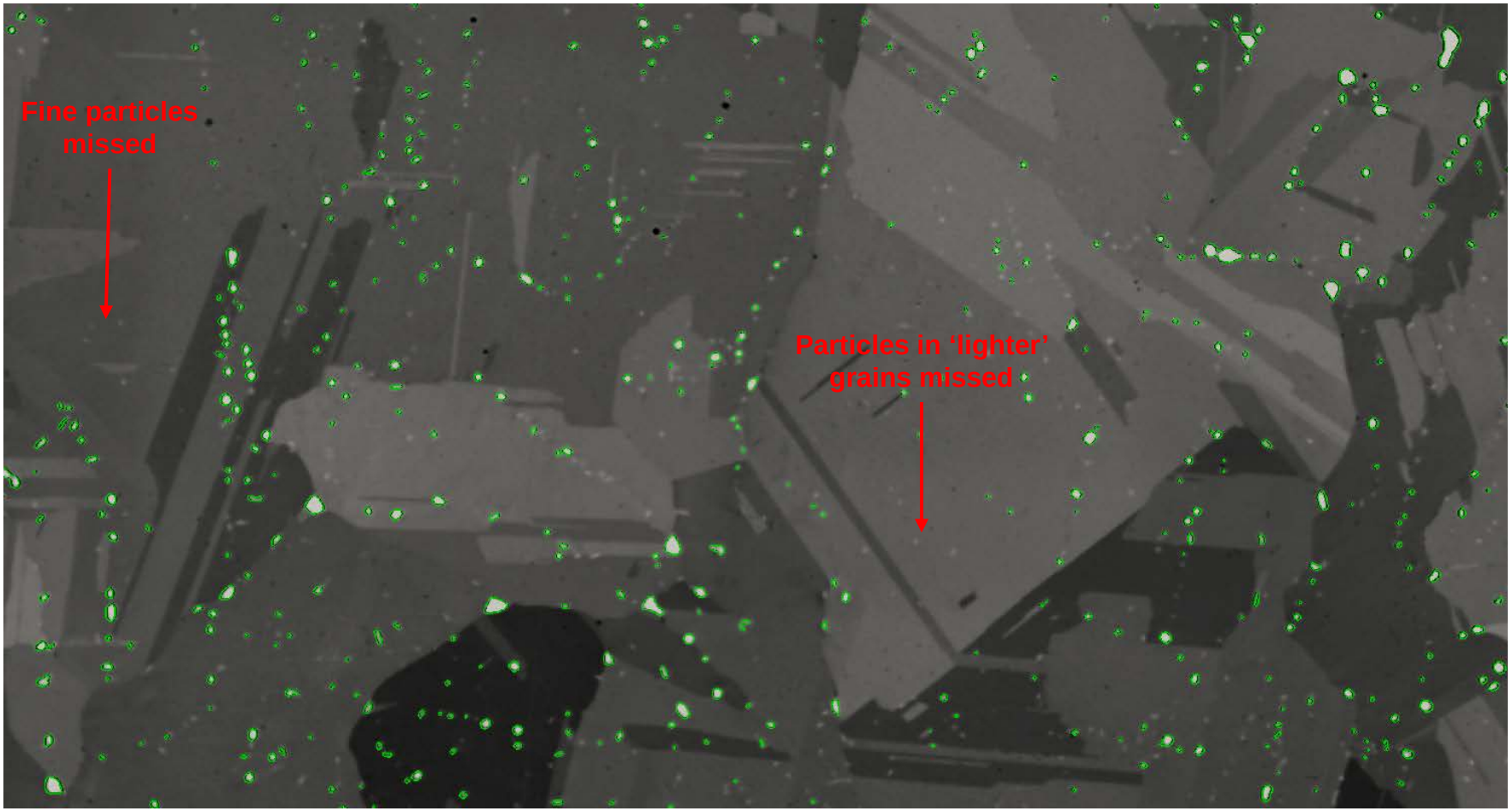


Fig. 18: Example segmentation of precipitates in BSE images of ASTM E8 bars with annotations showing missed particles

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

- Raw BSE images & analysis pipelines located in \Challenge3\CalibrationData\MicrostructureData\BSE

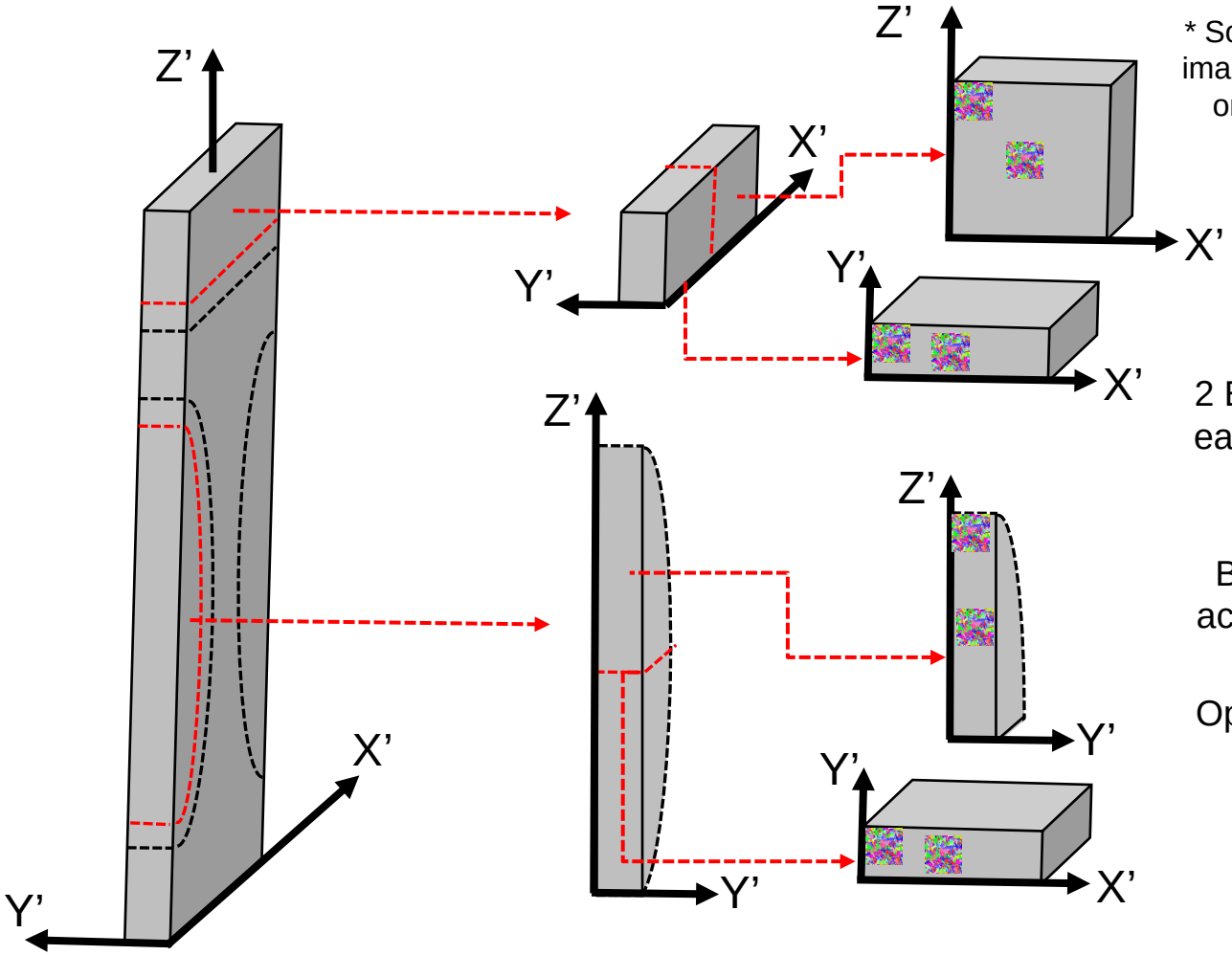
Data for Model Calibration

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

Table 10: Chemical Analysis of IN625 Powder (prior to build)

- Chemical analysis of powder lot used in builds of single tracks and 2D pads
- Chemical analysis performed by powder supplier
- Gas atomized powder
- No post-build chemical analysis performed

Characterization Details



* 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. 21: Schematic showing locations of characterization material extracted from milli-scale tensile specimen

Microstructural Input Data

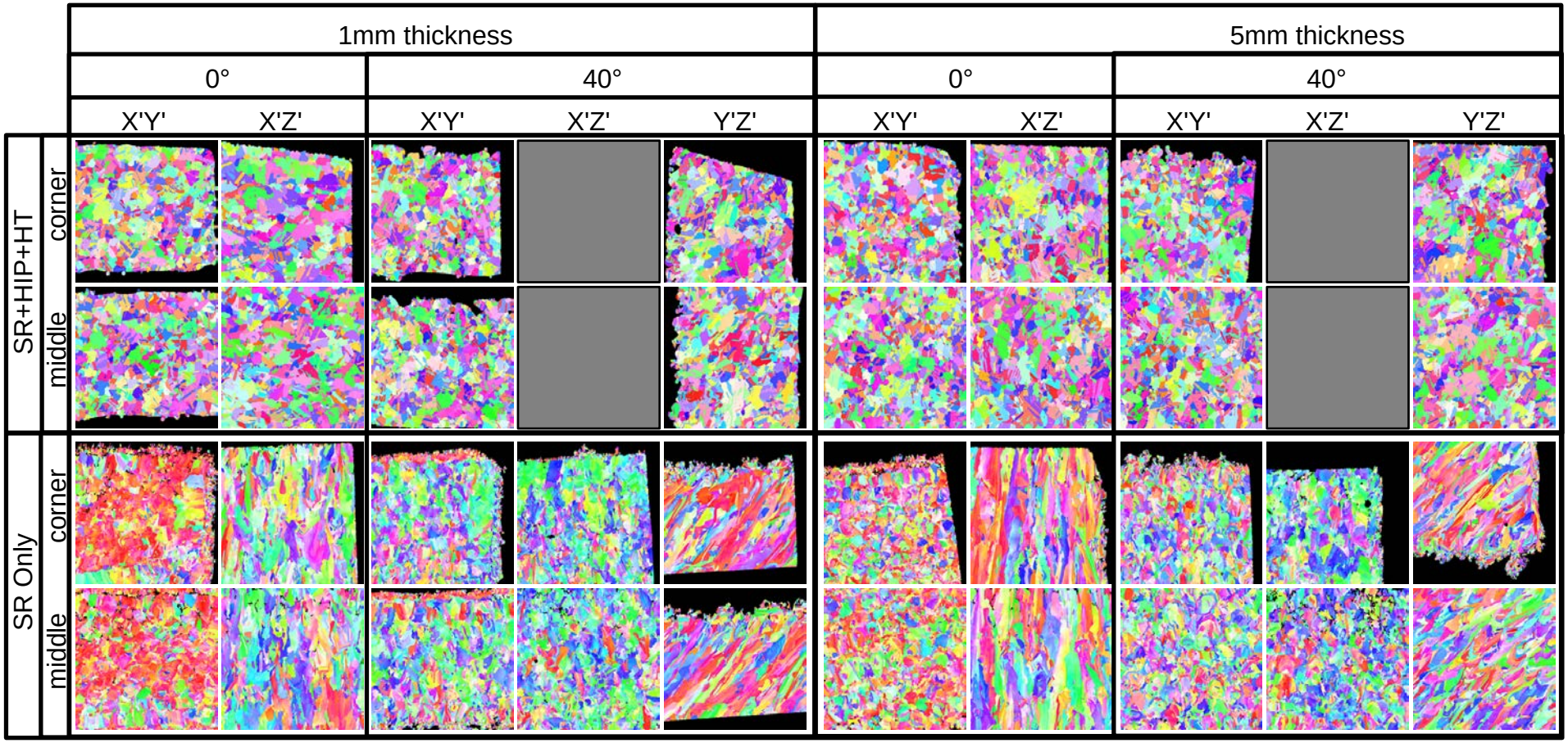
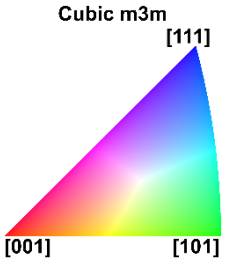


Fig. 22: EBSD Inverse Pole Figure (Z) scans for all microstructure conditions



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				
corner	X'Y'	Yes				
middle	X'Y'	No				
middle	X'Y'	Yes				
corner	X'Z'	No				
corner	X'Z'	Yes				
middle	X'Z'	No				
middle	X'Z'	Yes				

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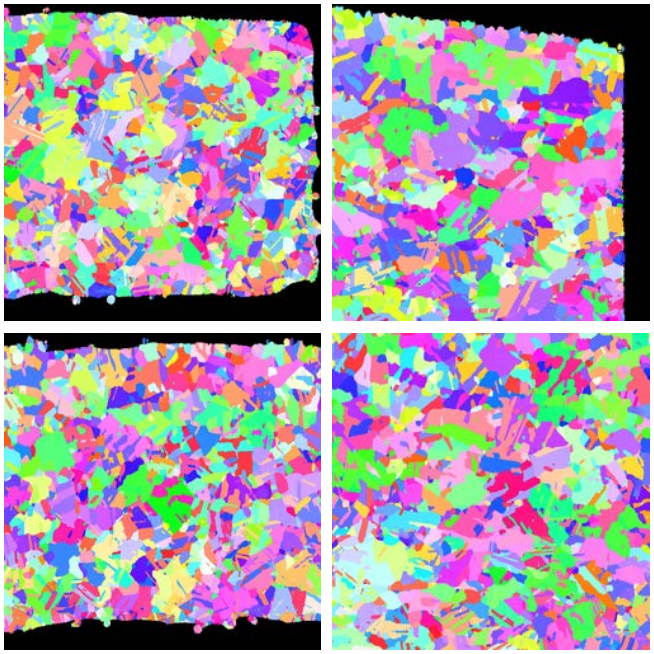
X'Y' X'Z'

corner

middle



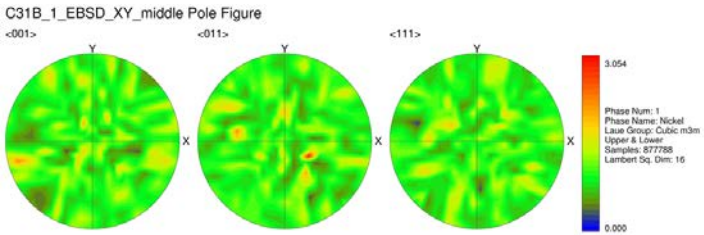
Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: Challenge3\Input Data\1mm - 0deg - SR+HIP+HT\

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]

Download Data Package for Input Values

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 [%]

Download Data Package for Input Values

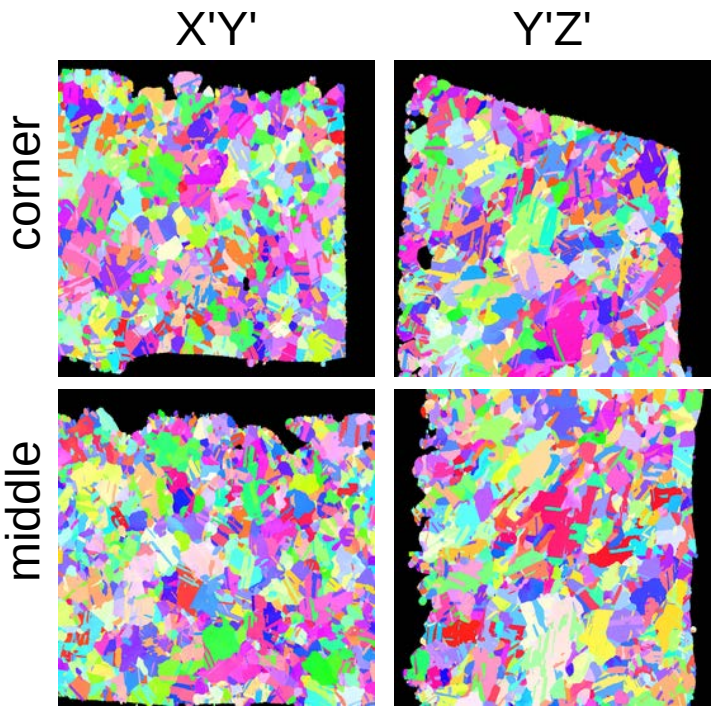


1mm - 40deg - SR+HIP+HT (C09)

	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				
corner	X'Y'	Yes				
middle	X'Y'	No				
middle	X'Y'	Yes				
corner	Y'Z'	No				
corner	Y'Z'	Yes				
middle	Y'Z'	No				
middle	Y'Z'	Yes				

Download Data Package for Input Values



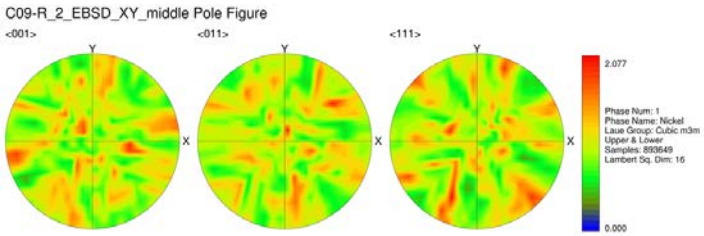
Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: \Challenge3\Input Data\1mm - 40deg - SR+HIP+HT

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]

Download Data Package for Input Values

Denuded Zone Thickness [µm]	X-Y Precipitate Size [µm] µ,	X-Y Precipitate V_f	Y-Z Precipitate Size [µm] µ,	Y-Z Precipitate V_f

Download Data Package for Input Values



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

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

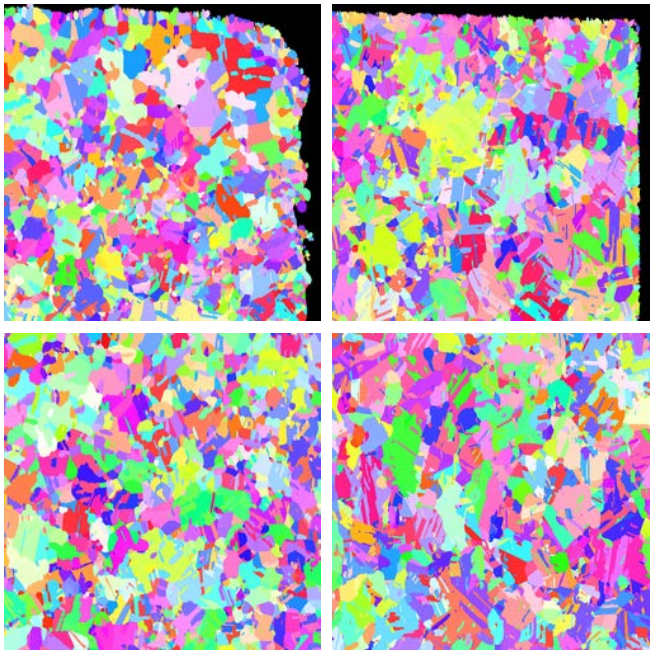
Location	View	Twins Merged	Grain Size – Mean [µm]	Grain Size – StdDev [µm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No				
corner	X'Y'	Yes				
middle	X'Y'	No				
middle	X'Y'	Yes				
corner	X'Z'	No				
corner	X'Z'	Yes				
middle	X'Z'	No				
middle	X'Z'	Yes				

Download Data Package for Input Values

X'Y' X'Z'

corner

middle



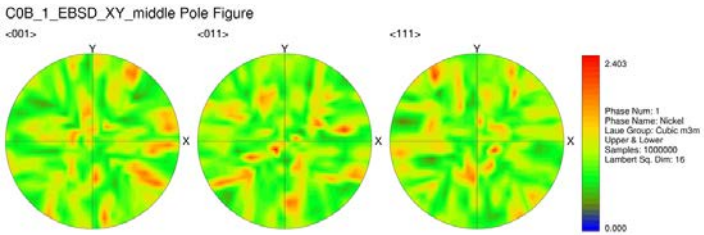
Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: \Challenge3\Input Data\5mm - 0deg - SR+HIP+HT

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]

Download Data Package for Input Values

Denuded Zone Thickness [µm]	X-Y Precipitate Size [µm] µ,	X-Y Precipitate V_f	X-Z Precipitate Size [µm] µ,	X-Z Precipitate V_f

Download Data Package for Input Values

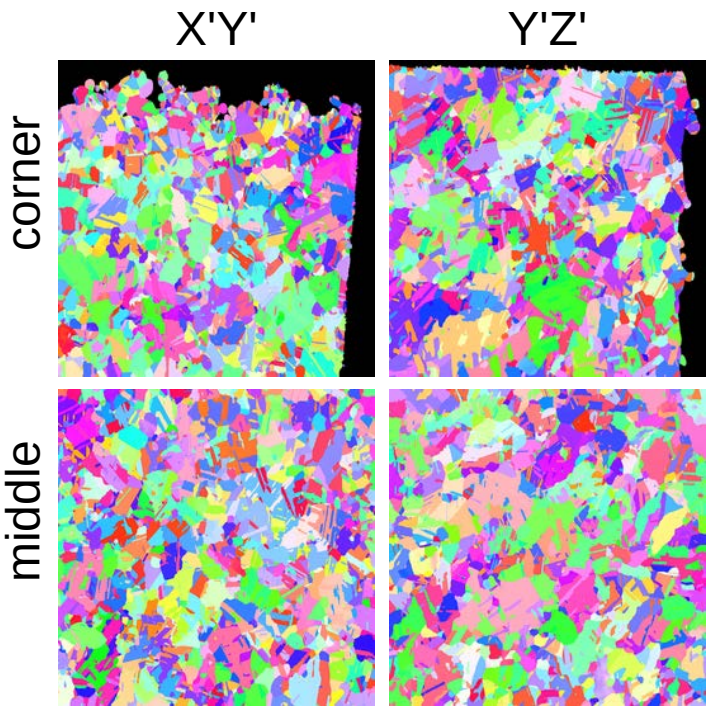


5mm - 40deg - SR+HIP+HT (C13)

	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				
corner	X'Y'	Yes				
middle	X'Y'	No				
middle	X'Y'	Yes				
corner	Y'Z'	No				
corner	Y'Z'	Yes				
middle	Y'Z'	No				
middle	Y'Z'	Yes				

Download Data Package for Input Values



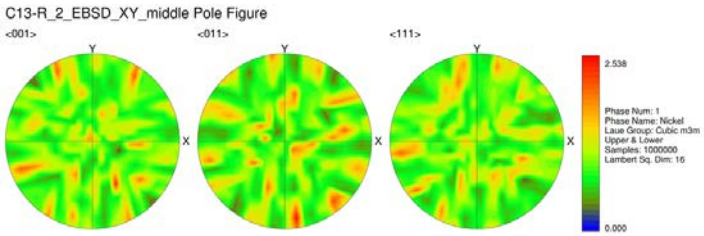
Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: \Challenge3\Input Data\5mm - 40deg - SR+HIP+HT

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]

Download Data Package for Input Values

Denuded Zone Thickness [µm]	X-Y Precipitate Size [µm] µ,	X-Y Precipitate V_f	Y-Z Precipitate Size [µm] µ,	Y-Z Precipitate V_f

Download Data Package for Input Values



1mm - 0deg - SR (G33)

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

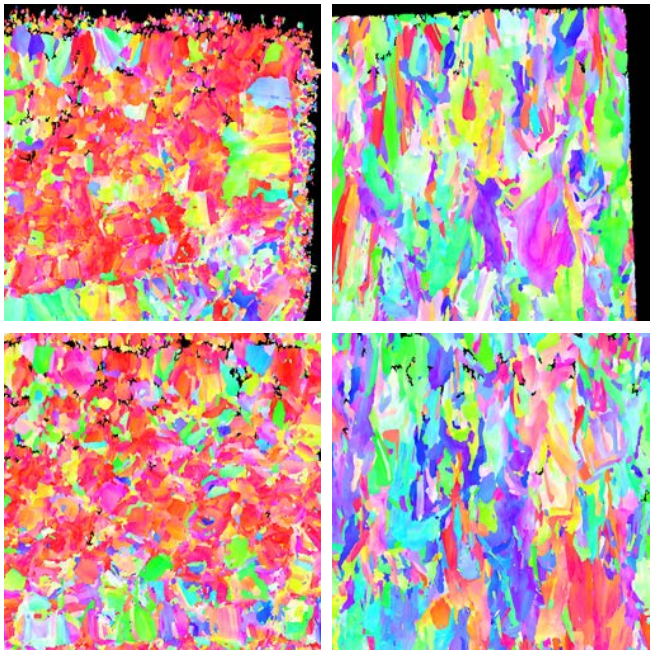
Location	View	Twins Merged	Grain Size – Mean [µm]	Grain Size – StdDev [µm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No				
middle	X'Y'	No				
corner	X'Z'	No				
corner	X'Z'	No				
corner	X'Z'	No				
middle	X'Z'	No				
middle	X'Z'	No				
middle	X'Z'	No				

Download Data Package for Input Values

X'Y' X'Z'

corner

middle



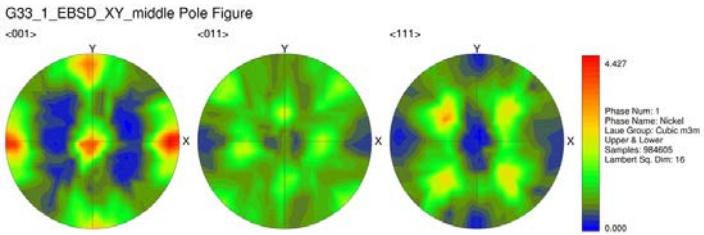
Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: \Challenge 3 Fixes\Input Data\1mm - 0deg - SR only

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]

Download Data Package for Input Values

Denuded Zone Thickness [µm]	X-Y Precipitate Size [µm] µ,	X-Y Precipitate V_f	X-Z Precipitate Size [µm] µ,	X-Z Precipitate V_f

Download Data Package for Input Values



1mm - 40deg - SR (H50)

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

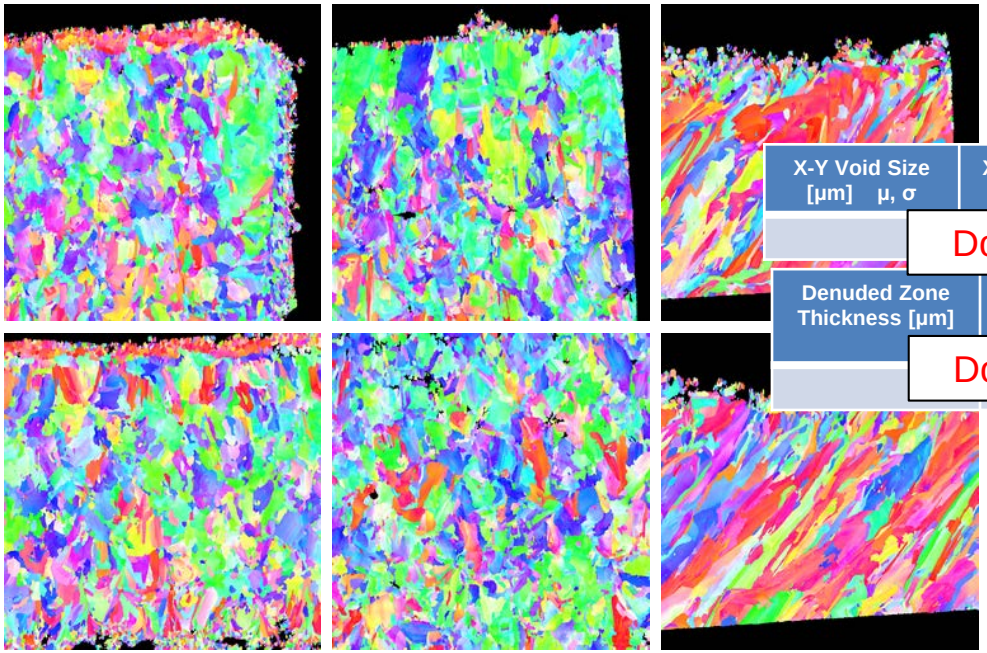
Location	View	Twins Merged	Grain Size – Mean [µm]	Grain Size – StdDev [µm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No				
middle	X'Y'	No				
corner	X'Z'	No				
middle	X'Z'	No				
corner	Y'Z'	No				
middle	Y'Z'	No				

Download Data Package for Input Values

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

corner

middle

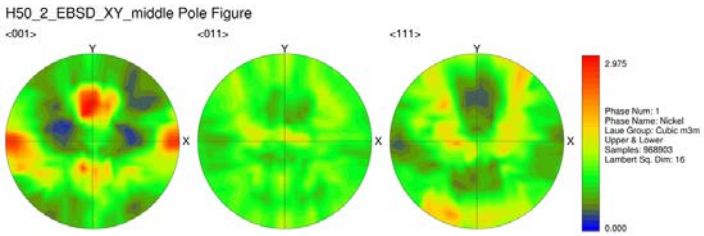


X-Y Void Size [µm] µ, σ	X-Y Void V_f %	Top R_a [µm]	X-Z Void Size [µm] µ, σ	X-Z Void V_f %	Bottom R_a [µm]

Download Data Package for Input Values

Denuded Zone Thickness [µm]	X-Y Precipitate Size [µm] µ,	X-Y Precipitate V_f	X-Z Precipitate Size [µm] µ,	X-Z Precipitate V_f

Download Data Package for Input Values



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)

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

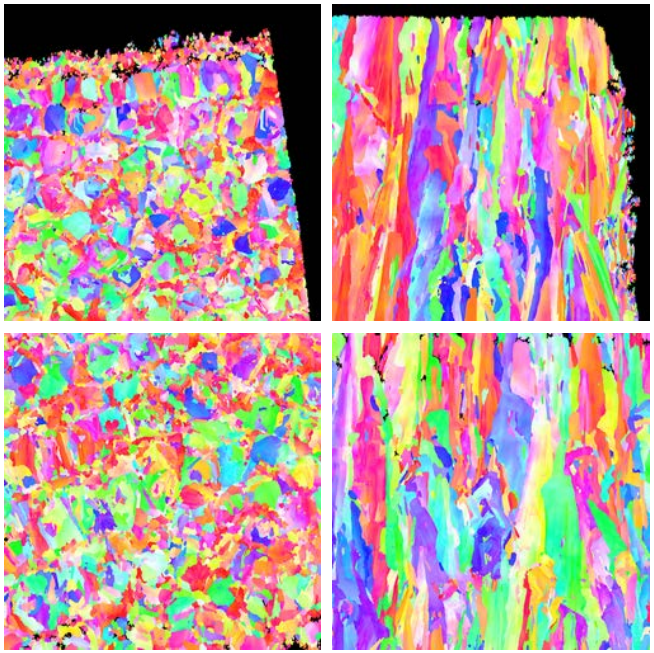
Location	View	Twins Merged	Grain Size – Mean [µm]	Grain Size – StdDev [µm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No				
middle	X'Y'	No				
corner	X'Z'	No				
corner	X'Z'	No				
corner	X'Z'	No				
middle	X'Z'	No				
middle	X'Z'	No				
middle	X'Z'	No				

Download Data Package for Input Values

X'Y' X'Z'

corner

middle



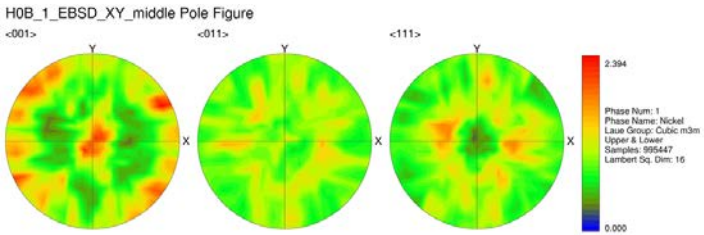
Original IPFZ map field of view: 1mm x 1mm, 1000 x 1000px.
Original Data at: \Challenge3\Input Data\5mm - 0deg - SR only

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]

Download Data Package for Input Values

Denuded Zone Thickness [µm]	X-Y Precipitate Size [µm] µ,	X-Y Precipitate V_f	X-Z Precipitate Size [µm] µ,	X-Z Precipitate V_f

Download Data Package for Input Values



5mm - 40deg - SR (G70)

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

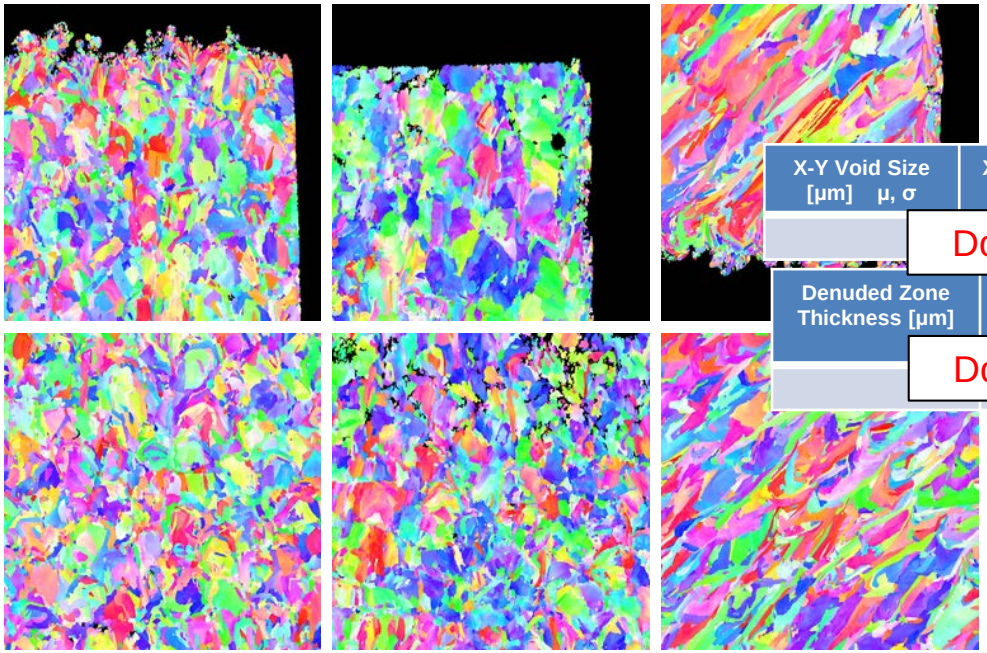
Location	View	Twins Merged	Grain Size – Mean [µm]	Grain Size – StdDev [µm]	Aspect Ratio Mean	Aspect Ratio StdDev
corner	X'Y'	No				
middle	X'Y'	No				
corner	X'Z'	No				
middle	X'Z'	No				
corner	Y'Z'	No				
middle	Y'Z'	No				

Download Data Package for Input Values

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

corner

middle

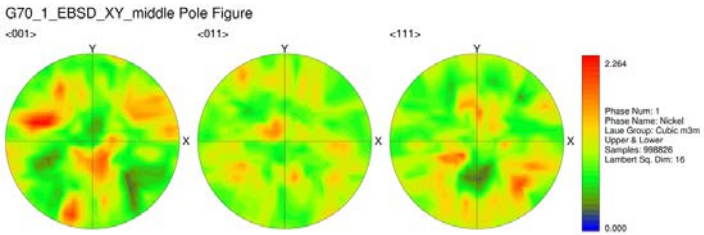


X-Y Void Size [µm] µ, σ	X-Y Void V_f %	Top R_a [µm]	X-Z Void Size [µm] µ, σ	X-Z Void V_f %	Bottom R_a [µm]

Download Data Package for Input Values

Denuded Zone Thickness [µm]	X-Y Precipitate Size [µm] µ,	X-Y Precipitate V_f	X-Z Precipitate Size [µm] µ,	X-Z Precipitate V_f

Download Data Package for Input Values



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

Answer Format

* Note: there will be two answer sheets, one for 'as-printed' and one for 'surface-machined' condition

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			**		
SR+HIP+HT	40	1	1600					
SR+HIP+HT	0	5	1600					
SR+HIP+HT	40	5	1600					
SR	0	1	1600					
SR	40	1	1600					
SR	0	5	1600					
SR	40	5	1600					

- Predictions for each geometry + microstructure + environment condition are worth same value
- Grades will consist of accumulating points based on accuracy of predictions:
  - 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 = 7 pts; +/- 20 MPa = 3 pts; +/- 40 = 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
  - ** For 1600ºF results, stress @ 16% will not be utilized for scoring, only report 1%, 2%, 4%, and 8%
- Answer sheet template located in \Challenge3\AnswerTemplate.xls