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

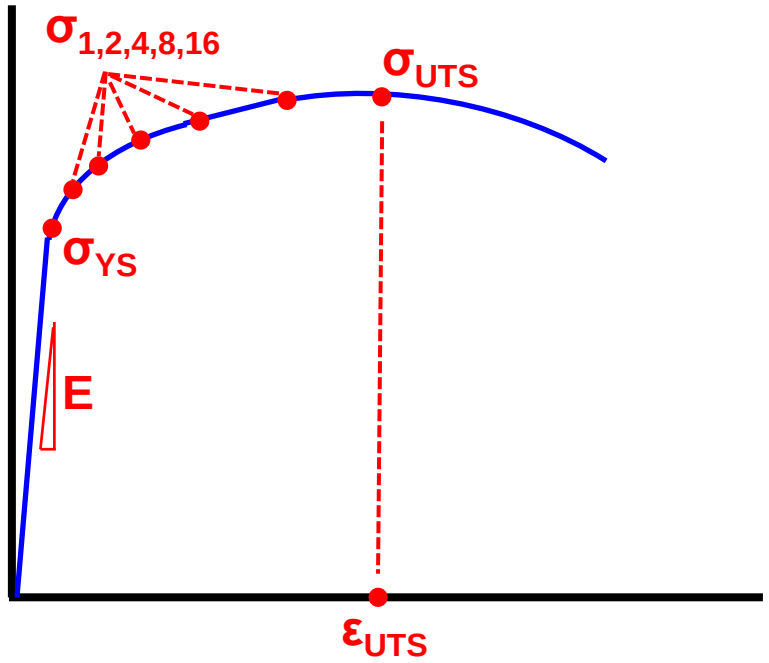


Fig. 1: Schematic of stress-strain curve with desired predictions

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

Coordinate Systems & Specimen Geometries

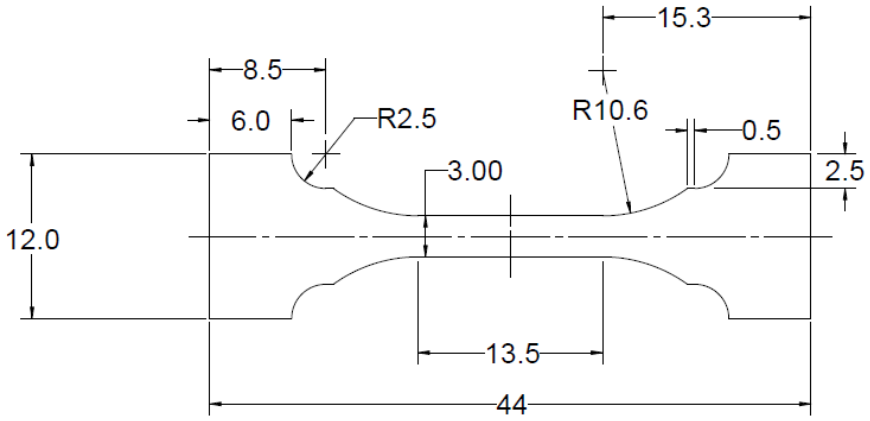


Fig. 2: Drawing of milli-scale tensile specimen (units in mm)

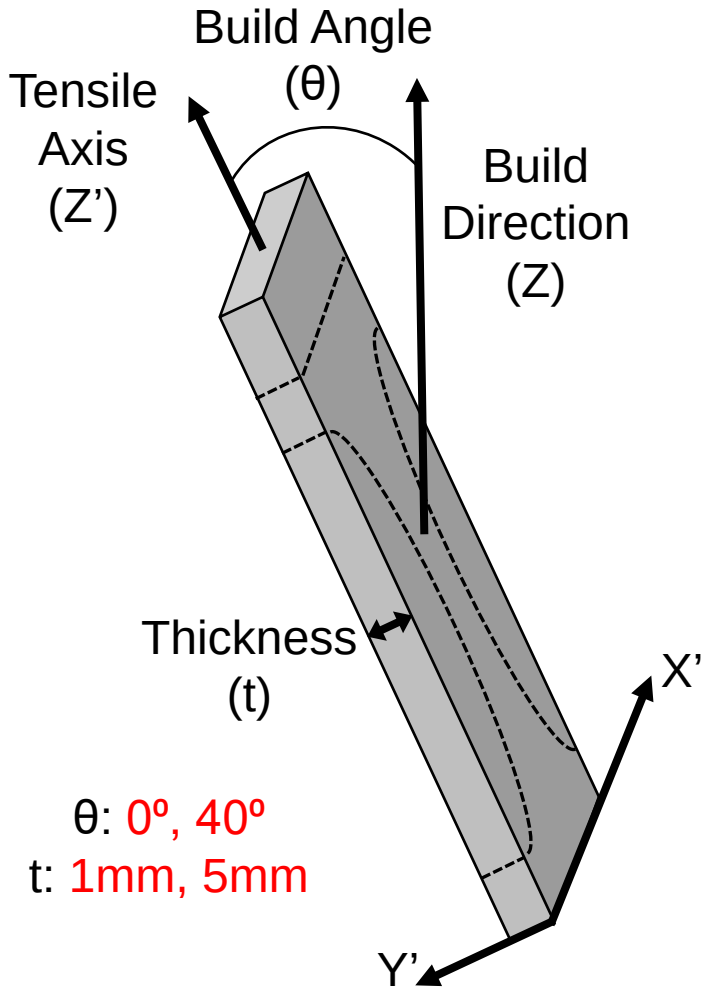


Fig. 3: Schematic showing extraction of tensile samples

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

Description of Requested Metrics

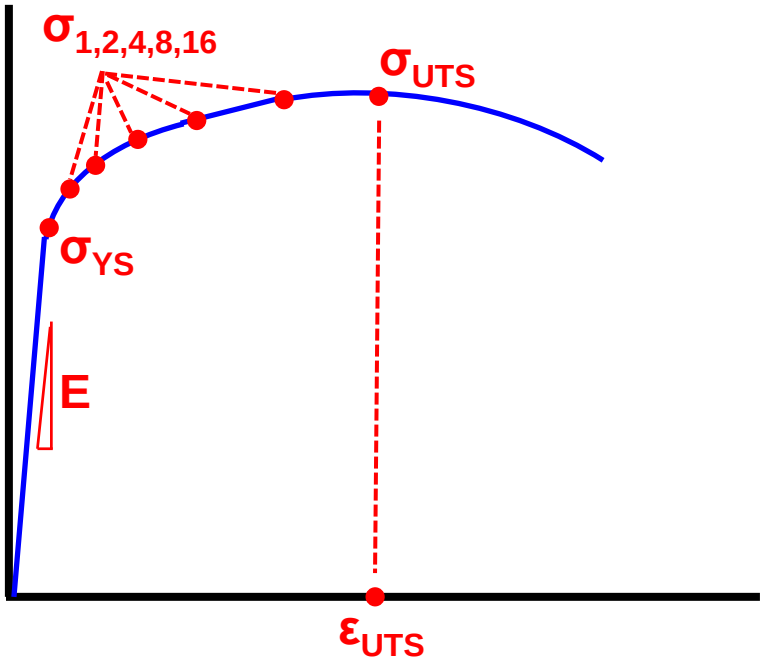


Fig. 4: Schematic of stress-strain curve with desired predictions

- Elastic Modulus (E): slope of the linear fit to data points from 25 MPa to the point 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”

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.

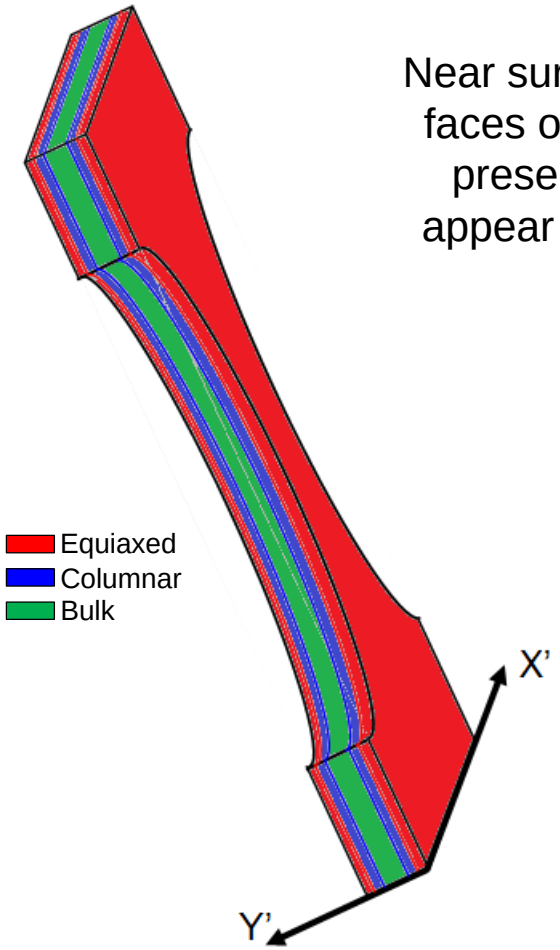


Fig. 5: Schematic of milli-scale tensile sample with potential ‘zones’ annotated to display ‘pseudo-laminate’ nature of microstructure

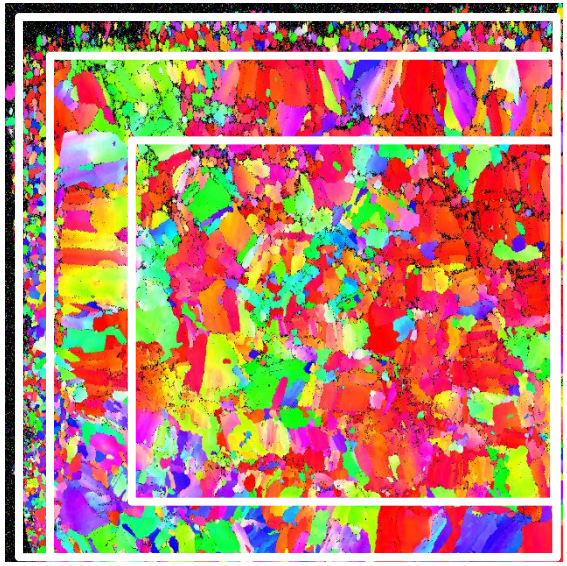


Fig. 6: EBSD scan of SR Only specimen showing apparent microstructure “zones”

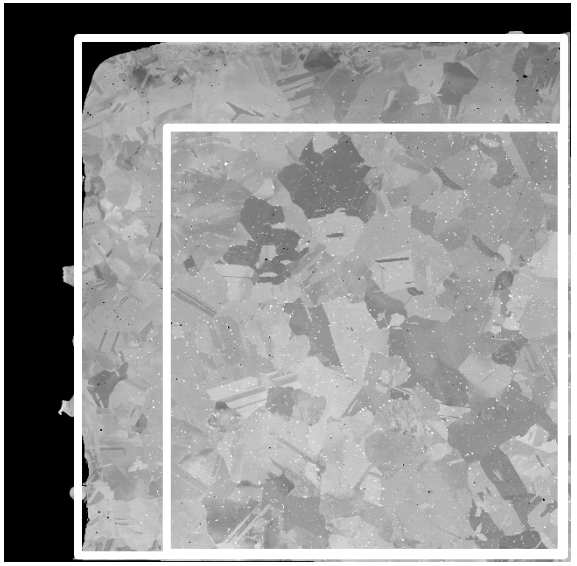


Fig. 7: BSE scan of SR+HIP+HT specimen showing precipitate denuded region

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 the presence of a 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

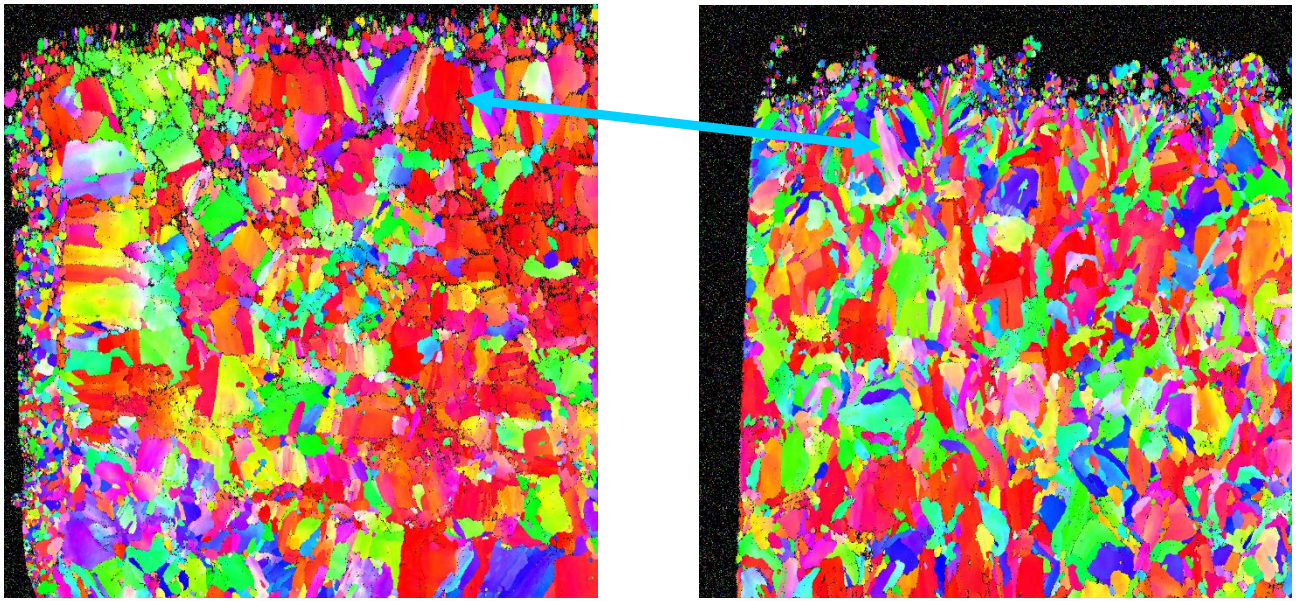


Fig. 8: EBSD scans of SR Only specimen showing/not-showing apparent microstructure “zones” along with complicating roughness. Both scans are of an X’-Y’ face.

Data for Model Calibration

Tensile test data from ASTM E8 bars of AM IN625

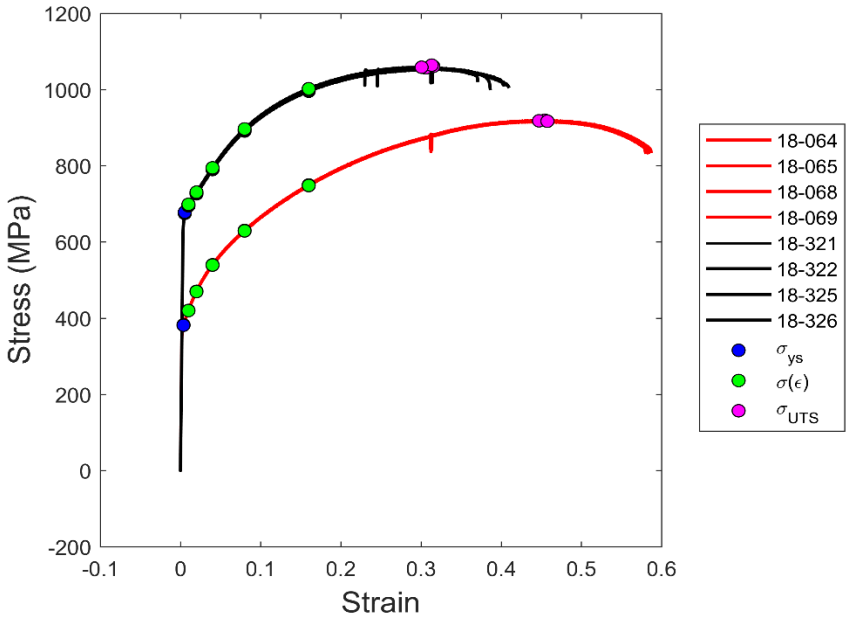


Fig. 9: Room temperature stress-strain curves for ASTM E8 tensile bars in SR Only (black) and SR+HIP+HT (red) conditions

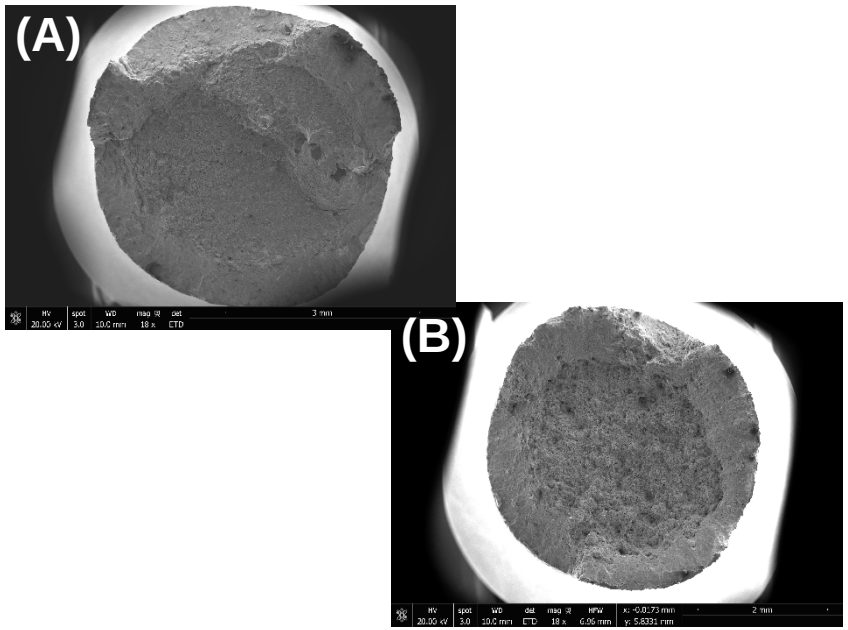


Fig. 10: Fracture surface images for ASTM E8 tensile bars at RT in (A) SR Only and (B) SR+HIP+HT conditions

	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	75					
SR	75					
SR+HIP+HT	1600					
SR	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

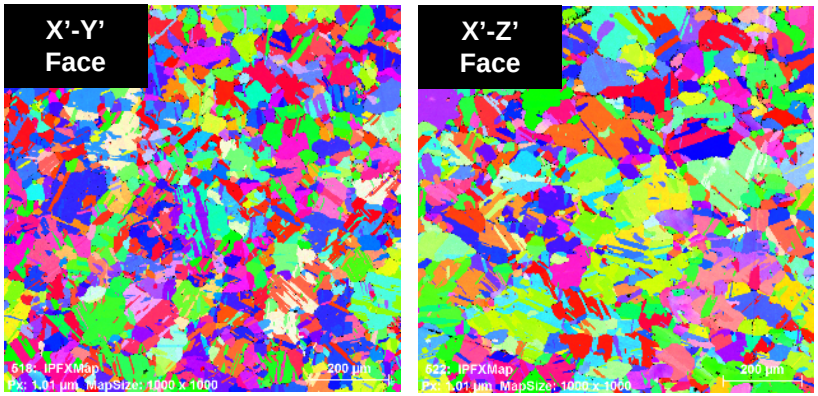


Fig. 11: EBSD scans of SR+HIP+HT ASTM E8 bar

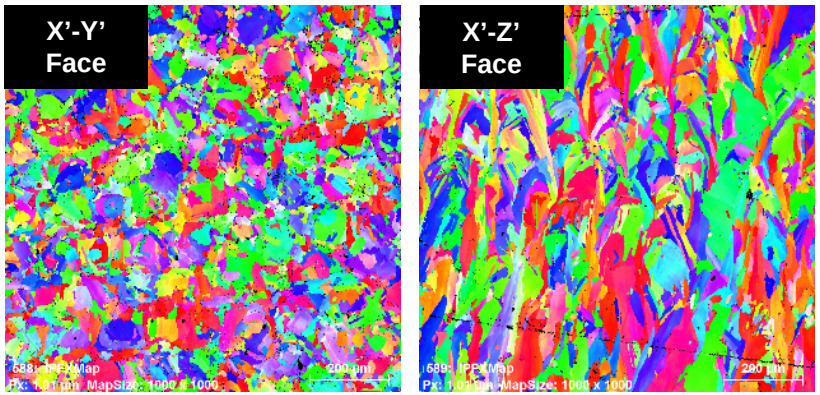


Fig. 12: EBSD scans of SR Only ASTM E8 bar

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	Download Data Package for Calibration Values			
Yes				

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

Data for Model Calibration

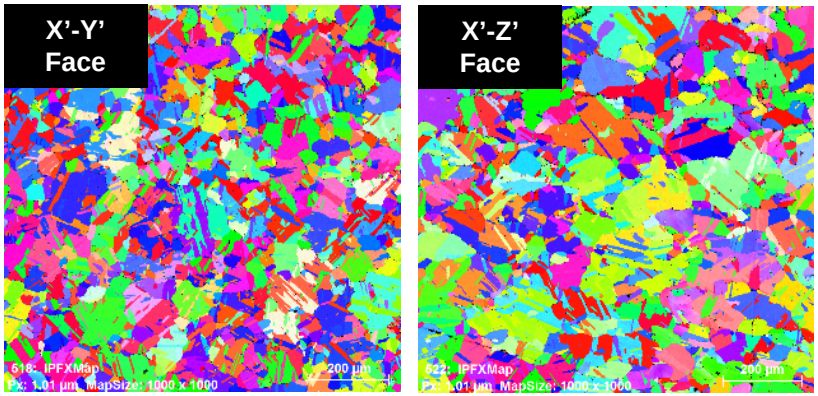


Fig. 11: EBSD scans of SR+HIP+HT ASTM E8 bar

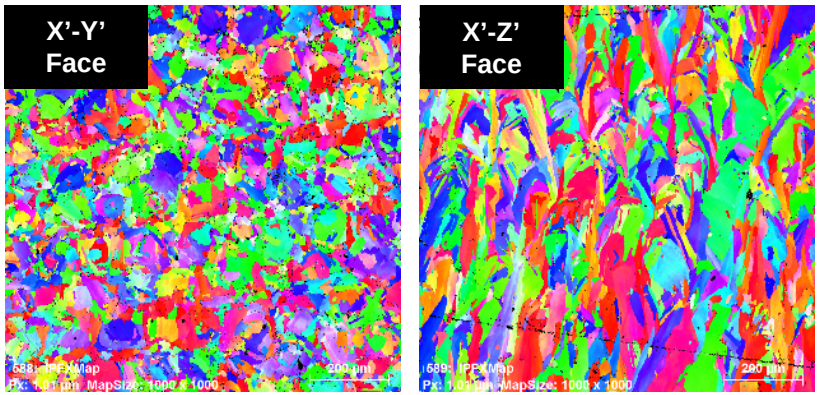


Fig. 12: EBSD scans of SR Only ASTM E8 bar

SR+HIP+HT

Pole Figures
Download Data Package for Calibration Values

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

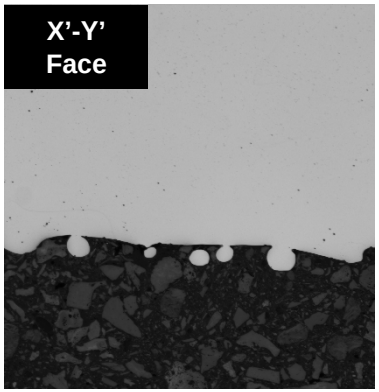
SR Only

Pole Figures
Download Data Package for Calibration Values

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

- Discrete list of orientations located in \Challenge3\CalibrationData\MicrostructureData

Data for Model Calibration



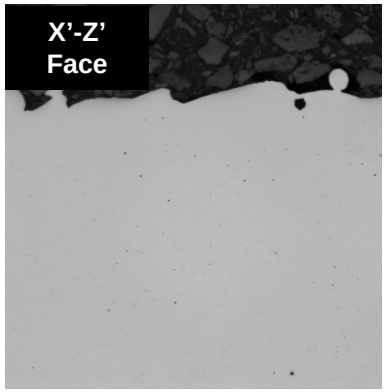
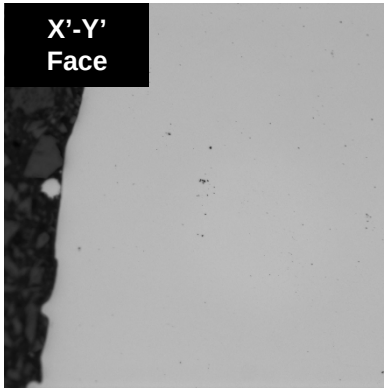


Fig. 13: OM images of SR+HIP+HT ASTM E8 bar



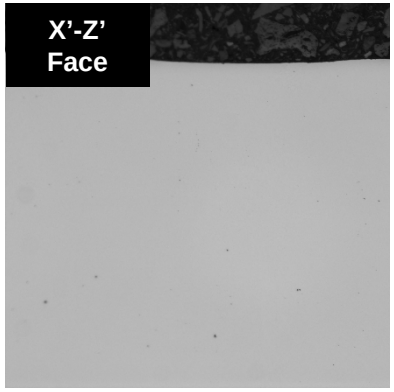


Fig. 14: OM images of SR Only ASTM E8 bar

* 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

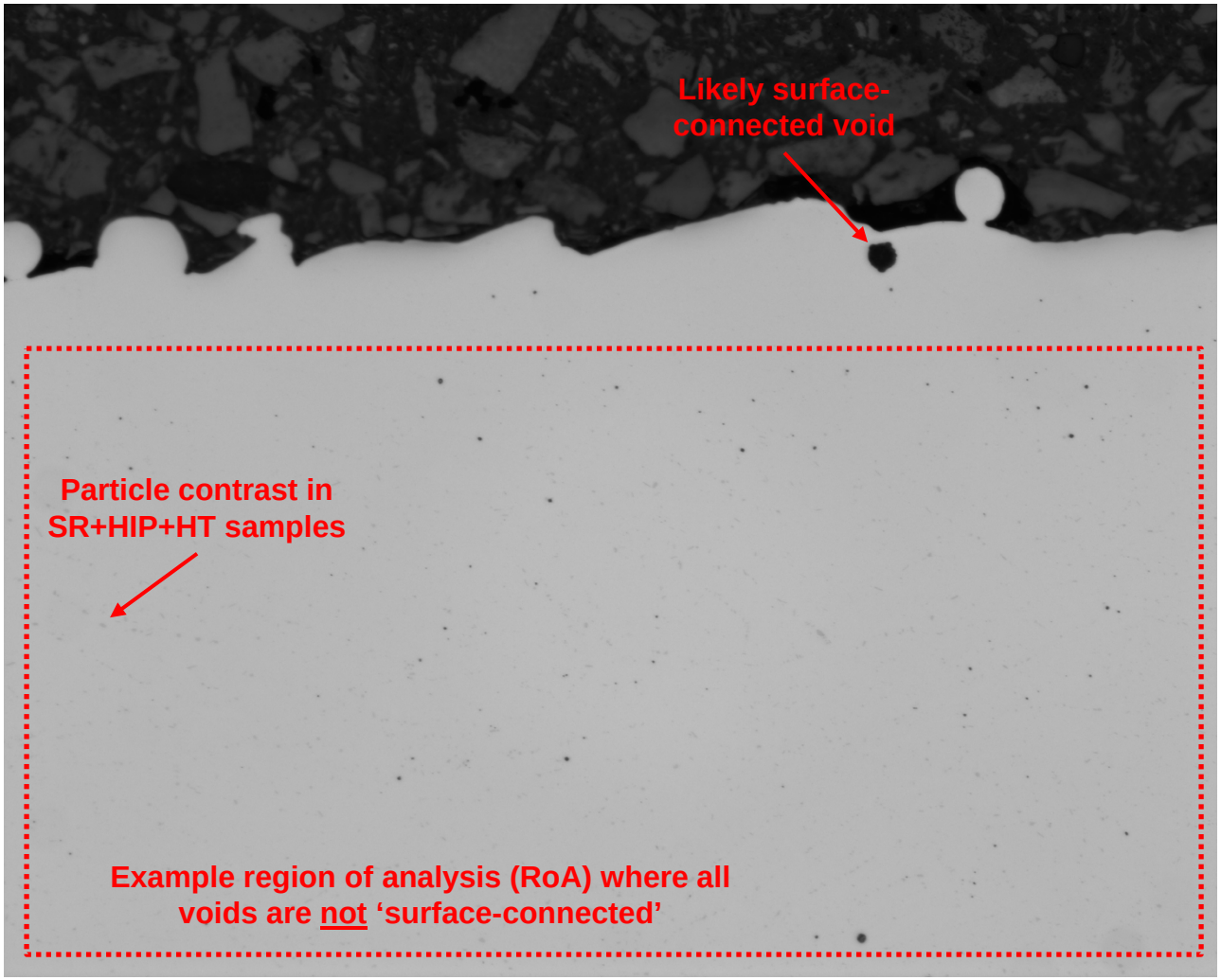
SR Only

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

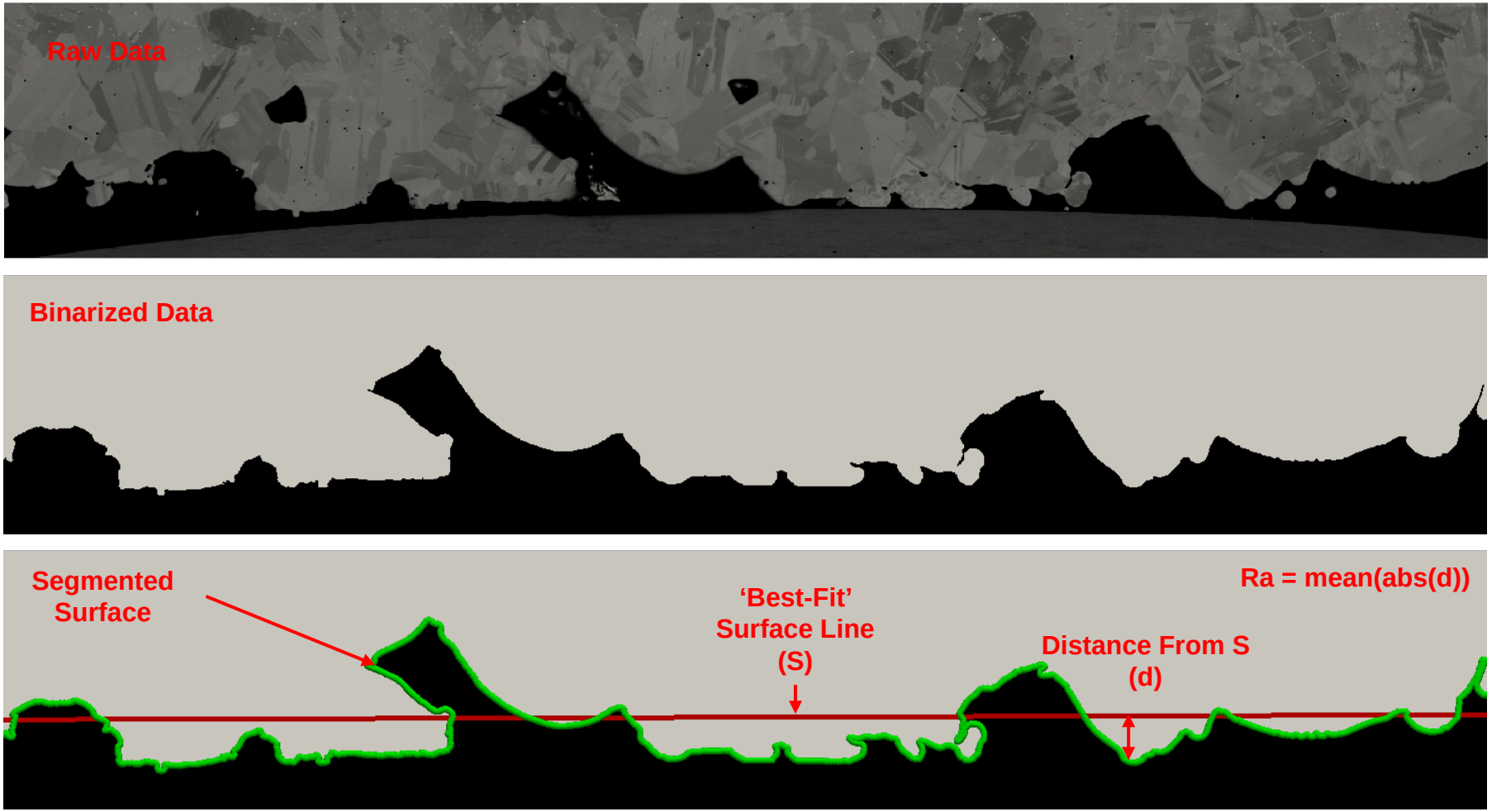


Fig. 16: Example of surface segmentation and Ra calculation method using BSE images

* 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

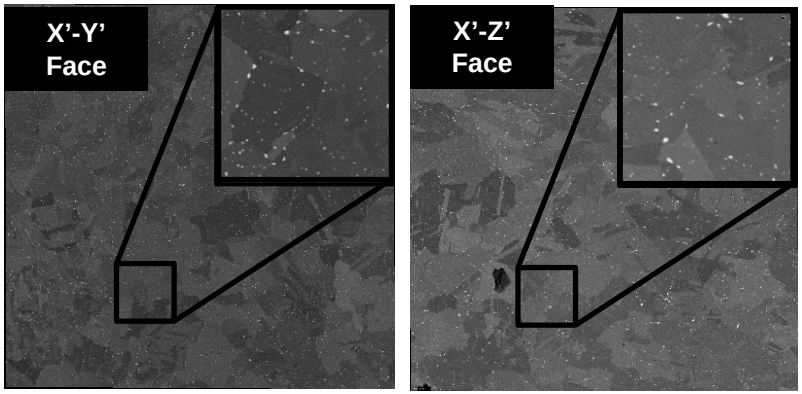


Fig. 17: BSE images of SR+HIP+HT ASTM E8 bar

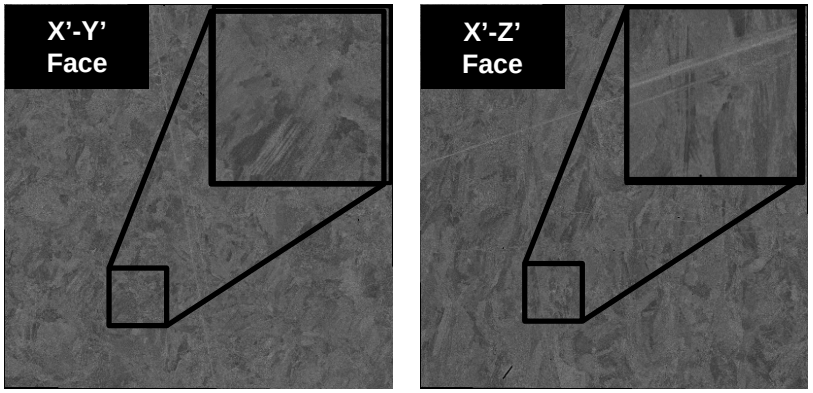


Fig. 18: BSE images of SR Only ASTM E8 bar

	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

Details of Methodology

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

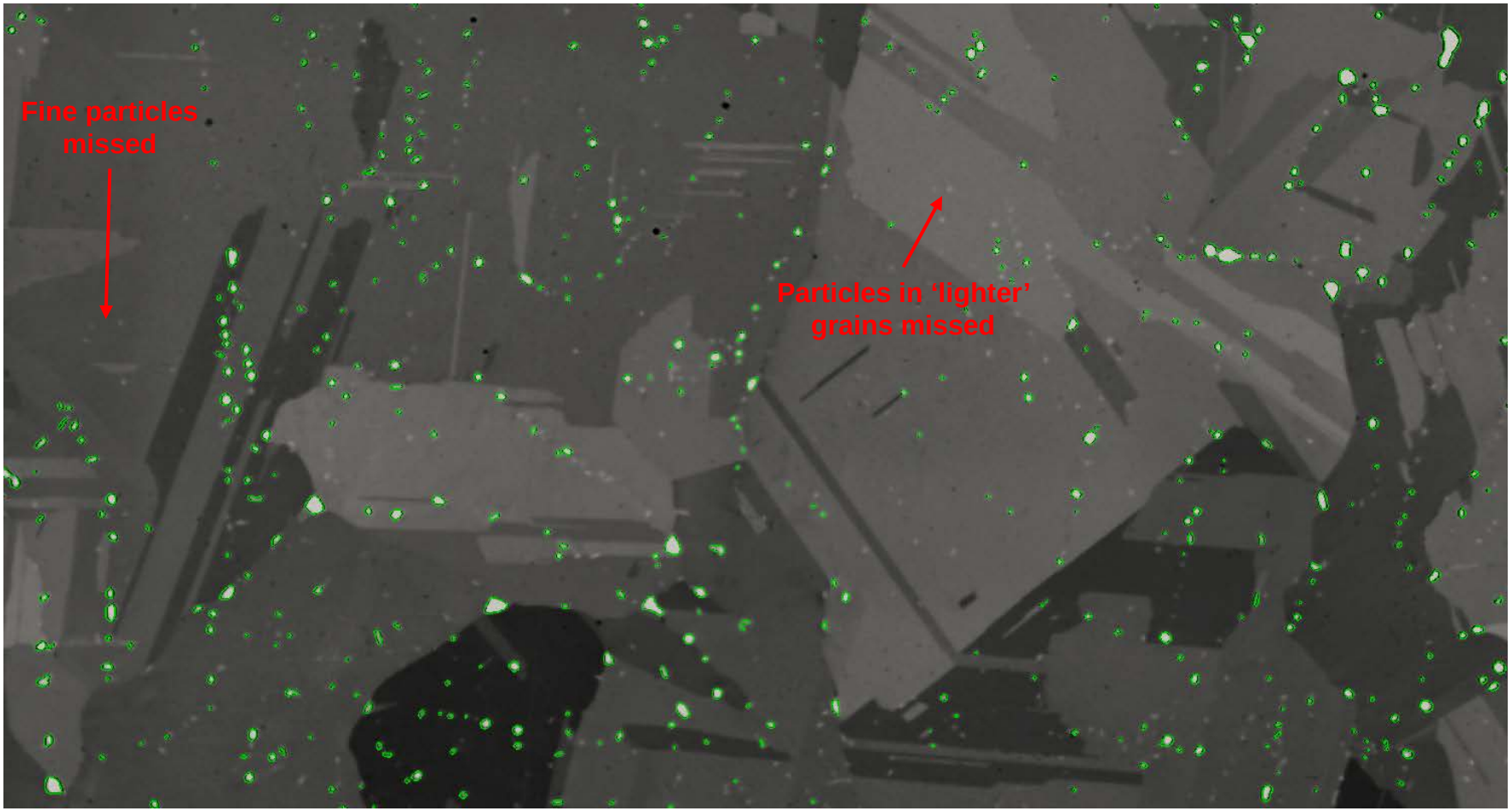


Fig. 19: Example segmentation of precipitates in a BSE image with annotations showing missed particles

* 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

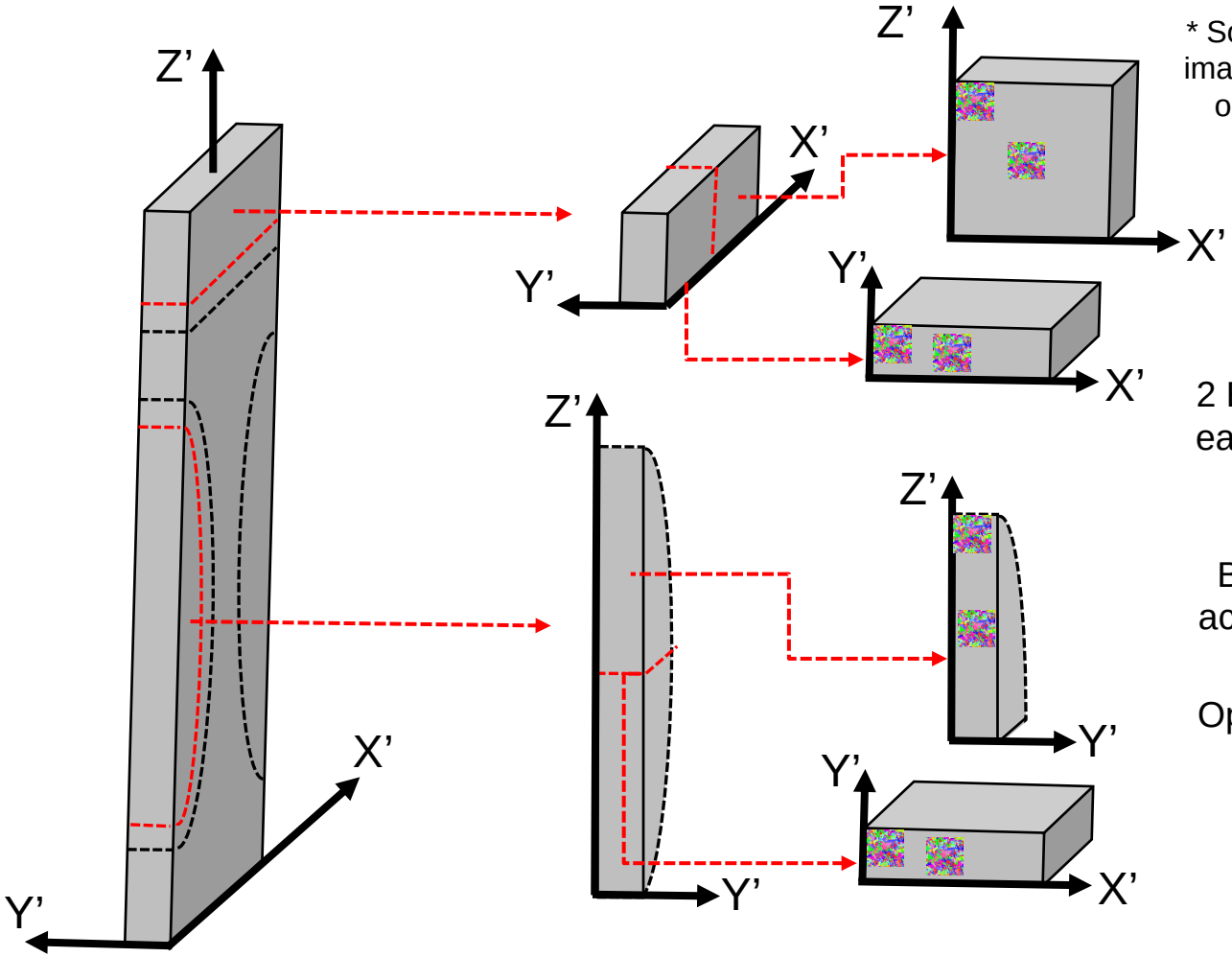
Data for Model Calibration

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

Microstructural Input Data

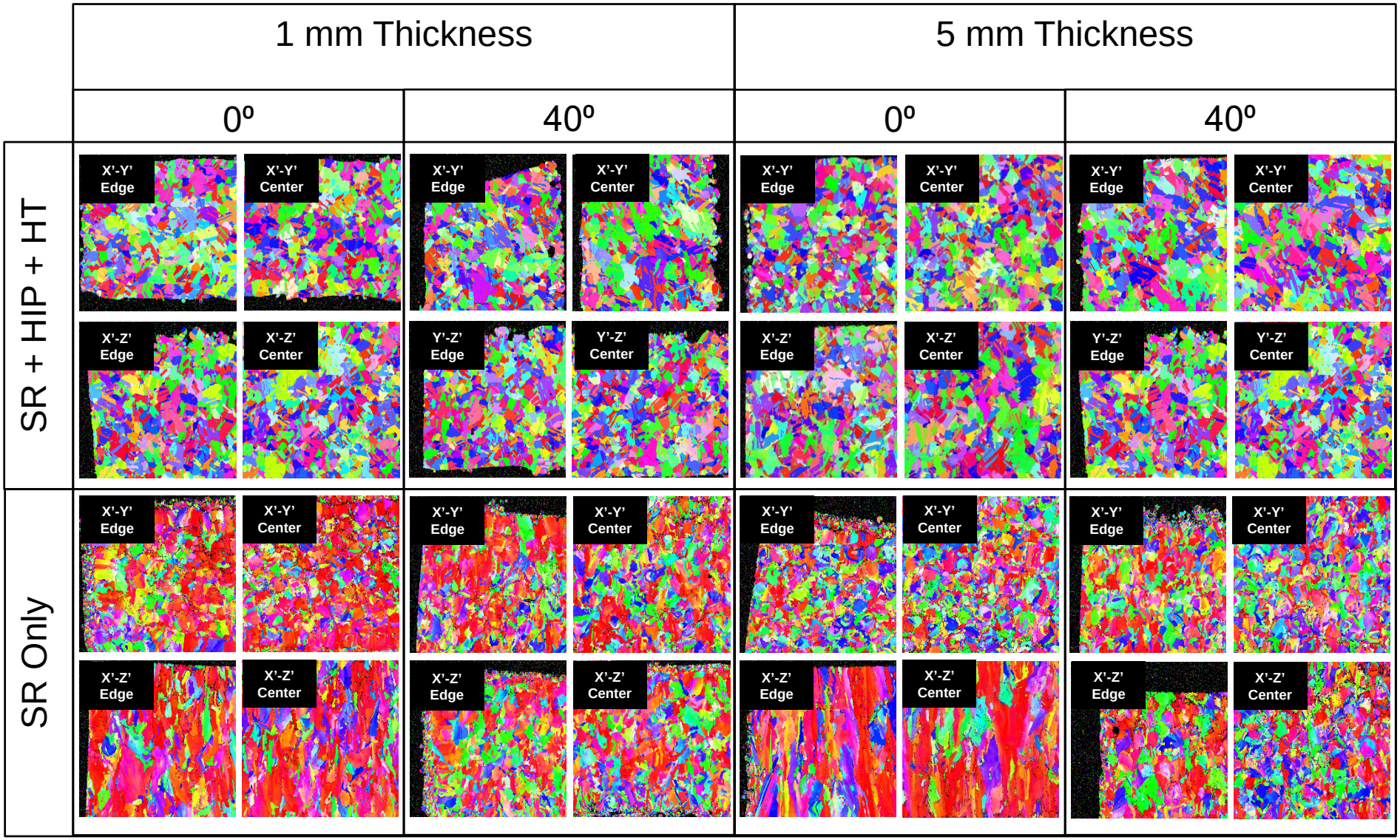
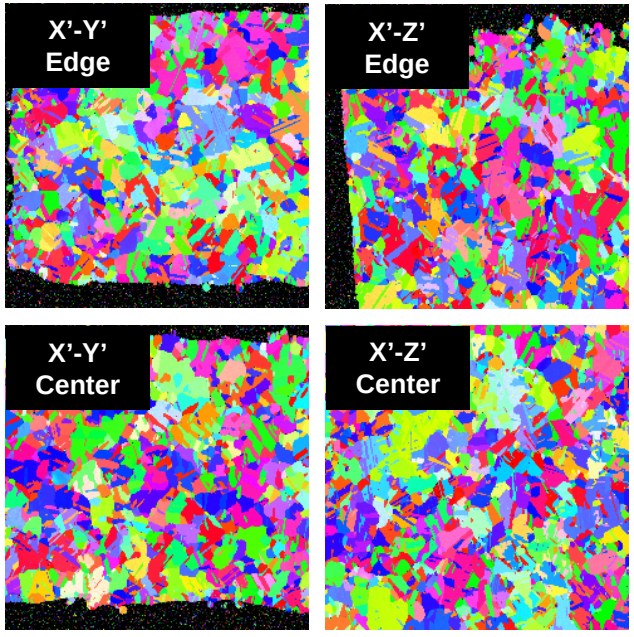


Fig. 21: EBSD scans for all microstructure conditions

Microstructural Input Data

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

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	Download Data Package for Input Values			
Yes				



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 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				

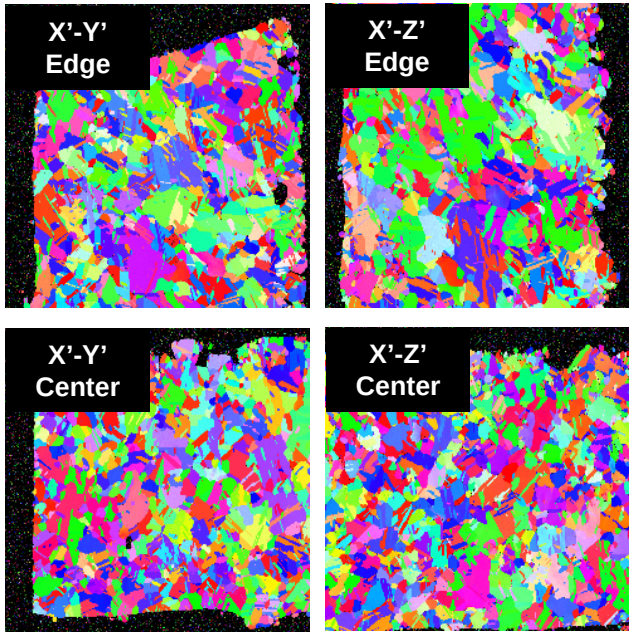
Pole Figures
Download Data Package for Input Values

- Tabulated grain, void & precipitate statistics located in \Challenge3\InputData
- Raw EBSD, BSE, OM images & analysis pipelines located in \Challenge3\InputData

Microstructural Input Data

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

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	Download Data Package for Input Values			
Yes				



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 Input Values					

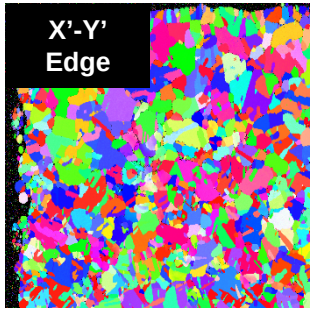
Denuded Zone Thickness [µm]	X-Y Precipitate Size [µm] µ, σ	X-Y Precipitate V_f	X-Z Precipitate Size [µm] µ, σ	X-Z Precipitate V_f
Download Data Package for Input Values				

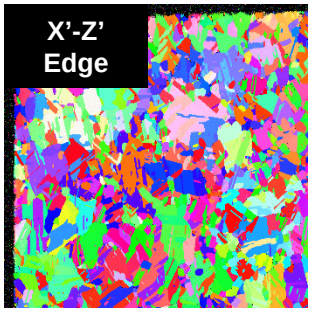
Pole Figures
Download Data Package for Input Values

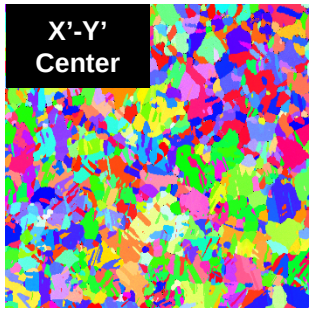
- Tabulated grain, void & precipitate statistics located in \Challenge3\InputData
- Raw EBSD, BSE, OM images & analysis pipelines located in \Challenge3\InputData

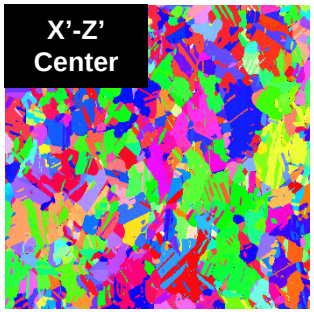
Microstructural Input Data

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









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	Download Data Package for Input Values			
Yes				

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 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				

Pole Figures
Download Data Package for Input Values

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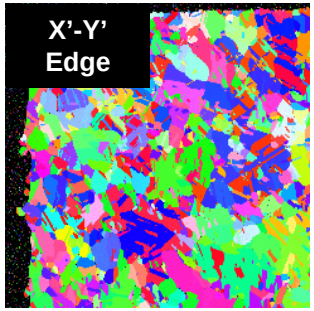
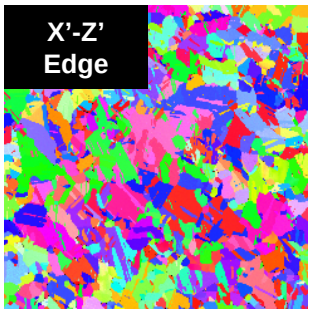
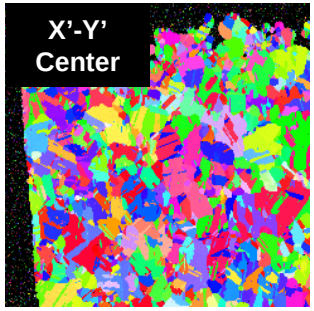
- Raw EBSD, BSE, OM images & analysis pipelines located in \Challenge3\InputData

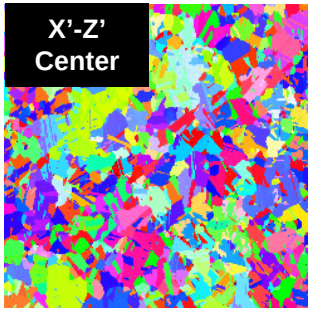
Microstructural Input Data

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









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	Download Data Package for Input Values			
Yes				

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 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				

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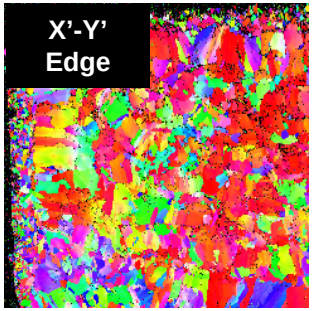
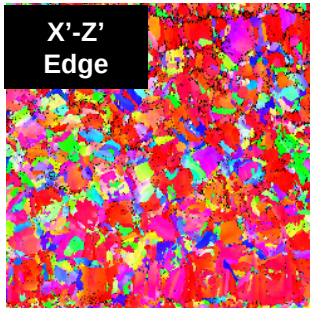
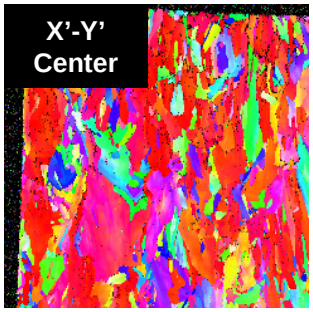
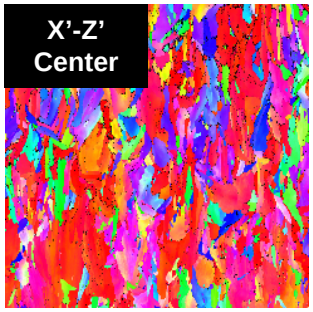
Microstructural Input Data

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









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 Input Values

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 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

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Pole Figures

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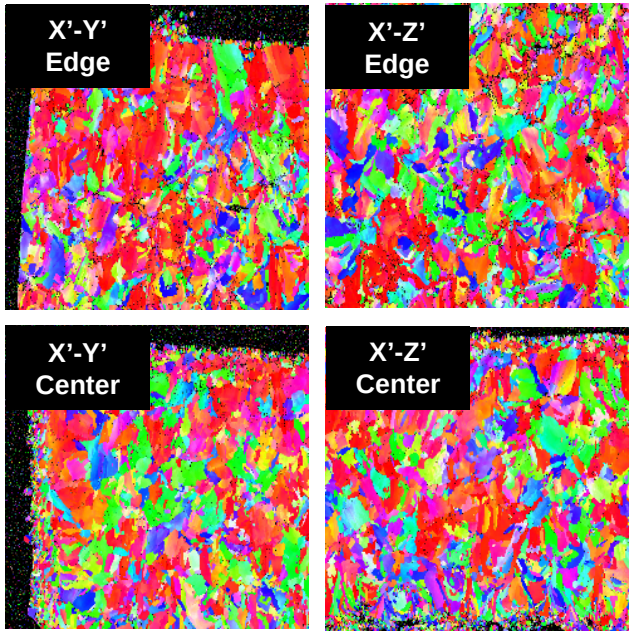
Microstructural Input Data

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



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 Input Values

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]

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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

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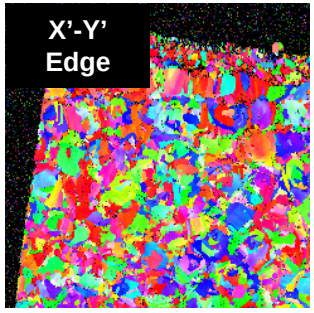
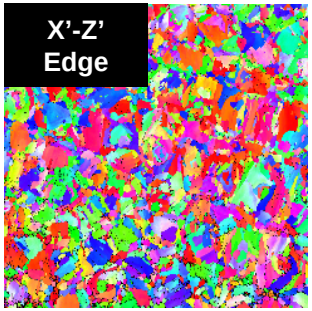
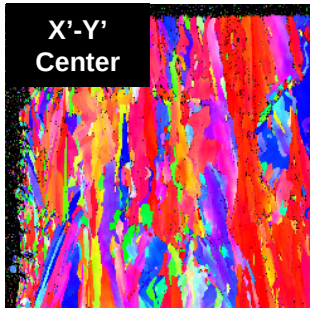
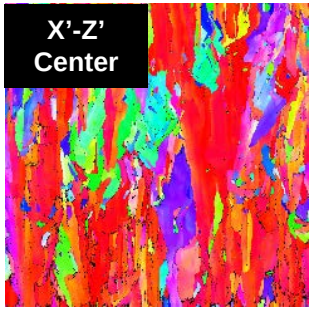
Microstructural Input Data

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









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 Input Values

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 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

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Pole Figures

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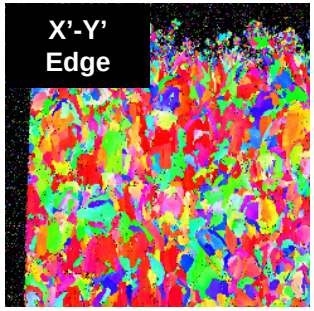
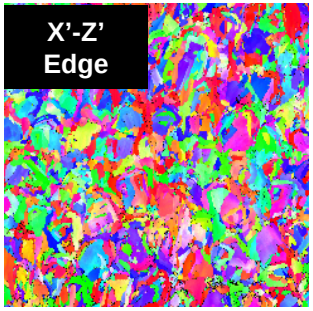
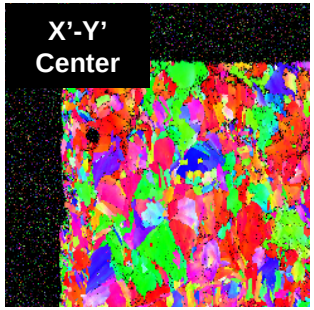
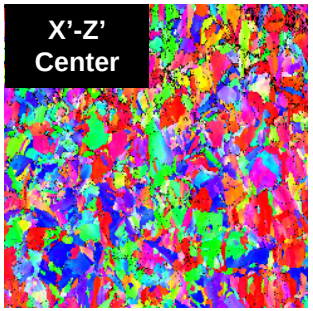
Microstructural Input Data

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









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 Input Values

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 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

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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

- Answer sheet template located in \Challenge3\AnswerTemplate.xls