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

Challenge Problem 1:

Macroscale Process-to-Structure

Released August 2019

Integrity ★ Service ★ Excellence

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General Problem Statement

Predict residual elastic strains at specified locations within additively manufactured IN625 articles in the as-printed condition

- Weighted residual strains will be provided for plates of different lengths & thicknesses (calibration articles shown in red)
- Report residual strain components at specified (measured) locations of challenge articles (shown in green)

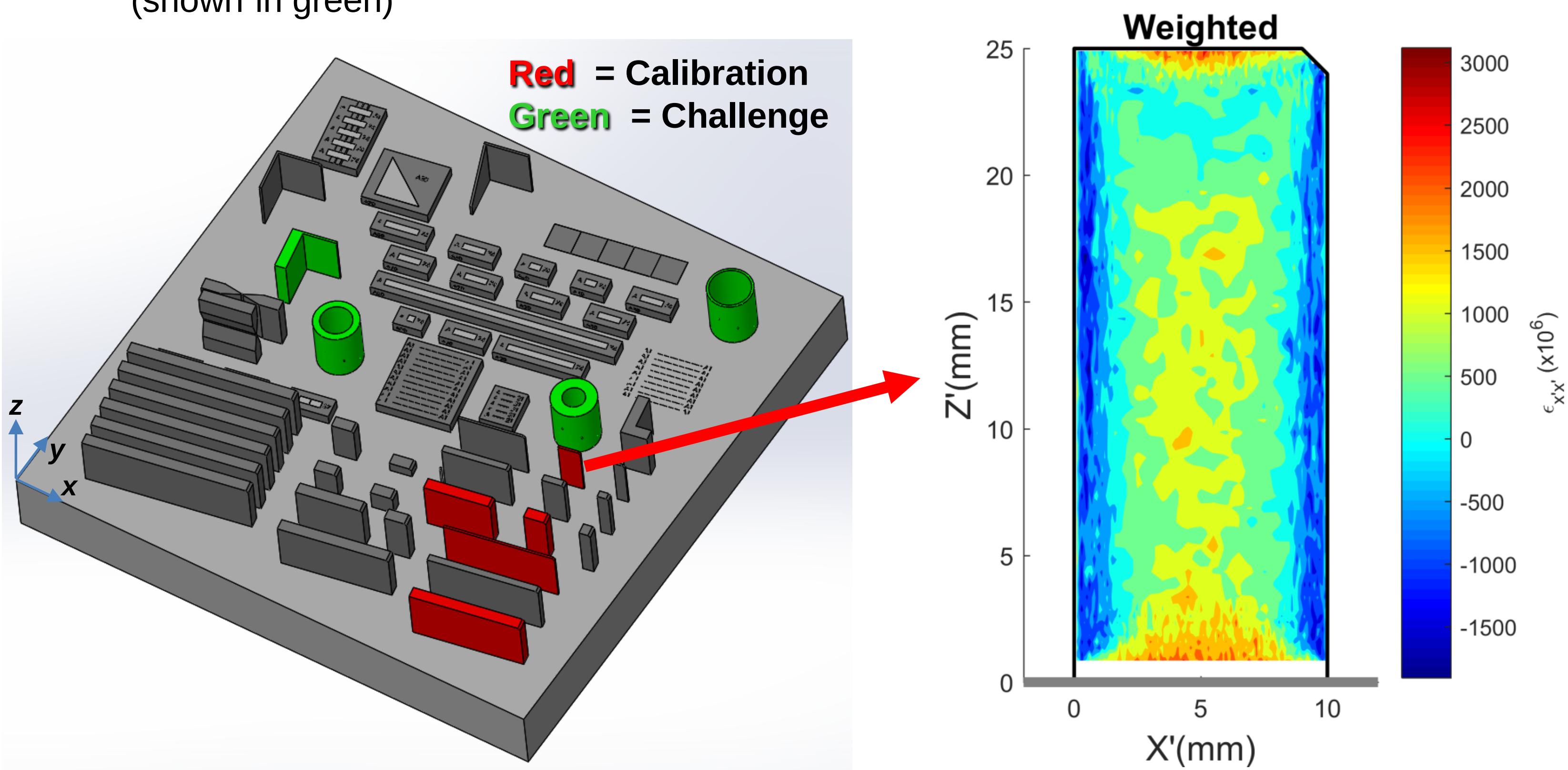


Fig. 1: Full build layout showing calibration (red) and challenge (green) articles and a representative raw (unsmoothed) residual strain map from a calibration article.

- Full build .stl file located in \Challenge1\CalibrationData\Build Layout Details\

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 26 for material data provided by supplier)
- Calibration walls and challenge articles, cylinders and L- shaped plates, were printed using nominal parameters

Table 1: Processing parameters used for all calibration and challenge articles.

Power [W]	Speed [mm/s]	Hatch Spacing [μm]	Layer Thickness [μm]
300	1230	100	40

- No post build heat treatment was performed
- A section of the steel base plate was electrical discharge machined (EDM) with the article still attached to preserve as much residual stress as possible within the build article

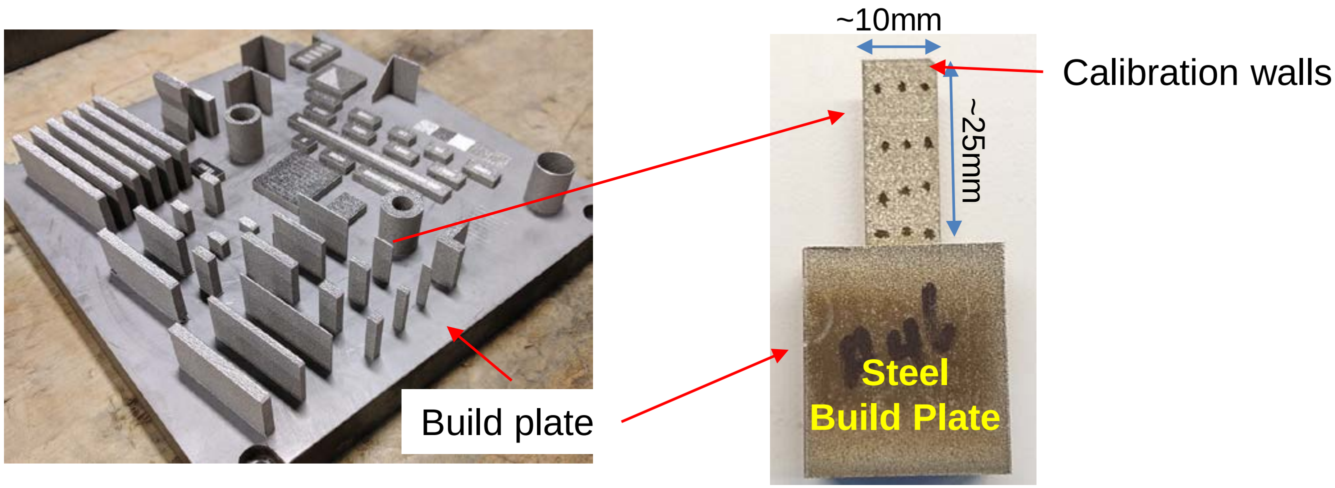


Fig. 2: Photographs of full build plate and an example of a calibration wall sample that has been sectioned from the build plate.

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).

X',Y',Z' is a Cartesian coordinate system used for the flat walls and L items where Z||Z' (the build direction), and the *X' Y'* axes are rotated 10° clockwise (+ sense with right hand rule) about the *Z* axis. The origin of this system is on the build plate, and at the item corner closest to the left front of the machine from the perspective of a user looking into the machine (as per ASTM coordinate system definitions).

R' θ' Z' is a polar system for the tubes where the origin is on the build plate, centered at the center of the tube. θ'=0 || *X*

See schematics on next slides

- Full build .stl file located in \Challenge1\CalibrationData\Build Layout Details\

Flat Wall Local Coordinate System

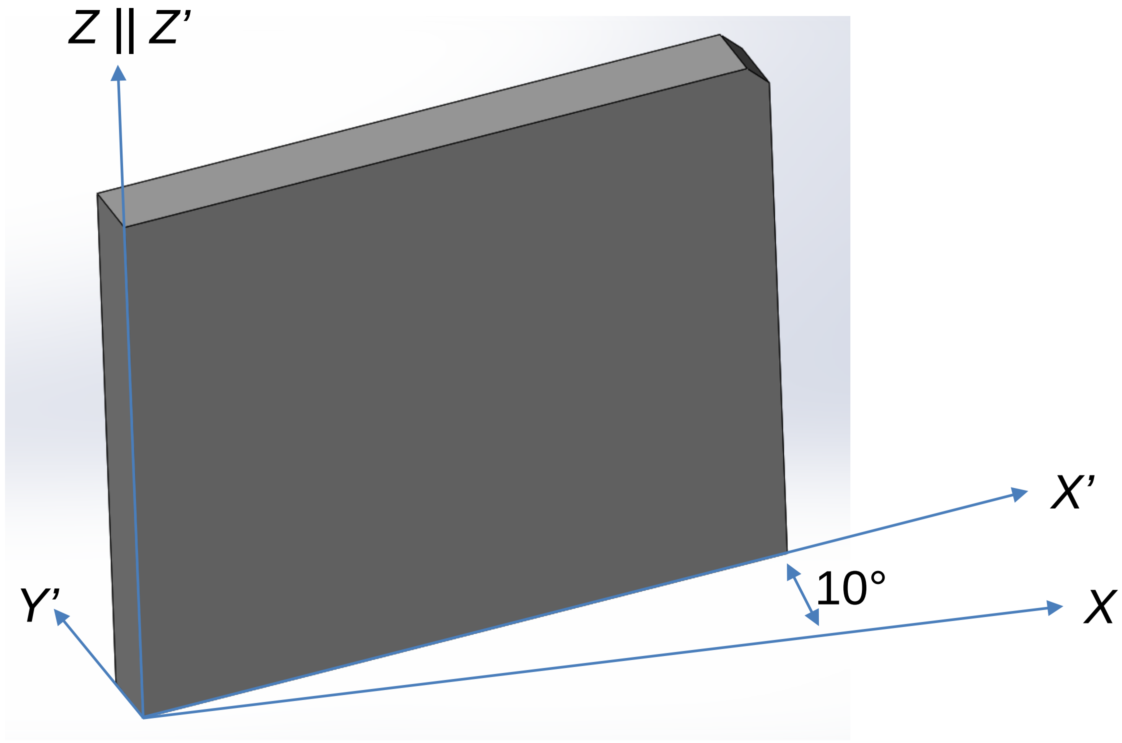


Fig 3: Local coordinate system origin is the corner closest to build plate, and the front, left of the machine. When viewing an *X'Z'* plane looking along the positive *Y'* direction, the chamfered corner will be in the upper right.

“L” Local Coordinate System

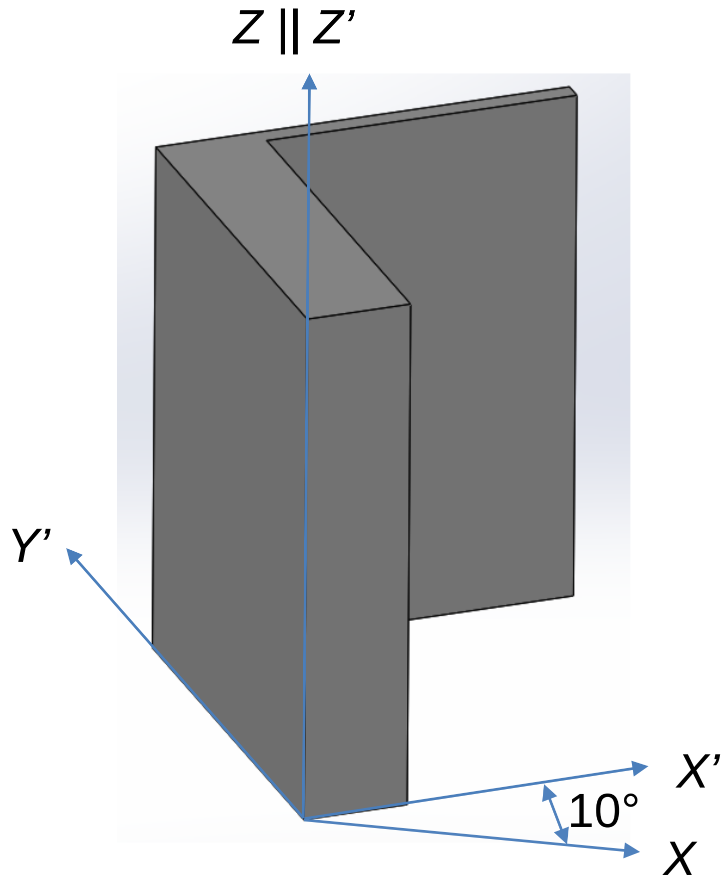


Fig 4: Local coordinate system for L-shaped plate where the origin is the corner closest to build plate, and the front, left of the machine.

Tube Local Coordinate System

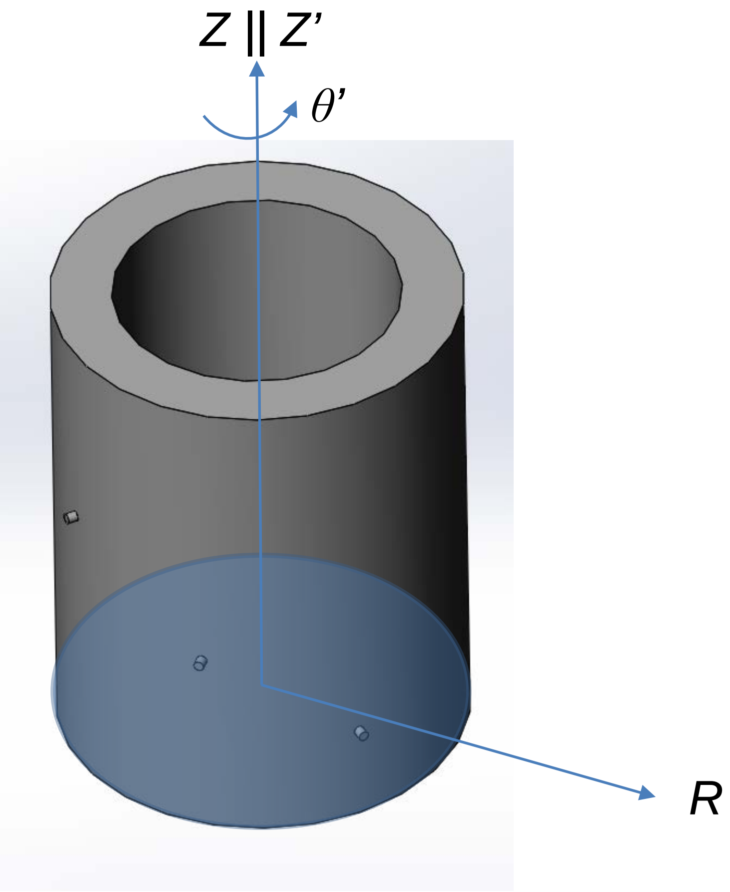


Fig 5: Local coordinate system for tube articles. R' θ' Z' is the polar coordinate system for the tubes where the origin is on the build plate, centered at the center of the tube. θ'=0 || *X.*

Coordinate Systems

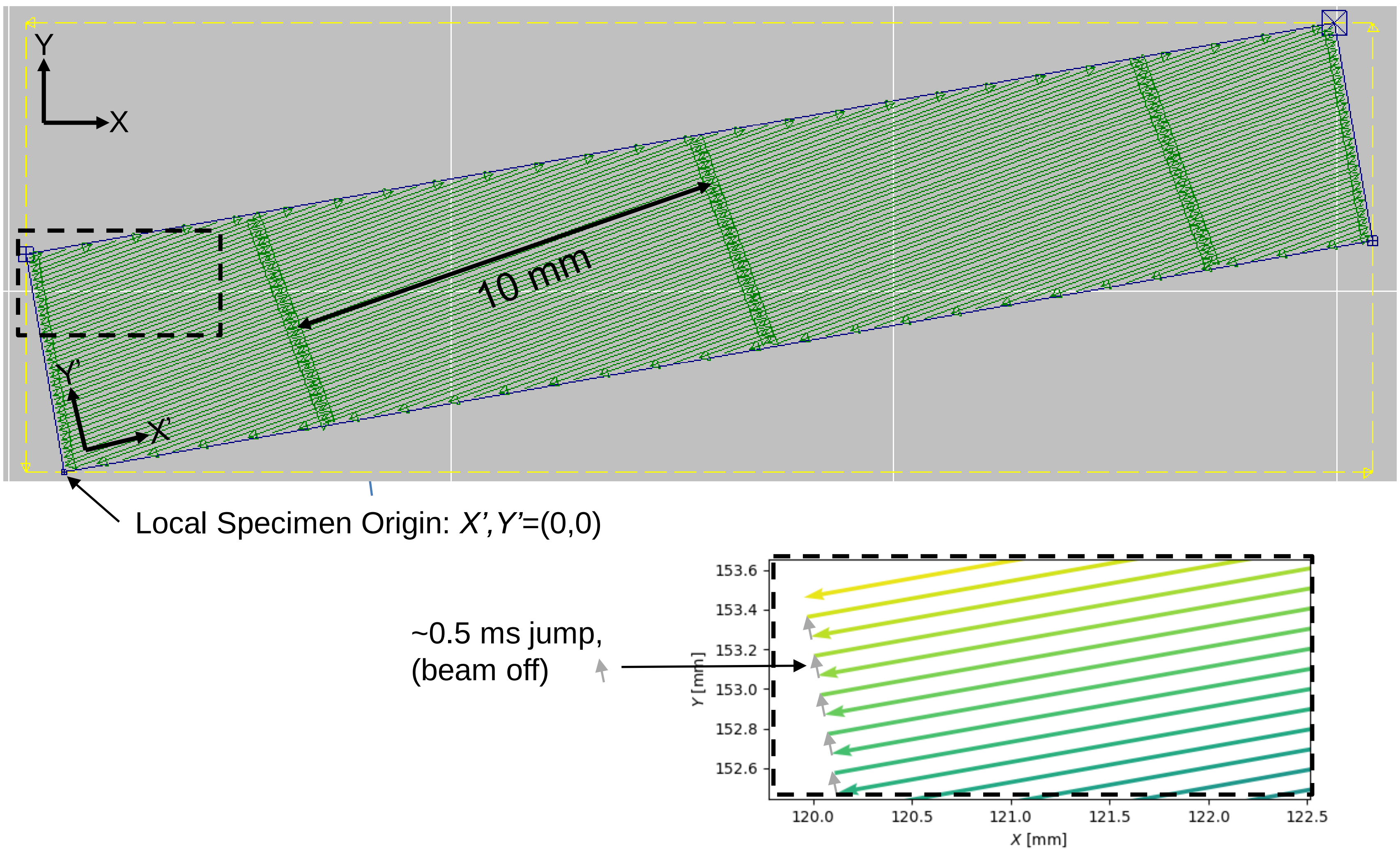


Fig. 6: Coordinate system of single layer out of representative article

- Scan vector images for selected layers of one representative article located in \Challenge1\CalibrationData\ScanVectorScreenShots

Scan Strategy

The scan strategy consists of a generic “snake” or rastering of scan vectors across the articles on a given layer.

All vectors are nominally 10 mm in length and run from one “stripe boundary” to another. The 10 mm spacing of stripe boundaries is commonly referred to as the *stripe width*. At the stripe boundaries, the beam turns around, while off, and proceeds in the opposite direction. If the vector intersects the outer perimeter of the article before reaching a stripe boundary, then it terminates and the beam turns around, while off, and proceeds in the opposite direction. The turn around time is approximately 0.5 ms.

Parallel scan vectors running between two stripe boundaries are termed *hatches* and are spaced by 100 µm, which is commonly referred to as the *hatch spacing*.

The orientation of the scan vectors are rotated by 67º every subsequent layer.

Substrate and Timings

All calibration and challenge items are built on top of a standard plain carbon steel base plate, approximately 30 mm in thickness, and 250 mm x 250 mm on each edge.

The build geometry shown in Fig. 1 contains additional articles beyond the calibration and challenge items used for this challenge problem. The layer times for the entire build are listed in a comma separated values (.csv) file located in the data package.

The times listed in the HomeIn-Build A.csv file correspond to the start of each layer. In general, the time to print each layer is about 12 s less than the ∆time calculated from the times listed in the file, with the additional 12 s corresponding to the time to rake a new layer of powder.

The calibration and challenge articles are not printed in any specific order on each layer, but the order is consistent throughout all layers in the build.

All articles are spaced by at least 10 mm from neighboring articles and were considered to be isolated from thermal effects from other articles.

- Layer times are given in \Challenge1\CalibrationData\HomeIn-Build A.csv

Measurement Technique and Geometry

- Each article was measured while still attached to the steel base plate. To make article & measurement locations more manageable, a section of the steel base plate was electrical discharge machined (EDM) with the article still attached to preserve as much residual stress as possible within the build article.
- Strain measurements were collected using Energy Dispersive Diffraction (EDD) [1] at the Advanced Photon Source at Argonne National Laboratory (6-BM-A)
  - All samples were mounted upside-down because of downward scattering geometry
  - Horizontal and vertical components of strain were measured starting Z' ≈ +1mm away from the build plate
  - Interaction volume where strain components are measured over is described in next slides
- A reference lattice parameter of a0 = 3.598 Angstroms was measured from powder used to build samples

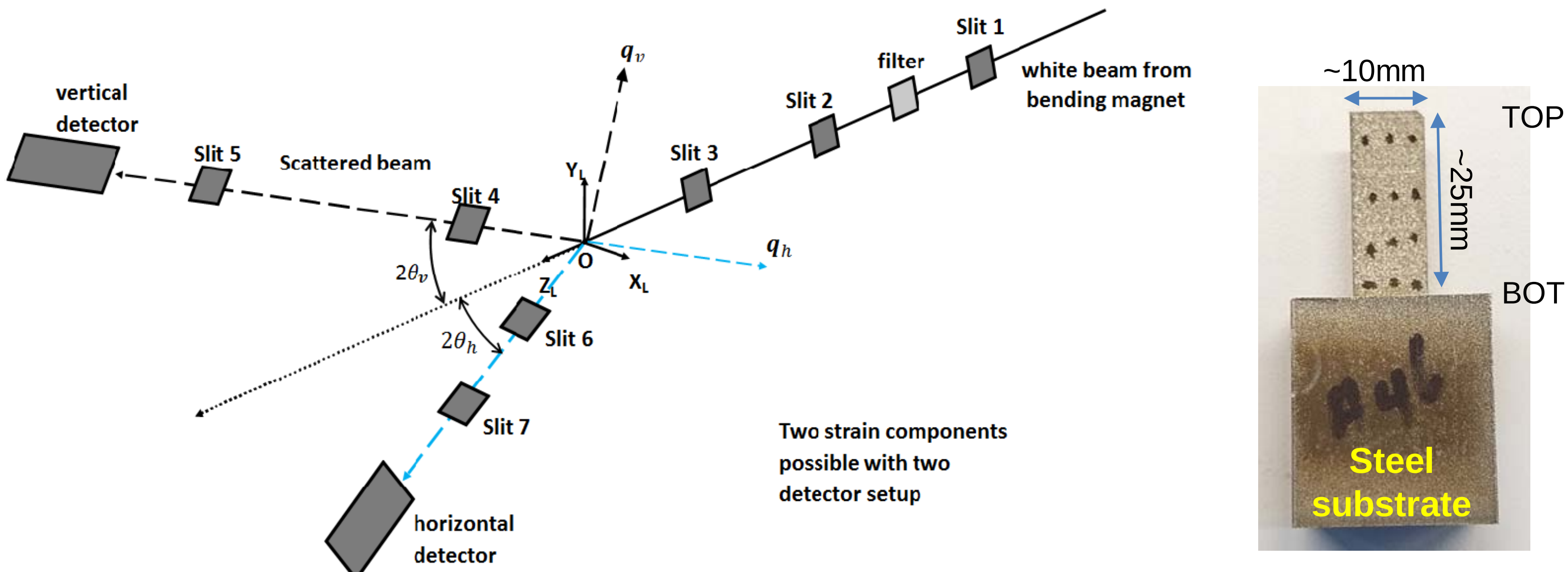


Fig. 7: Schematic of EDD measurement methodology (left) and image of article with section of steel base plate still attached (right).

[1] Croft M, Zakharchenko I, Zhong Z, Gurlak Y, Hastings J, Hu J, Holtz R, DaSilva M, Tsakalakos T. 2002. Strain field and scattered intensity profiling with energy dispersive x-ray scattering. *J Appl Phys* 92:578-586. ; https://doi.org/10.1063/1.1483373

Measurement Description – Interaction Volume

Each measurement "point" actually constitutes a measurement of average strain components within an "interaction volume" centered through the thickness of the specimen

Beam dimensions used for all measurements were 0.050mm wide x 0.200mm tall

Length of interaction depth for the horizontal and vertical components of strain are different. Estimated full width, half max (FWHM) values for interaction depth:

- Horizontal component ~ 2.7mm
- Vertical component ~ 4.6mm

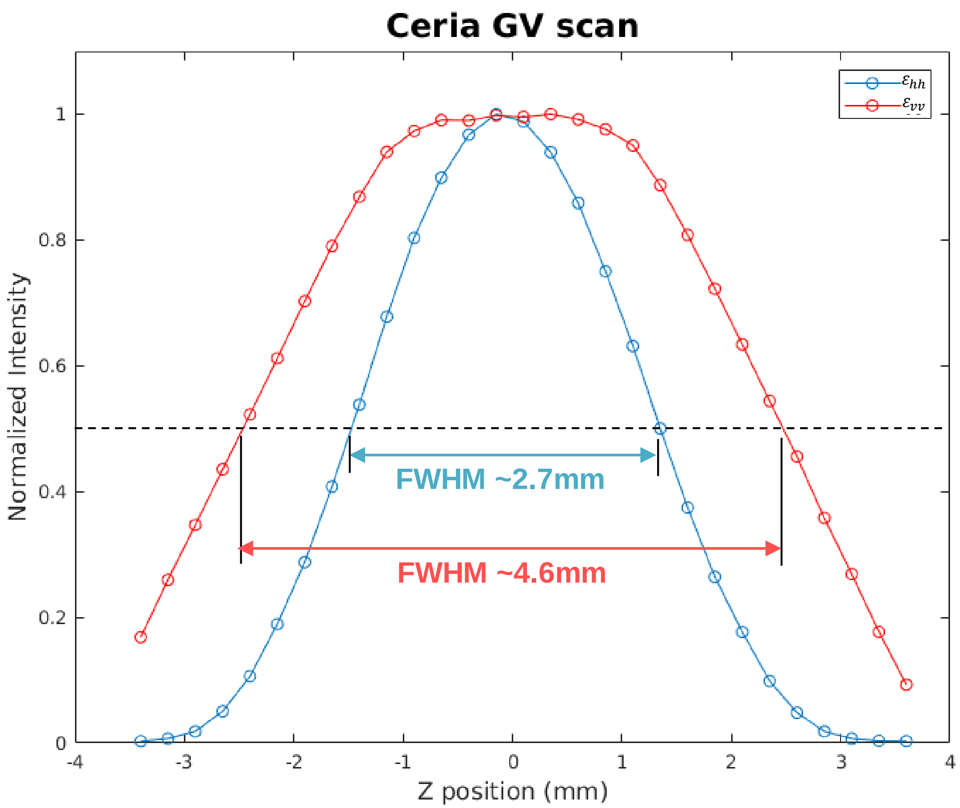


Fig. 8: Calibration of interaction depth using thin ceria foil.

Measurement Description – Interaction Volume for Horizontal Component of Strain

Interaction depth for horizontal component of strain is ~2.7mm. Horizontal diffraction angle was $2\theta_h$ = 4.5-4.75° for all EDD measurements.

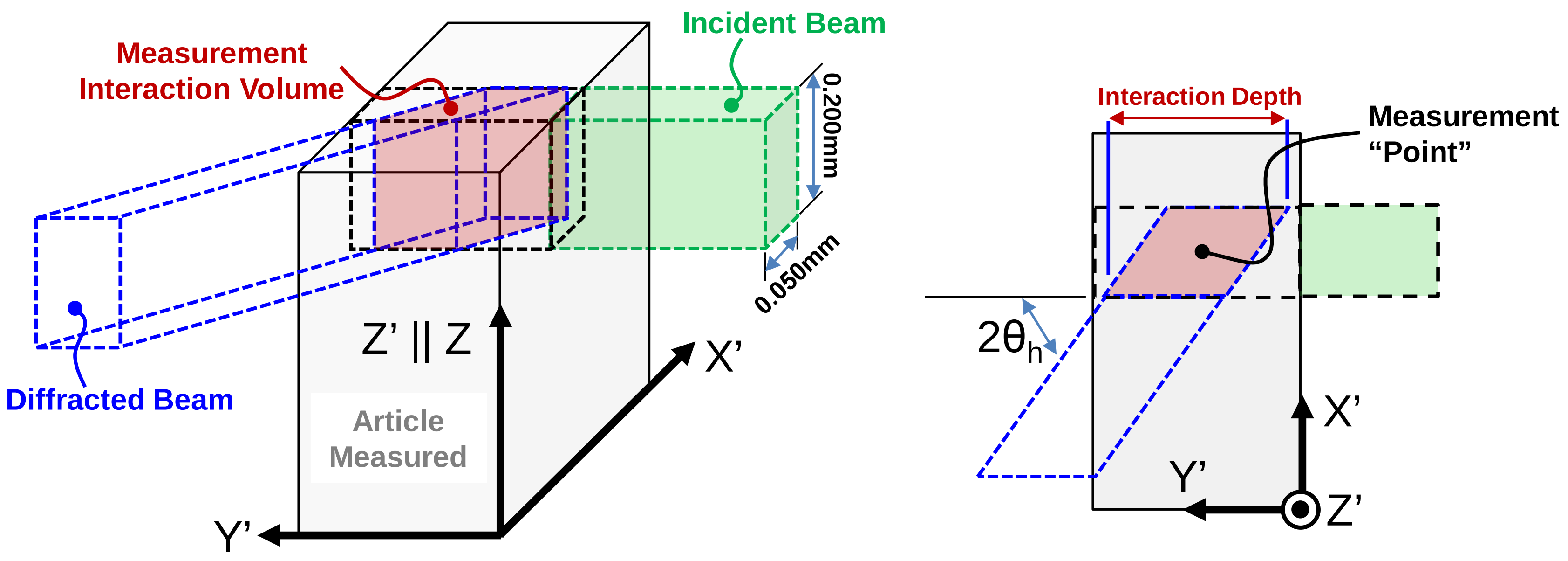


Fig. 9: Schematic (not to scale) illustrating interaction volume for each EDD measurement of the horizontal component of strain. Note, $2\theta_h$ angle is exaggerated in schematic for illustrative purposes.

Measurement Description – Interaction Volume for Vertical Component of Strain

Interaction depth for vertical component of strain is ~4.6mm. Vertical diffraction angle was $2\theta_v$ = 4.5-4.75° for all EDD measurements.

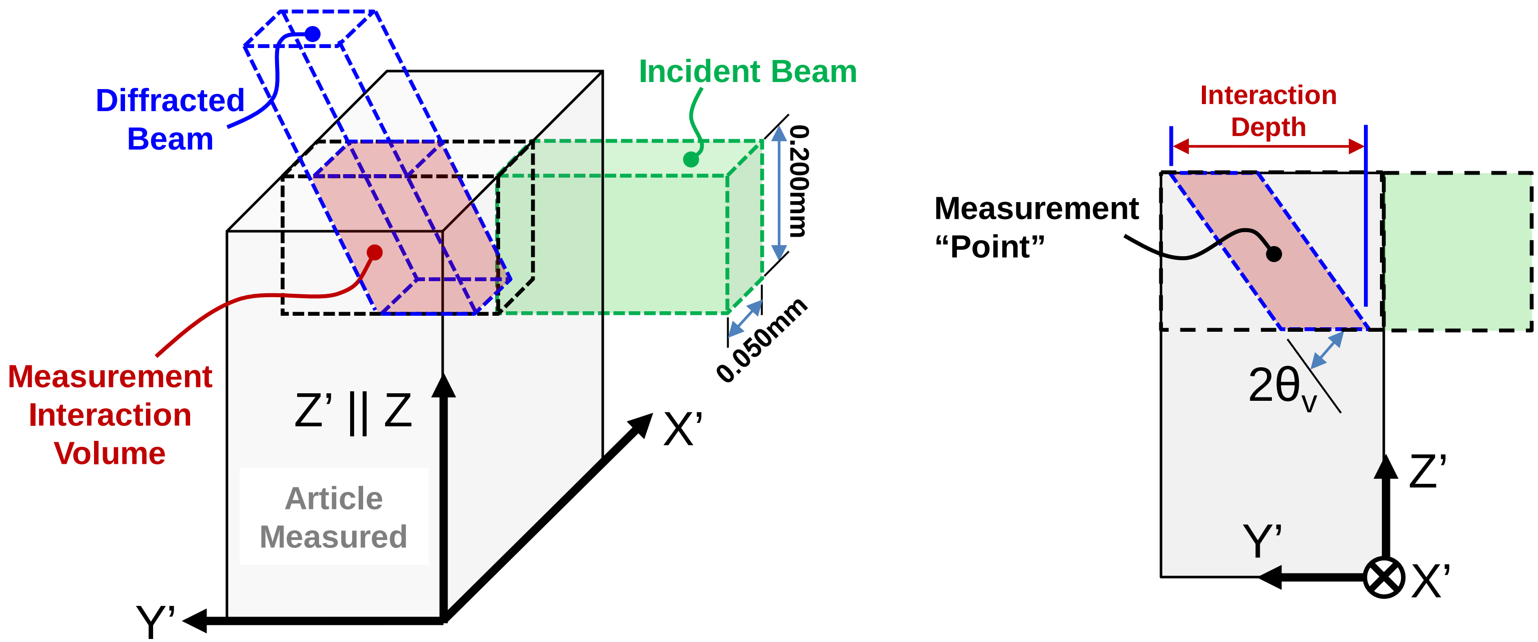


Fig. 10: Schematic (not to scale) illustrating interaction volume for each EDD measurement of the vertical component of strain. Note, $2\theta_v$ angle is exaggerated in schematic for illustrative purposes.

Measurement Description – Raster Spacing

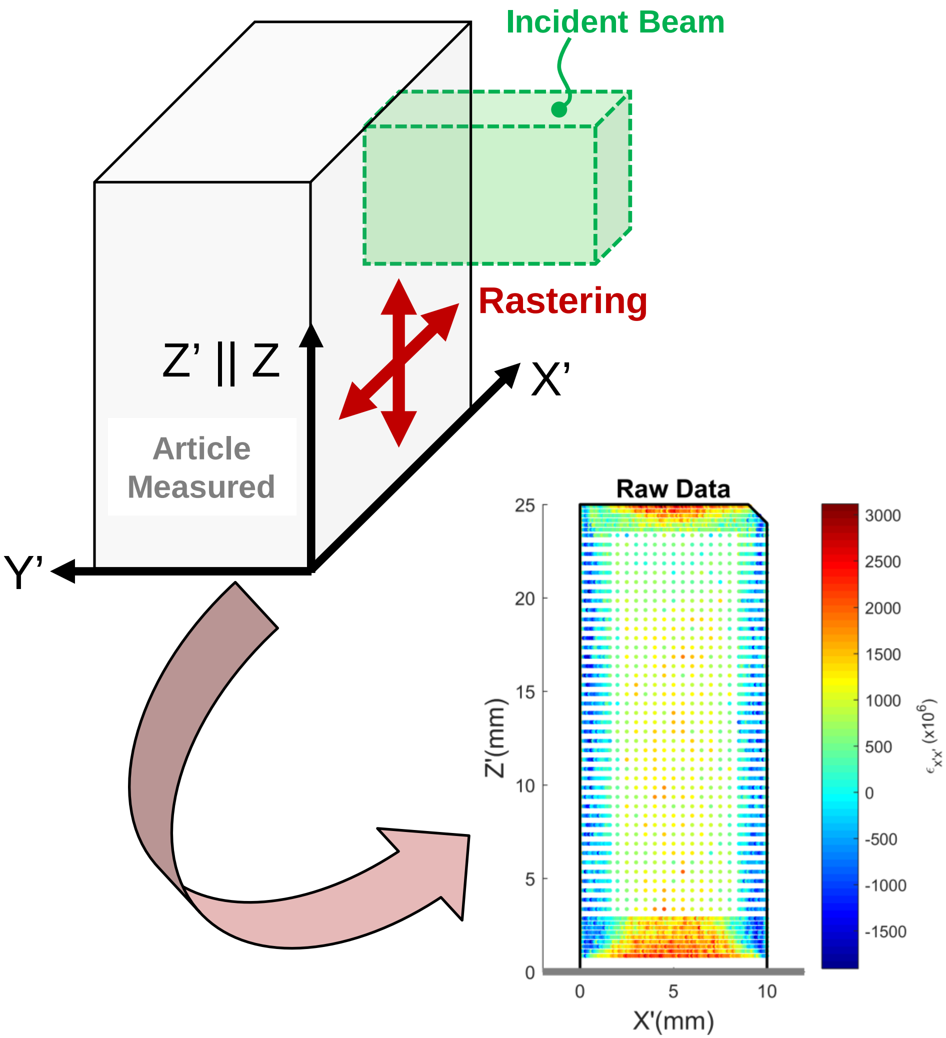


Fig. 11: Schematic showing rastering of measurement data over whole article. Note, raster spacing is non-uniform.

The articles measured were rastered in the X' and Z' directions to obtain horizontal and vertical components of strain at different locations within the article. Measurements were started at Z'= ~1mm.

Only one interaction depth (centered through the Y' thickness) was assessed per each (X',Z') coordinate measured and detector.

Each sub-volume produced diffraction peaks for selected crystallographic planes.

The diffraction peaks of the selected crystallographic directions were used to determine a weighted average residual strain for the horizontal and vertical components of strain.

The raster spacing of the x-ray beam was non-uniform. A higher density of measurement points was used in areas containing large gradients in residual strain.

Measurement Description – Weighted Average Strain

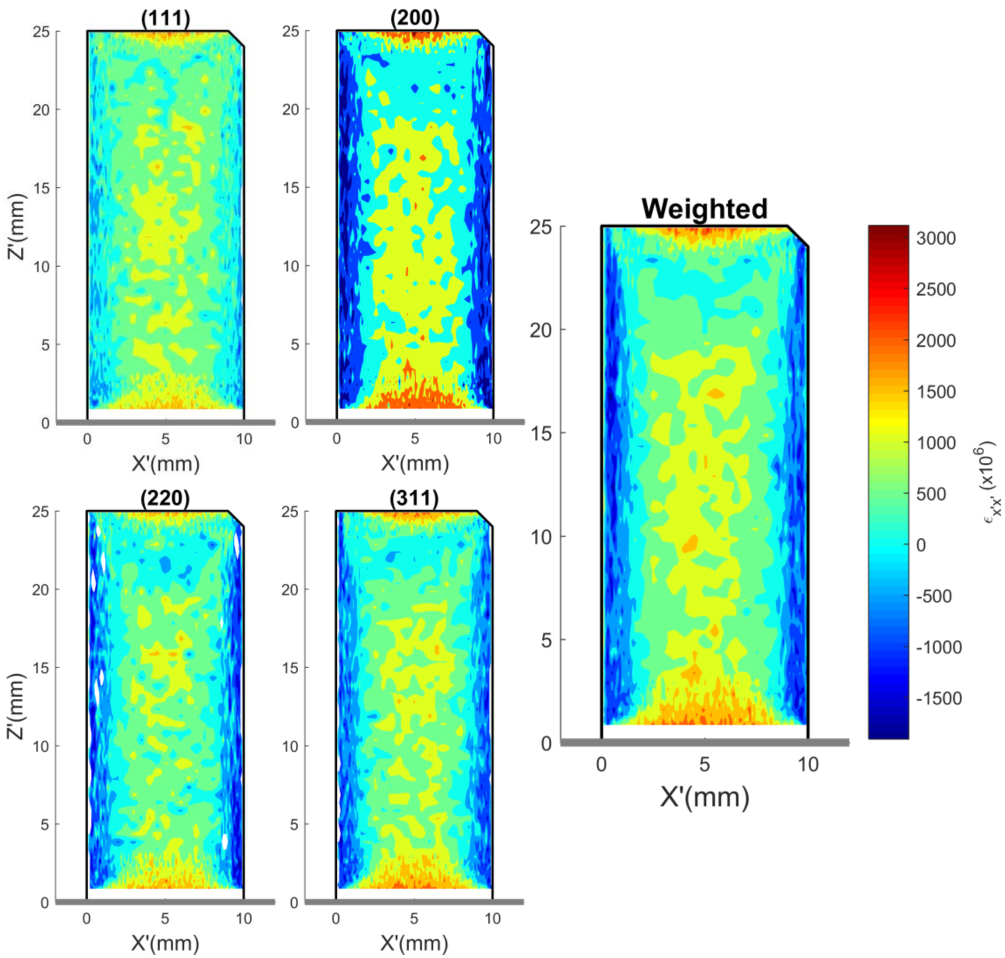


Fig. 12: Example of 4 crystallographically-resolved strain maps (left) and resultant weighted average strain (right).

At each raster position of the beam, horizontal and vertical strains are determined by analyzing the diffraction peaks of 4 crystallographic planes.

The strain values for each crystallographic plane/peak can be thought of as the aggregate average for all grains oriented for diffraction on that plane within the irradiated interaction volume.

The grain aggregates contain varying numbers of grains depending on the texture of the sample and the sampled/irradiated interaction volume.

The intensity of the diffraction peaks, accounting for attributes of the diffraction process, are used to weight the individual aggregates to obtain a "weighted average strain" (similar to a rule of mixtures technique) in the horizontal and vertical directions.

The weighted average strain is the strain that will be used for grading purposes.

Smoothing of Weighted Average Strains

- Due to the variation in the raw data related to the EDD measurement technique and local microstructure, all EDD measurements were smoothed using a Gaussian process regression (a.k.a. Kriging) model
  - Smoothed (Kriged) data will be provided for the calibration walls and used for grading of answers

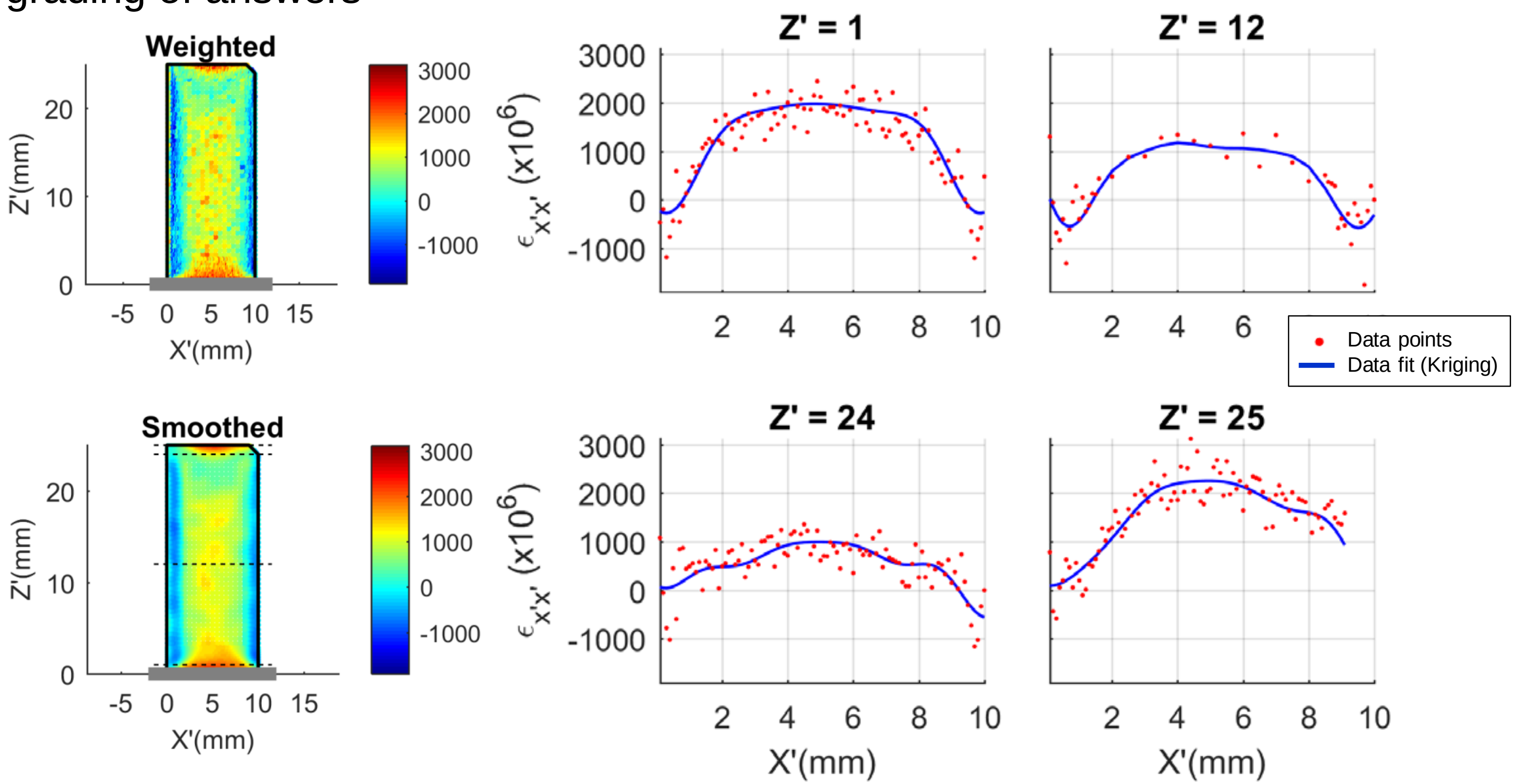


Fig. 13: Comparison of raw weighted EDD data (left top) and smoothed Kriging data (left bottom) and line profiles (also refereed to as: line out plot, plot over line, or plot along a line) showing comparison of raw data and smoothed function at various plate heights (right).

Calibration Data

Data for Model Calibration – EDD Measurements

- Five calibration articles (in red below) were measured.
- There are two files per calibration article, one labeled XX and one labeled ZZ, corresponding to horizontal and vertical components of strain, respectively.
  - Files contain (X’, Z’) coordinates and weighted average residual strains

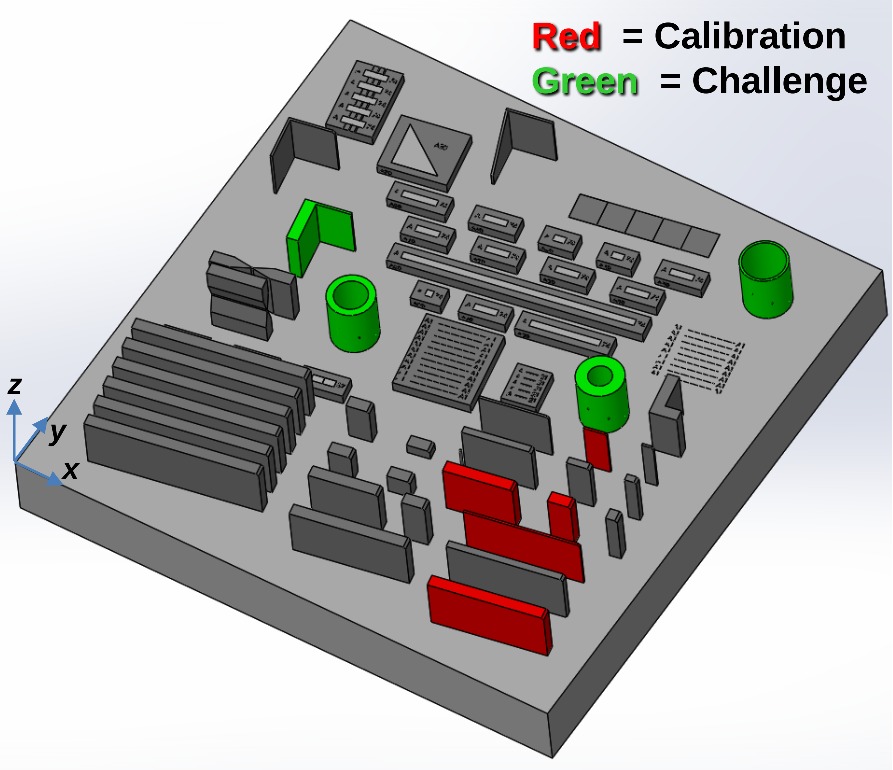


Fig. 14: Full build layout showing calibration articles (highlighted in red).

Table 2: Designed geometries for calibration (red) articles

Spec ID	Length X’ (mm)	Width Y’ (mm)	Height Z’ (mm)
A46	10	1	25
A48	10	5	25
A51	30	5	25
A52	50	1	25
A54	50	5	25

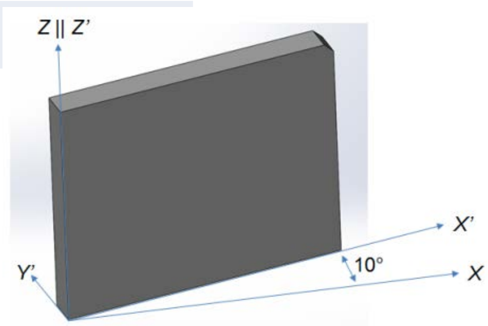
- Processed strain maps/data for calibration items listed in \Challenge1\CalibrationData\StrainData

Data for Model Calibration – EDD Measurements

- Calibration data is provided in a .csv file format
- There are two files per calibration article
  - One file contains horizontal (X'X') component of strain
  - Other file contains vertical (Z'Z') component of strain
- Each file contains the smoothed strain as a function of X'Z' position

Table 3: Illustration of .csv file format

X' [mm]	Z' [mm]	Smoothed Strain [um/m]
0.1	0.85	
0.2	0.85	
0.3	0.85	
…	…	



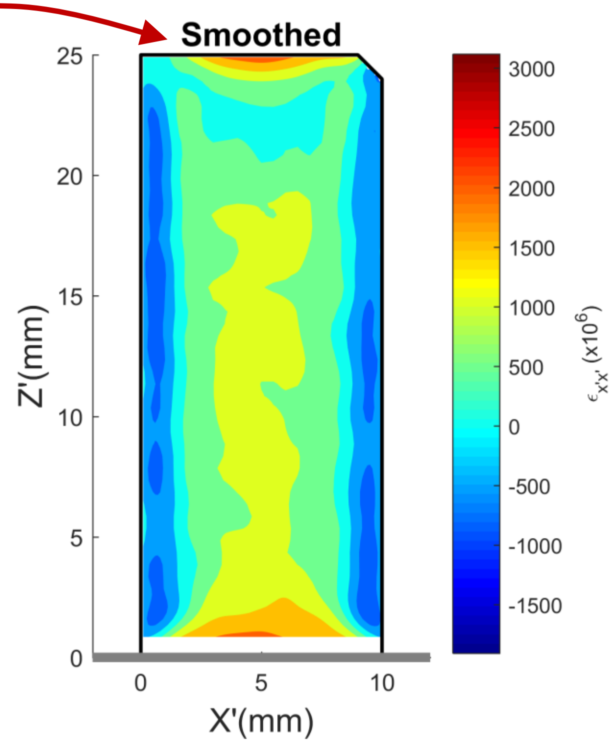


Fig. 15: Example calibration data .csv file format (left) containing smoothed weighted strain data and is depicted in contour plot (right).

- Processed strain maps/data for calibration items listed in \Challenge1\CalibrationData\StrainData

Dimensional Tolerance
Build Intent vs Built Structures

The as-printed calibration walls were measured using a FaroArm set up while still attached to the steel build plate. Approximately 120K – 730K (dependent on geometry length) surface measurements were taken for each calibration wall and relevant geometries were calculated (table 4).

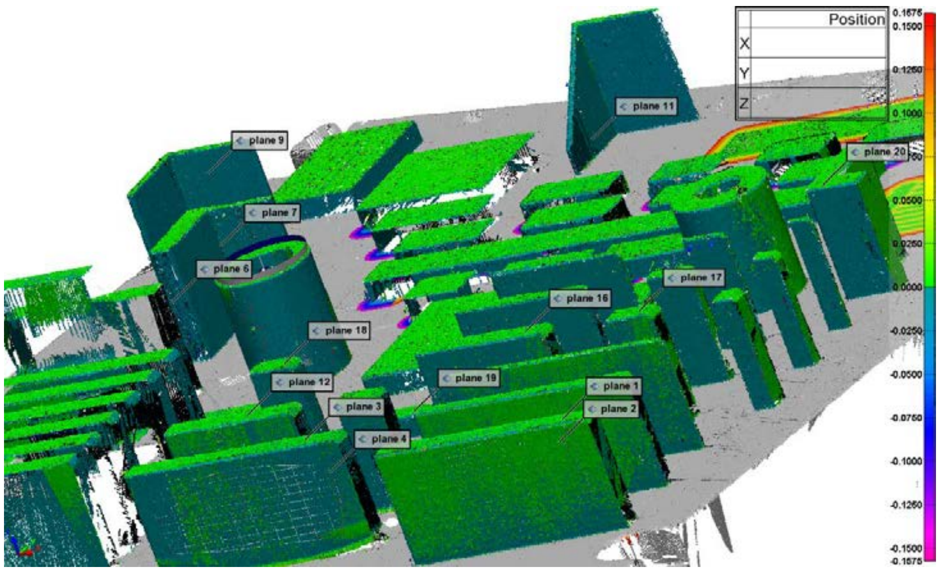


Fig. 16: Schematic of FaroArm data collected

Table 4: Average thickness and height for each of the calibration walls

Spec ID	Width Y' (mm)	Height Z' (mm)
A46	0.79	24.89
A48	4.81	24.88
A51	4.80	24.91
A52	0.80	24.94
A54	4.78	24.95

Dimensional Tolerance
Build Intent vs Built Structures

After EDD measurements and other characterization, two calibration walls (A46 and A48) were sectioned, mounted, polished and optically imaged to characterize the geometry at a single cross section of the sample.

No effort was made to analyze the observed curvature in the optical images of the cross section of wall A46 because the cause of deformation is not known (samples were sectioned and then mounted under pressure)

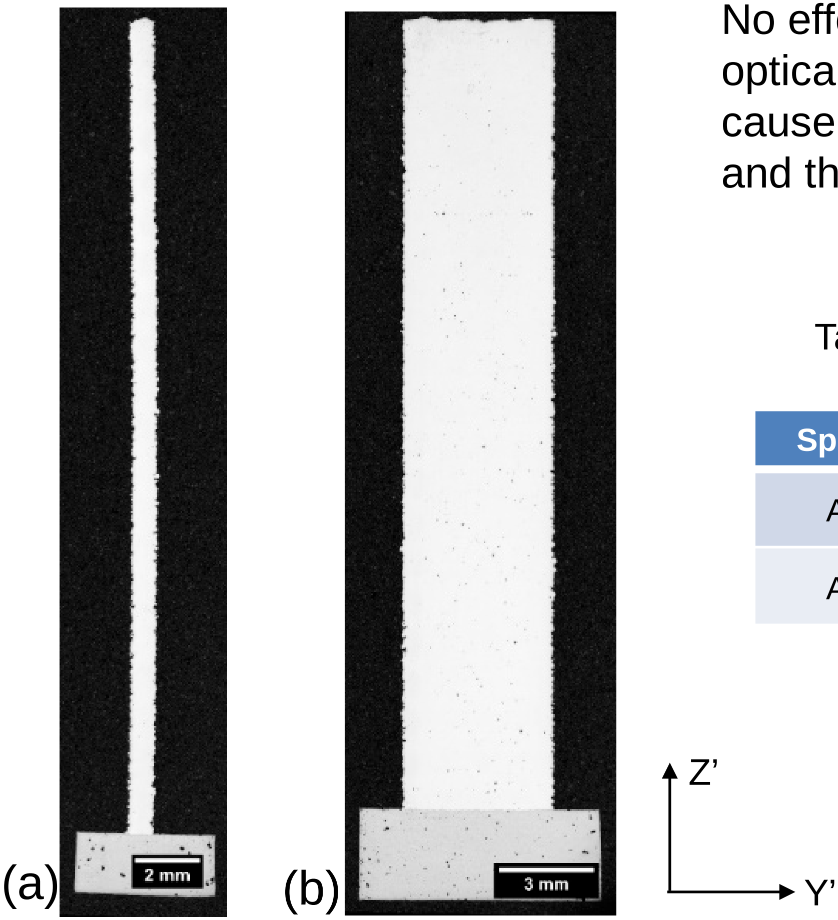


Fig. 17: Optical images of (a) A46 and (b) A48 calibration wall cross sections

Table 5: Average $\pm$ 1 standard deviation for thickness & height for A46 & A48.

Spec ID	Width Y' (mm)	Height Z' (mm)
A46	0.77 $\pm$ 0.04	-
A48	4.76 $\pm$ 0.04	24.97 $\pm$ 0.03

- Optical images of A46 & A48 calibration walls are in \Challenge1\CalibrationData\OpticalCrossSections

Data for Model Calibration – Powder Properties

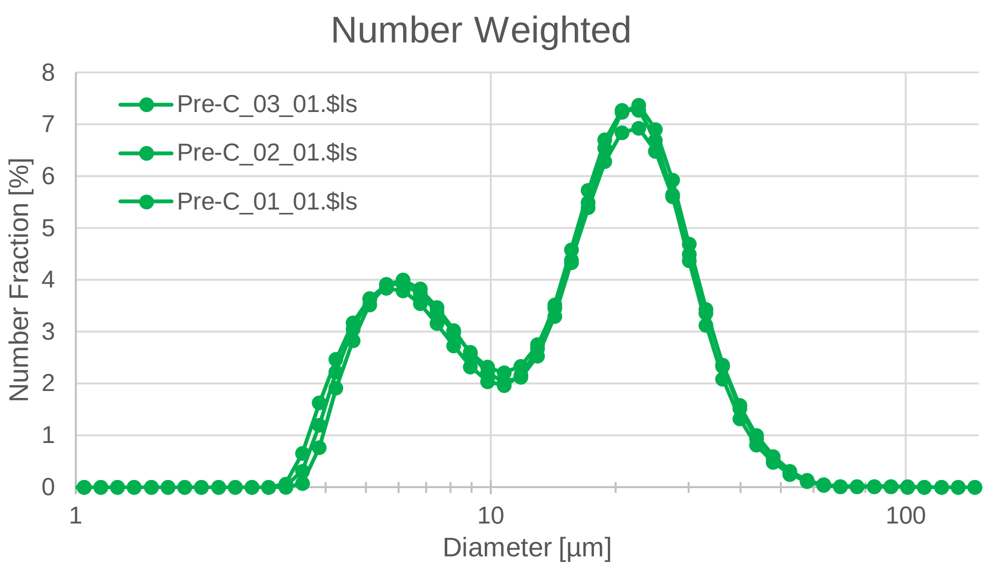


Fig. 18: Powder particle size distribution after build was completed

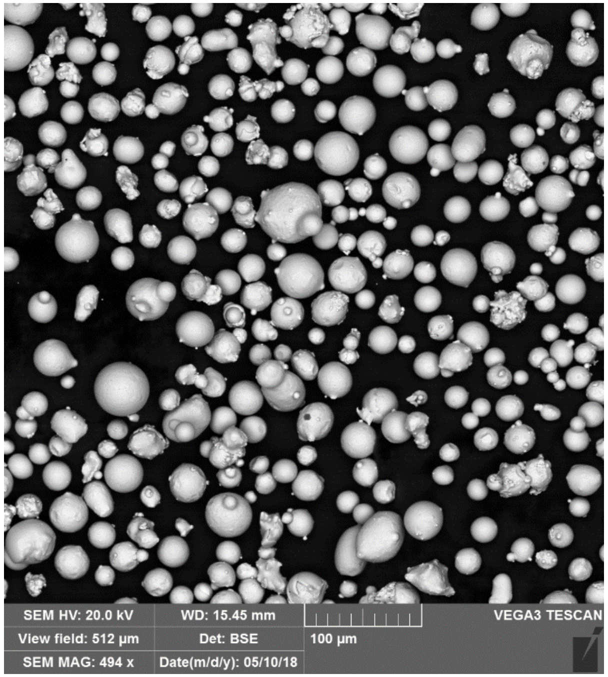


Fig. 19: BSE image of powder particles after build was completed

- 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 \Challenge1\CalibrationData\Powder Size.xlsx
- Powder morphology images located in \Challenge1\CalibrationData\Powder Images

Data for Model Calibration – Powder Properties

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 6: Chemical Analysis of IN625 Powder

- Chemical analysis of powder lot used in builds of single tracks and 2D pads
- Chemical analysis performed by powder supplier
- Gas atomized powder

Input Data for Challenge Questions

Challenge Article - Processing

- 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
- Printed using nominal parameters

Table 7: Processing parameters used for all calibration and challenge articles.

Power [W]	Speed [mm/s]	Hatch Spacing [µm]	Layer Thickness [µm]
300	1230	100	40

- No post build heat treatment was performed
- A section of the steel base plate was electrical discharge machined (EDM) with the article still attached to preserve as much residual stress as possible within the build article

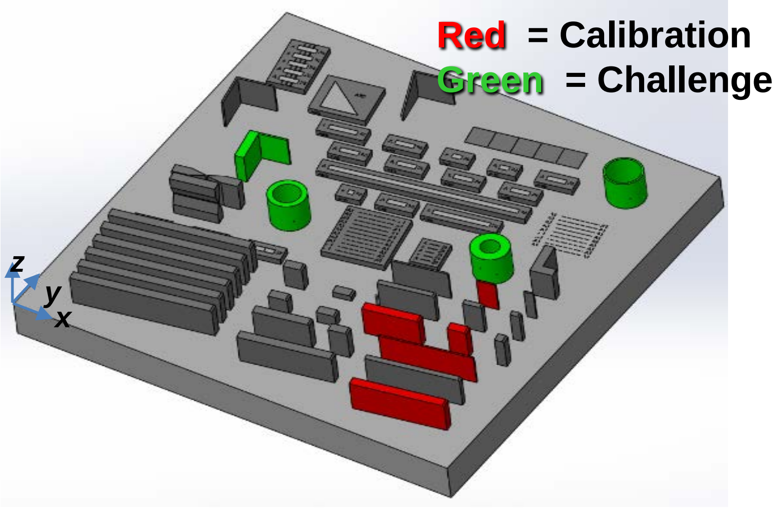


Fig. 20: CAD representation of the full build plate with calibration articles highlighted in red and challenge articles highlighted in green.

- Full build .stl file located in \Challenge1\InputData\Build Layout Details\

Dimensional Tolerance
Build Intent vs Built Structures

The as-printed cylinders were measured using a FaroArm while still on the steel build plate. Outer diameter (OD) measurements were averaged over the range of Z'=[2-23]mm and the inner diameter values were averaged over the range of Z'=[18-23]mm. Intended geometry and average FaroArm measurements of as-printed articles are listed below in Tables 8 & 9 respectively.

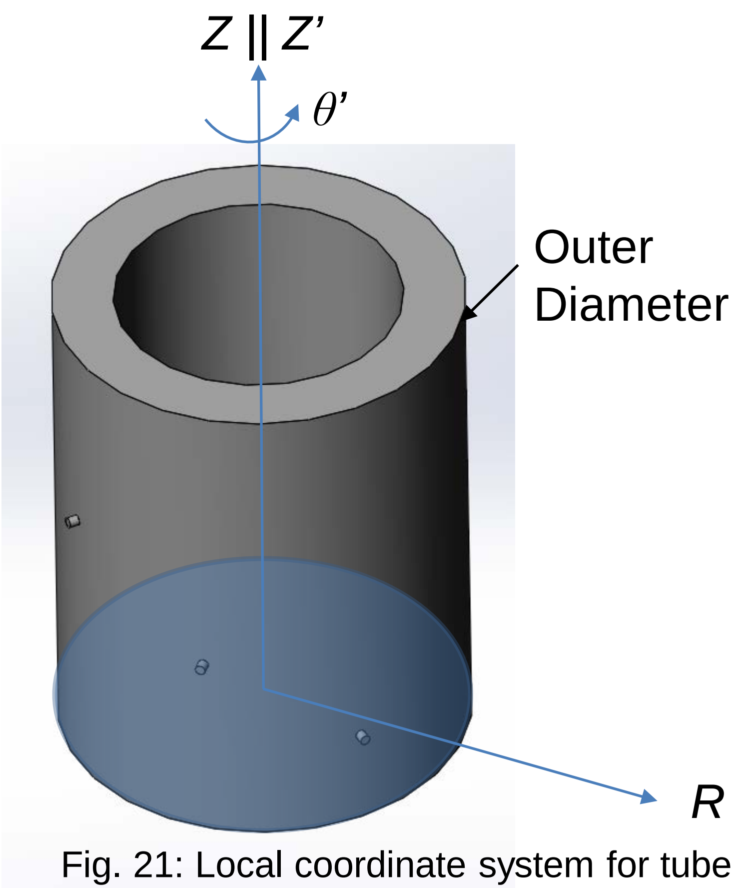


Fig. 21: Local coordinate system for tube articles.

Table 8: Designed geometries challenge articles (tubes)

Spec ID	Outer Dia R'(mm)	Inner Dia R'(mm)	Height Z' (mm)
A67	10	9	25
A68	10	7	25
A69	10	5	25

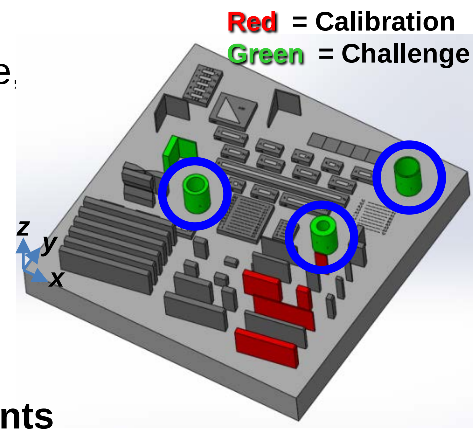
Table 9: Average FaroArm measurements of as-printed challenge cylinders over specific areas describe above.

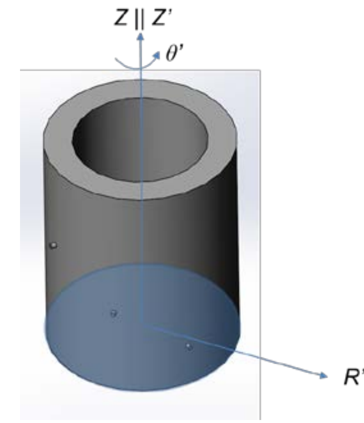
Spec ID	Outer Dia R'(mm)	Height Z' (mm)
A67	9.83	24.91
A68	9.86	24.93
A69	9.86	24.87

Measurement of Challenge Articles – Tubes

The residual strains in tubes were measured similarly to calibration plates. For the purpose of this modeling challenge, no theta dependence is assumed.

Due to the variations in the article's surface and EDD measurement confidence at the surface, residual strain measurements made within ~100µm of the challenge article free surface will not be included in the challenge.





Challenge Question: Predict residual strain components (radial and axial) in the measured locations depicted below.

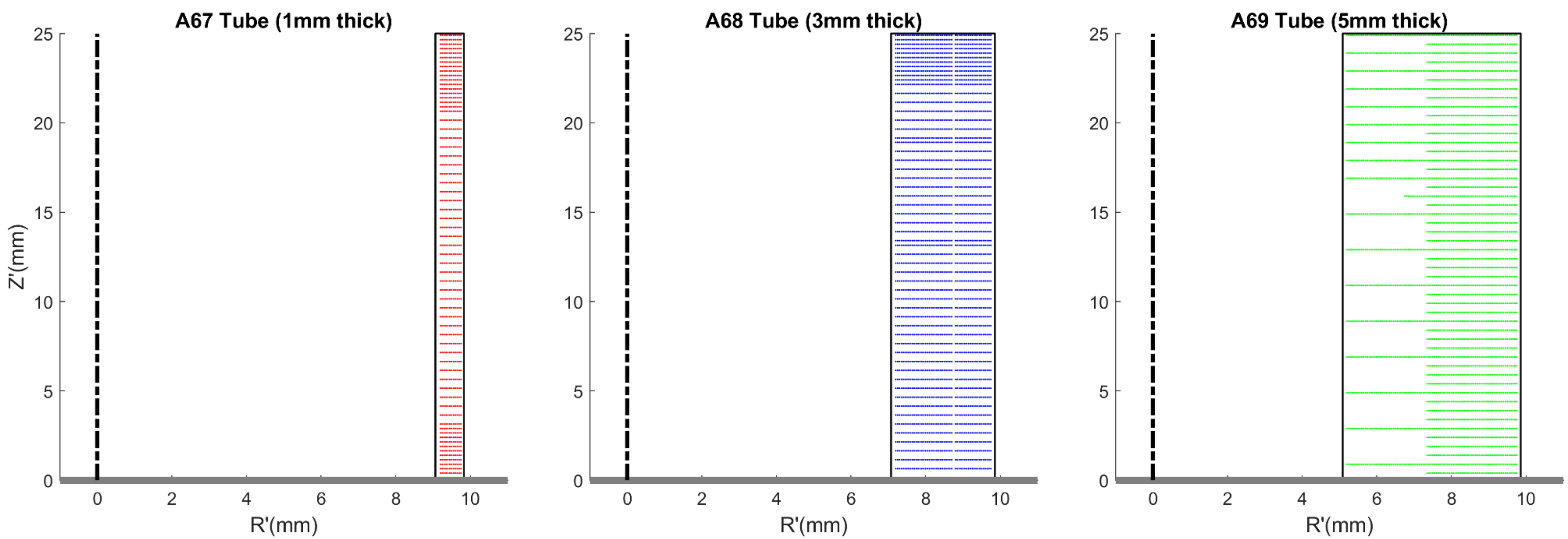


Fig. 22: Full build layout showing challenge articles highlighted in green (top) and depiction of measurement locations for radial and axial/vertical components of strain in tubes (bottom). Specific measured location coordinates are listed in the challenge answer sheet Challenge 1 Answer Templlate.v2.xlsx

Dimensional Tolerance
Build Intent vs Built Structures

The as-printed L plate was measured using a FaroArm while still on the steel build plate. Average thickness of each L plate wall was calculated using FaroArm measurements located at least 2mm from the attachment region, the build plate, and free surface edges.

Intended geometry and average FaroArm measurements of the as-printed article are listed below in Table 10.

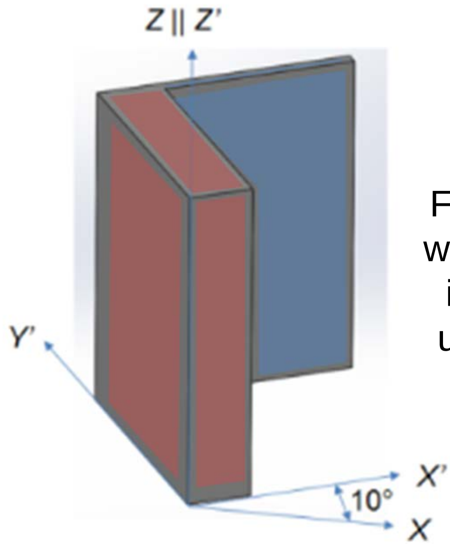
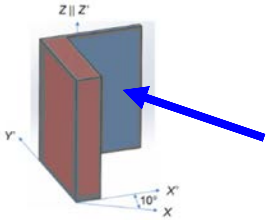
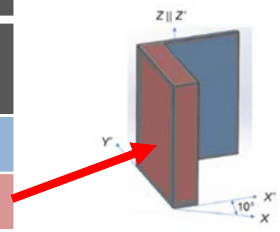


Fig. 23: Local coordinate system for L-shaped plate with highlighted schematic of the challenge article to identify areas were FaroArm measurements were used to calculate average part geometries listed in Table10.

Table 10: The designed geometry and average FaroArm measurements of the as-printed challenge L-plate over specific areas of the L plate challenge article is summarized



Designed Geometry (mm)			Average Measured Geometry (mm)	
Length X'	Thickness Y'	Height Z'	Thickness Y'	Height Z'
20	1	25	0.79	24.90
20	5	25	4.80	24.90

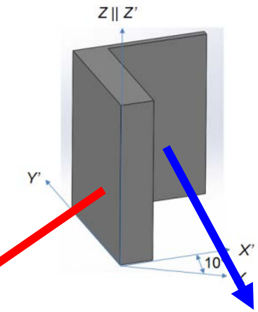


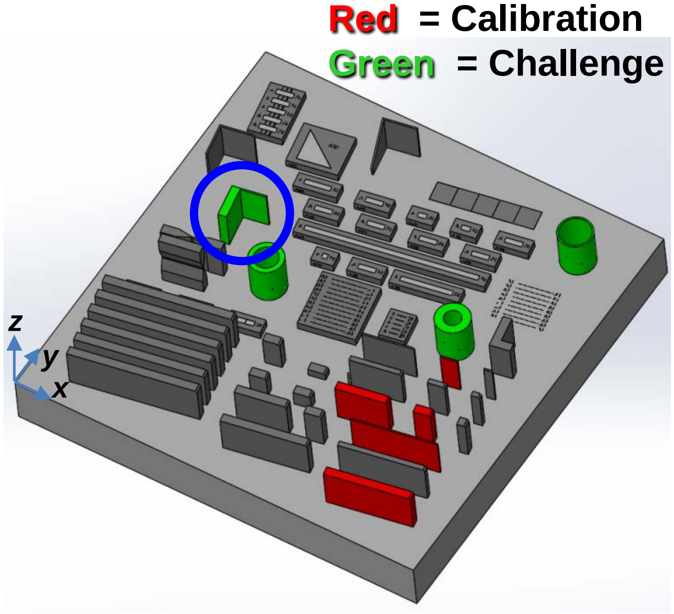
Measurement of Challenge Articles – L plate

The residual strains in thick and thin sections of L shaped plate (A64) were measured similarly to calibration plates

Due to the variations in the article's surface and EDD measurement confidence at the surface, residual strain measurements made within ~100µm of the challenge article free surface will not be included in the challenge.

- **Challenge Question: Predict residual strain components (horizontal and vertical) in the measured locations depicted below.**





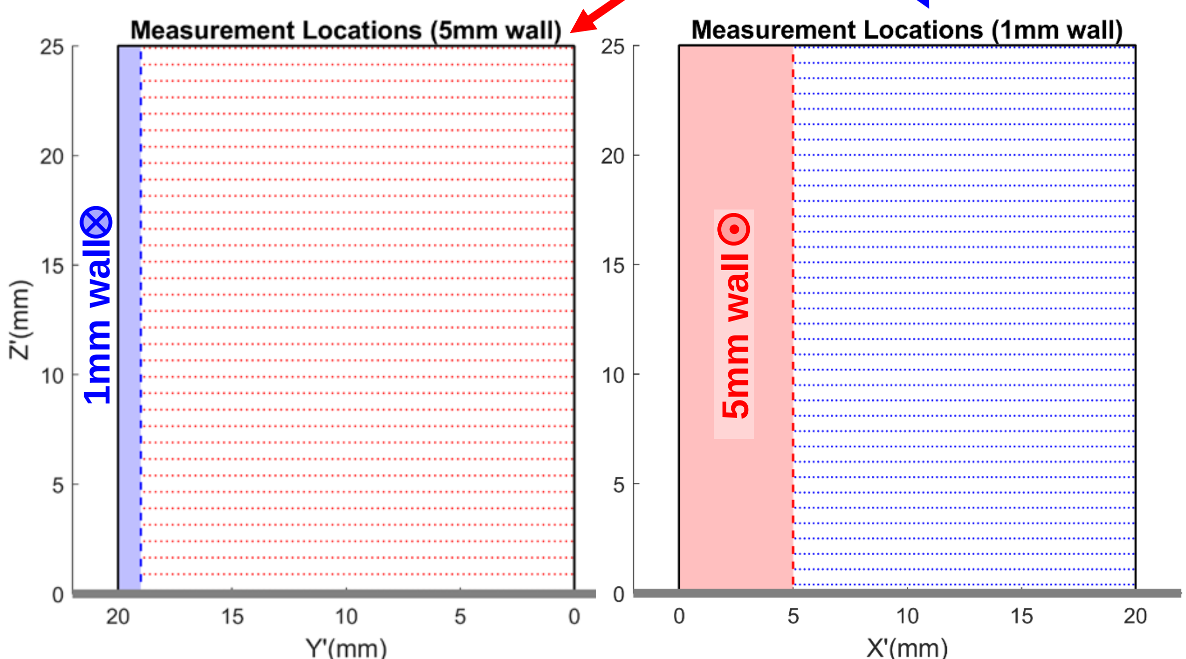


Fig. 24: Full build layout showing challenge articles highlighted in green (left) and depiction of measurement locations for horizontal and vertical components of strain in L shaped plate (right). Specific measured location coordinates are listed in the challenge answer sheet Challenge 1 Answer Templlate.v2.xlsx

Challenge Question and Scoring

Answer Grading

- Due to the variations in the raw data related to the EDD measurement technique and local microstructure, all EDD measurements were smoothed using a Gaussian process regression (a.k.a. Kriging) model. The smoothed function will be used to create the grading bounds at each location. Grades will consist of accumulating points based on accuracy of predictions and weighted by the measurement confidence of the strain values collected by EDD.
  - For each requested location, the predicted strain will receive points corresponding to the green, yellow, or red regions illustrated below (right image). For example, the selected strain bounds of +/- 2.5e-4, +/- 5.0e-4, and 7.5e-4 correspond to approximate values of stress (~50, 100, and 150 MPa).
  - Answers outside these error bounds will receive 0 pts.

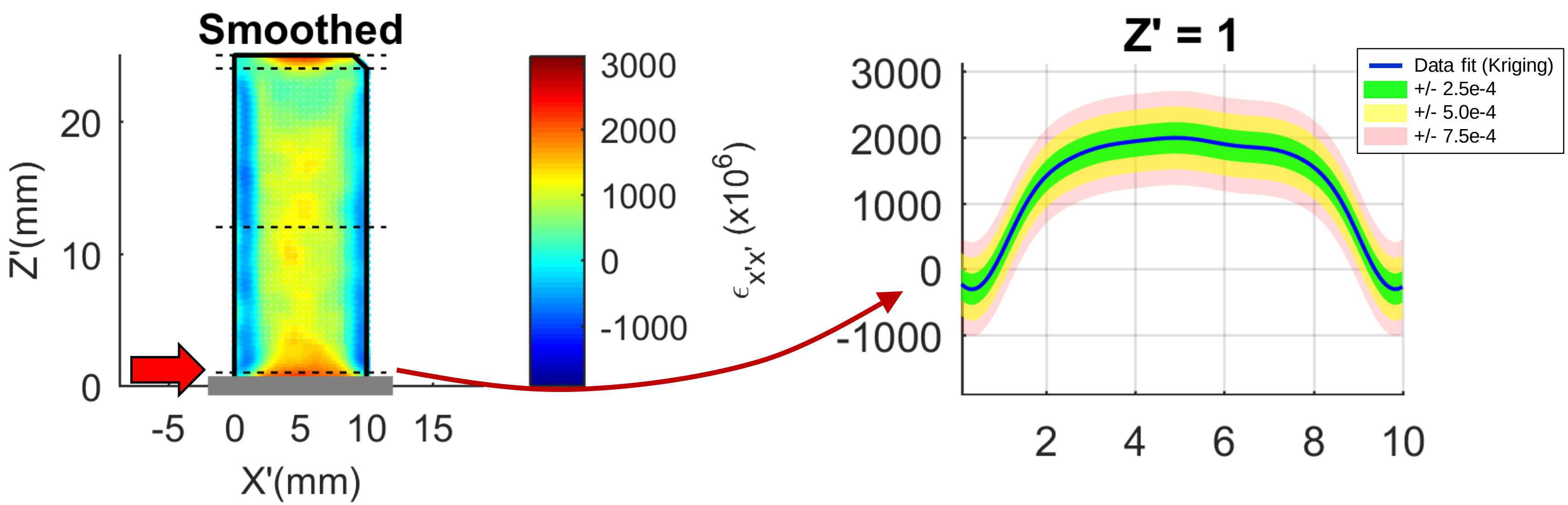
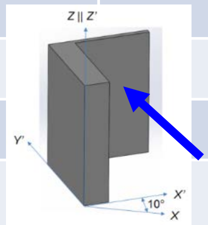


Fig. 25: Example of smoothed Kriging data (left), and line out plot showing comparison of smoothed data and error bounds used for grading simulation results (right).

Answer Format

X' [mm]	Z' [mm]	$\varepsilon_{x'x'}$ (Horizontal Component)	$\varepsilon_{z'z'}$ (Vertical Component)
0.1	0.85		
0.2	0.85		
0.3	0.85		
…	…		



Y' [mm]	Z' [mm]	$\varepsilon_{y'y'}$ (Horizontal Component)	$\varepsilon_{z'z'}$ (Vertical Component)
0.1	0.85		
0.2	0.85		
0.3	0.85		
…	…		

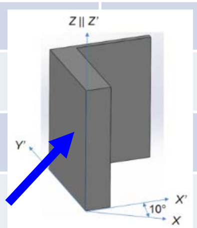


Table 11: Answer Submission Templates for L-shaped plate (top:1mm, bottom: 5mm)

- Answers will be returned in a single Excel file
- There are two tabs for L-shaped plate, one labeled A64_1mm_L and one labeled A64_5mm_L, corresponding to each plate thickness.
- There is one tab per tube article thickness.

R' [mm]	Z' [mm]	$\varepsilon_{R'R'}$ (Horizontal Component)	$\varepsilon_{z'z'}$ (Vertical Component)
0.1	0.85		
0.2	0.85		
0.3	0.85		
…	…		

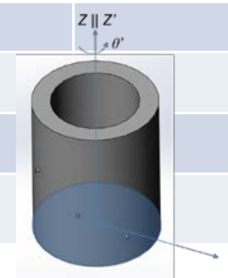
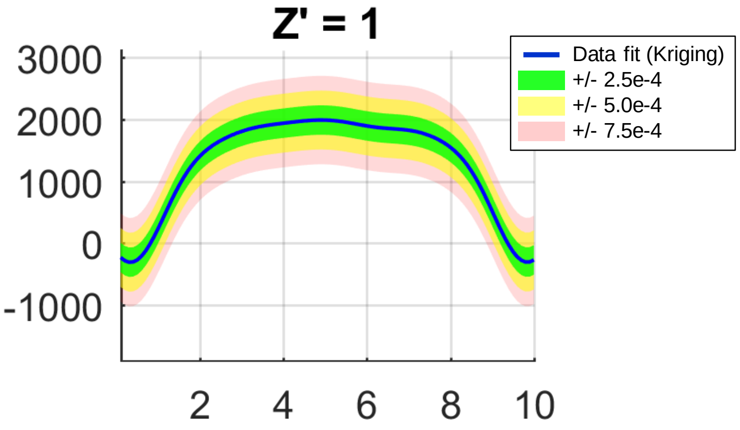


Table 12: Answer Submission Template for tube article

- Request horizontal and vertical components of strain for all measurement points given in the .xlsx file
- All answers should be submitted in the .xlsx file with horizontal and vertical components of strain inserted into the 3rd and 4th column, respectively, of the .xlsx tab corresponding to each measured article
- Note that sampling is non regular grid
  - Answer sheet template for each question are located in \Challenge1\Challenge 1 Answer Template.xlsx

Scoring

- Grades will consist of accumulating points based on accuracy of predictions.
- Smoothed (Kriged) data will be used to assess each strain value.
- Points will be weighted based on the EDD measurement confidence.
- For each location in the answer template, points will be assigned.



- Answers outside these error bounds will receive 0 pts.

- Responses must be returned within the document Challenge 1 *Answer Template.xlsx*. The template and challenge measurement location points should not be edited. ***Answers returned in any other format will not be scored***.

- Answer sheet template located in \Challenge1\ Challenge 1 Answer Template.xlsx

Supplemental Data

Supplemental Data (non-AFRL data)

Thermophysical Properties from General Electric – America Makes

Temperature (C)	Specific Heat Capacity, Cp (J/kg/C)	Thermal Conductivity, K (W/m-C)
	IN625 powder	IN625 powder
23.9	451	0.0824
301.7	491	0.1027
576.7	535	0.1258
704.4	619	0.1522
1093.3	717	0.9065
1204.4	723	4.6020

Table 13: Specific Heat and Thermal Conductivity of IN625 Powder

IN625 Room Temperature Density		
AM Machine: SLM250	Density (g/cc)	Ratio
Free powder	4.3300	0.51
Compacted powder	5.0334	0.60
As-built solid density	8.4400	1.00

Table 14: Densities of Powder Compared to As-Built Solid

*Note powder is from different lot of same alloy

Temperature (C)	IN625 As-built solid	
	Specific Heat Capacity, Cp (J/kg/C)	Thermal Conductivity, K (W/m/C)
21	410	9.8
93	427	10.8
204	456	12.5
316	481	14.1
427	511	15.7
538	536	17.5
649	565	19.0
760	590	20.8
871	620	22.8
982	645	25.2
1093	670	26.0

Table 15: Specific Heat and Thermal Conductivity of As-Built Solid

Additional Sources for Thermophysical Properties

"Metallic Materials Properties Development and Standardization Handbook". Ch.6 Battelle Memorial Institute(2015). [specifically, Sec. 6.3.3, Inconel 625]

Maglic, K.D., Perovic, N.Lj., & Stanimirovic, A.M. (1994). Calorimetric and transport properties of Zircalloy 2, Zircalloy 4, and Inconel 625. International Journal of Thermophysics, 15(4), 741-755.

Special Metals INCONEL alloy 625 Datasheet: www.specialmetals.com/assets/smc/documents/alloys/inconel/inconel-alloy-625.pdf

- Tabulated thermophysical property data located in \Challenge1\SupplementalData\Supplemental AM IN625 Data.pdf

Supplemental Data (non-AFRL 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 16: 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 \Challenge1\SupplementalData\Supplemental AM IN625 Data.pdf