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

Challenge Problem 2:
Microscale Process-to-Structure

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General Problem Statement

Predict selected aspects of meltpool geometry for 2-dimensional features at specified locations (red dashed lines in Fig. 1)

- Predict geometric dimensions (Figs. 6-7, Slide 10) along specified line
  - <u>Do not</u> include 3 outermost vectors on each end of line
- Report average (μ) and standard deviation (σ) across all geometric dimensions on each line

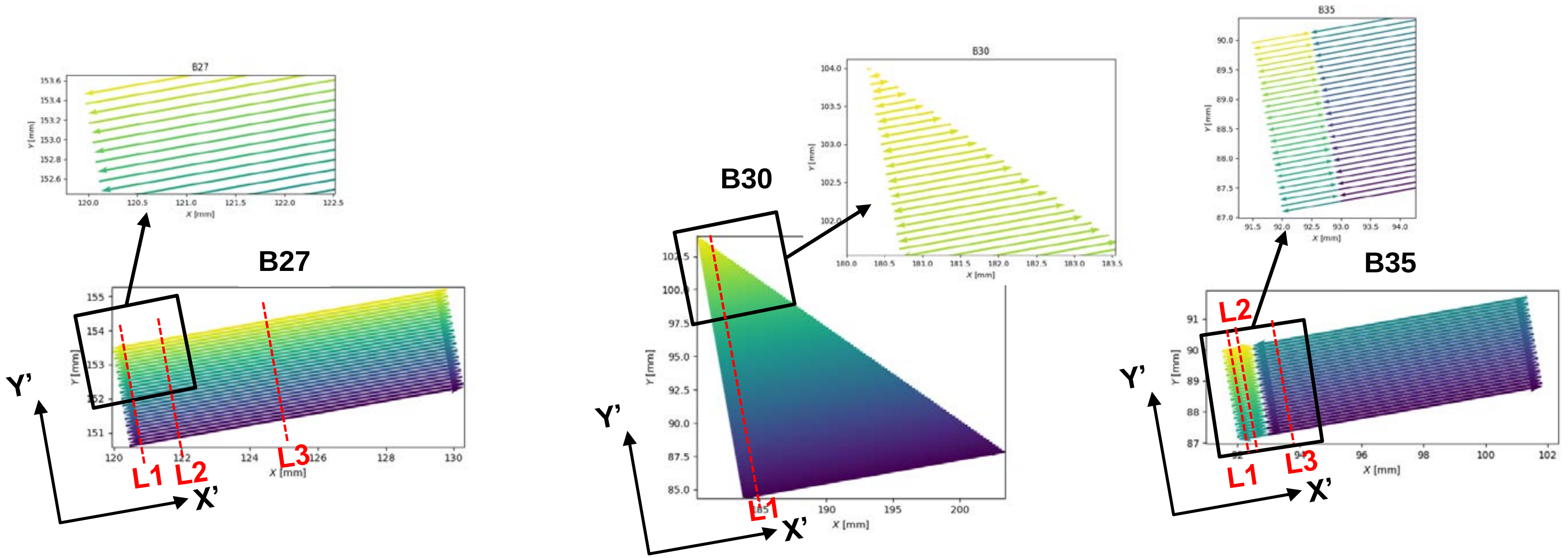


Fig. 1: Example Schematic of X-Y 2D Pad Scan Paths (B27, B30, B35)

- Explicit scan vectors contained in .cli files of 2D pads located in \Challenge2\InputData\Challenge Item Path Descriptions
- 2D pad geometries listed in Input Data section of this document

Coordinate Systems

Explicit scan vectors for all items are reported in *.cli files. The coordinates used in these files are 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.

The nominal geometry of all items being printed is provided in a .stl file, again expressed in the machine coordinate system *X,Y,Z*.

Locations where the meltpool geometry is to be predicted are described in a *specimen centered* coordinate system denoted as *X',Y',Z'* defined for each specimen on which measurements are to be made. In general, *Z'* is parallel to *Z*, and *X'* and *Y'* are rotated 10 degrees in the counter-clockwise or positive sense about the *Z* axis from the machine centered *X* and *Y* directions.

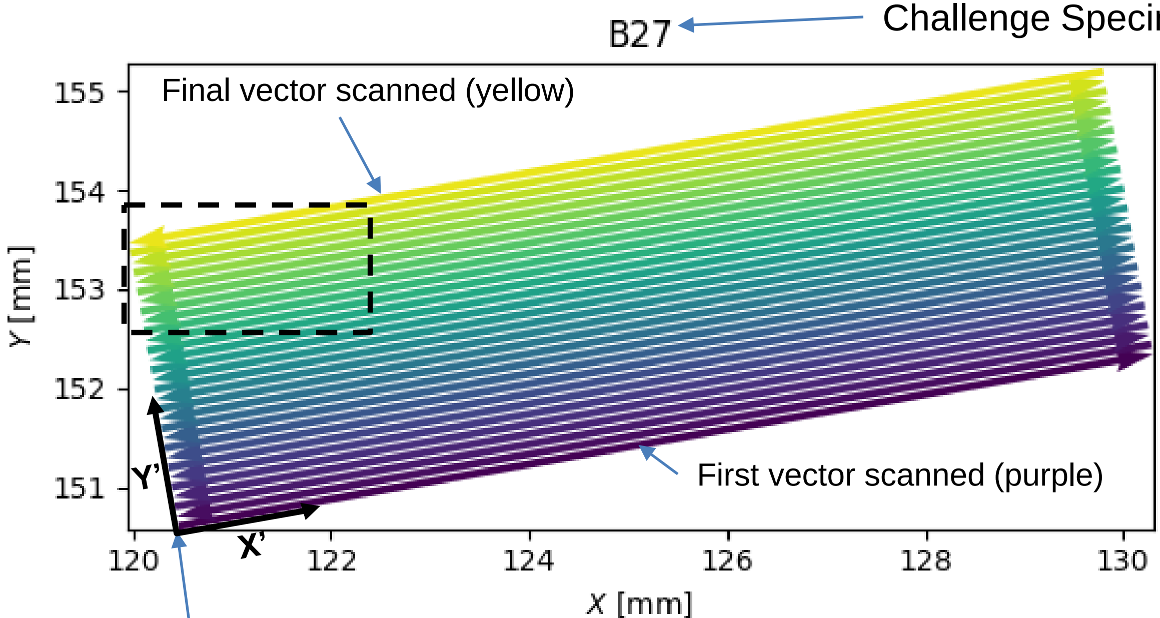
The local origin for each specimen *X',Y' =(0,0)* is coincident with the scan vector that has the lowest *Y* value in the machine coordinate system.

See schematic on next slide

- Explicit scan vectors contained in .cli files of 2D pads located in \Challenge2\InputData\Challenge Item Path Descriptions
- Full build .stl file located in \Challenge2\CalibrationData
- 2D pad geometries listed in Input Data section of this document

Coordinate Systems

Challenge Specimen ID



Local Specimen Origin: *X',Y'*=(0,0)

Absolute position in machine coordinate system, also used in .cli and .stl description of the vectors/geometry

0.5ms jump, (beam off)

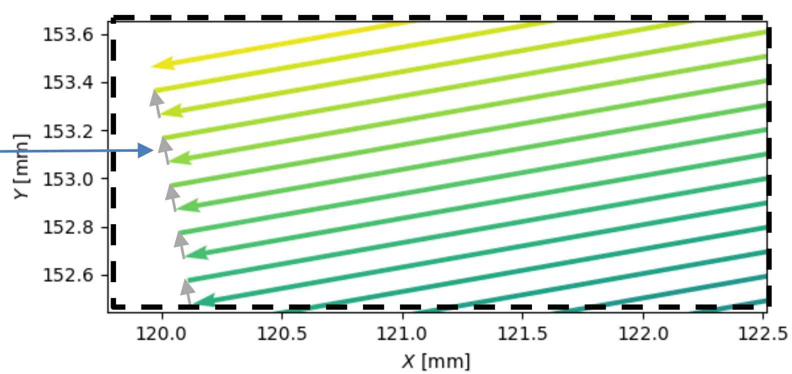


Fig. 2: Coordinate System of X-Y 2D Pad Scan Paths

Scan Strategy

The scan strategy consists of a generic “snake” or rastering across scan vectors, and is described explicitly in .cli file format.

The individual scan vectors for the items in question are either parallel or antiparallel to *X’*, and always perpendicular to *Y’.*

Vectors are scanned successively beginning with the vector with the lowest *Y’* value and working toward the most positive *Y’*, this order is also reflected in the .cli files.

When the beam reaches the end of a scan vector, there is a 0.5 ms period during which the laser beam is off (e.g. no energy delivered to the material) while the beam moves to the beginning of the next scan vector.

Substrate and Timing

All calibration and challenge items are built on top of AM printed substrate blocks 5mm in height. The blocks are rectangular and extend at least 3 mm beyond the extent of the calibration and challenge items. The blocks are directly printed onto a standard plain carbon steel base plate, approximately 300 mm in thickness, and 250 mm x 250 mm on each edge.

All substrate blocks consist of AM printed Inconel 625 using nominal processing conditions, and are 'top-skinned' for 3 successive layers before the calibration and challenge items are deposited to produce a nominally smooth top surface.

The final processing of the substrate blocks occurs at the beginning of layer 125. The calibration and challenge items are processed at the end of layer 126, at an absolute height of 5.04 mm. Full description of layer timings are provided in the input data package, but layer times are approximately 90 seconds up to layer 122, 275 seconds for layers 123-125, 39 seconds on 126, and then 27 s thereafter.

When the beam reaches the end of a scan vector, there is a 0.5 ms period during which the laser beam is off (i.e. no energy is delivered to the material during this time) while the beam moves to the beginning of the next scan vector. These movements are *not* explicitly described in the .cli file.

- Layer times are given in \Challenge2\InputData\HomeIn-Build B.csv

CLI File Description

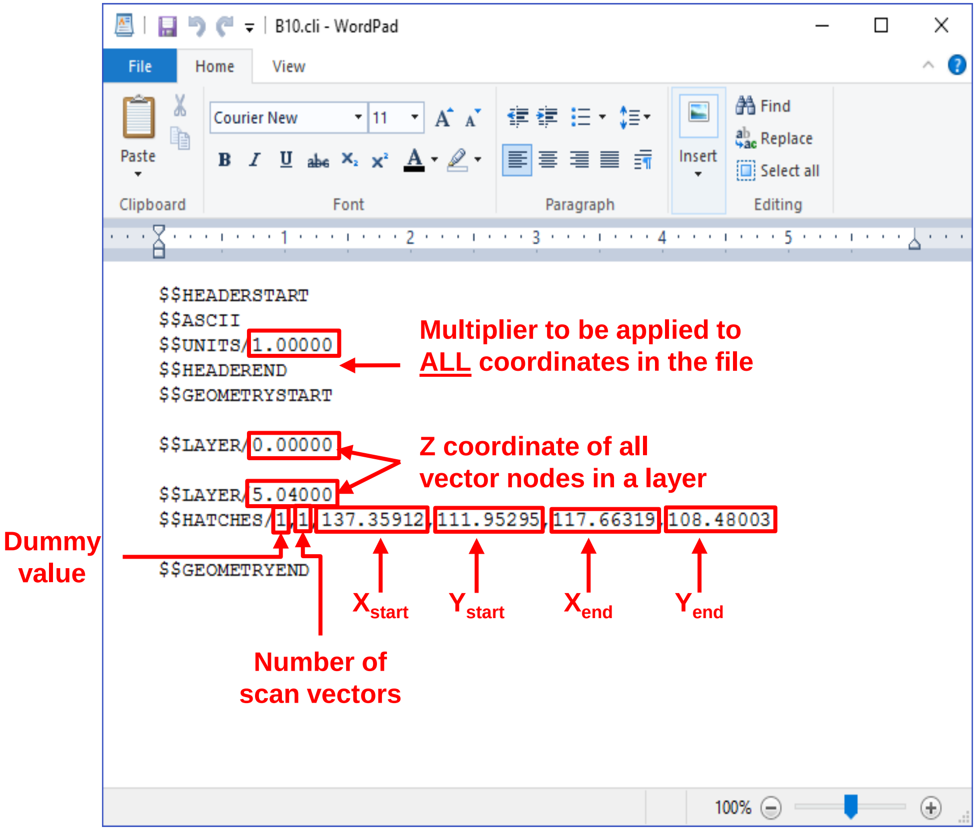


Fig. 3: Annotated CLI File for Single Track Calibration Item B10

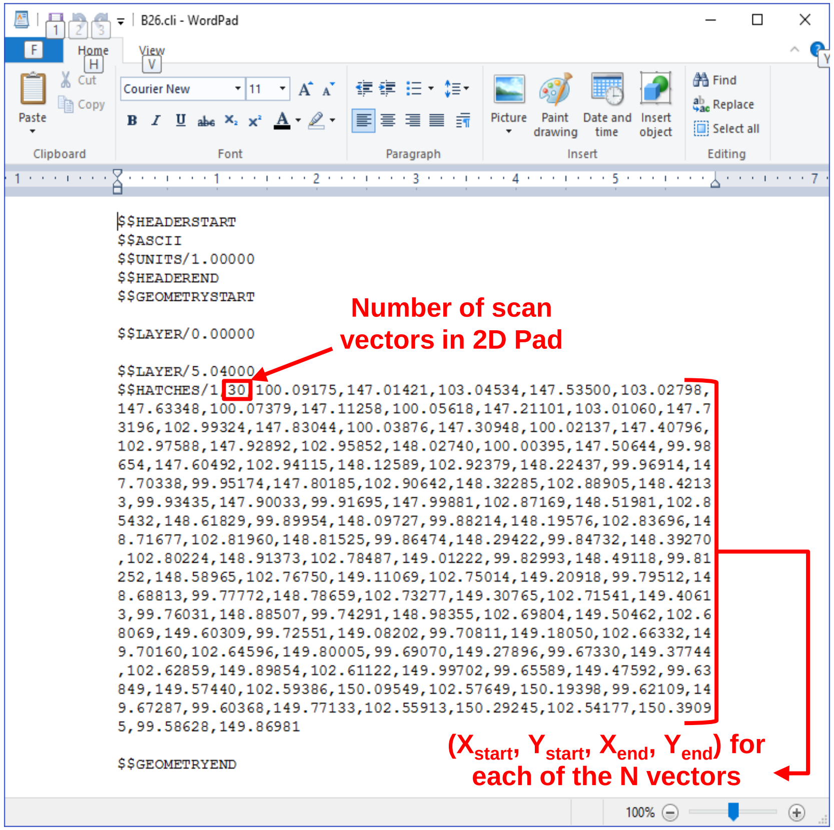


Fig. 4: Annotated CLI File for Challenge Item B26

Unofficial website detailing .cli format - http://www.hmilch.net/downloads/cli_format.html

Detailed Prediction Locations

For each challenge item, one to three "measurement lines" are defined in the answer template at the end of this document, and examples are shown as red dashed lines below. These lines are parallel to the *Y'* axis, and are specified in terms of their *X'* coordinate (recall the *X',Y'* coordinate system is unique to each specimen).

The various measurements of the meltpool dimensions (described in detail on slide 10) should be collected for each scan vector that crosses the measurement line, excluding the first 3 vectors (lowest *Y'* values) and the last 3 vectors (highest *Y'* values). The meltpool dimensions should be collected for all vectors that cross the measurement line, and the mean and standard deviation of the collection should be reported in the answer template on slide 17.

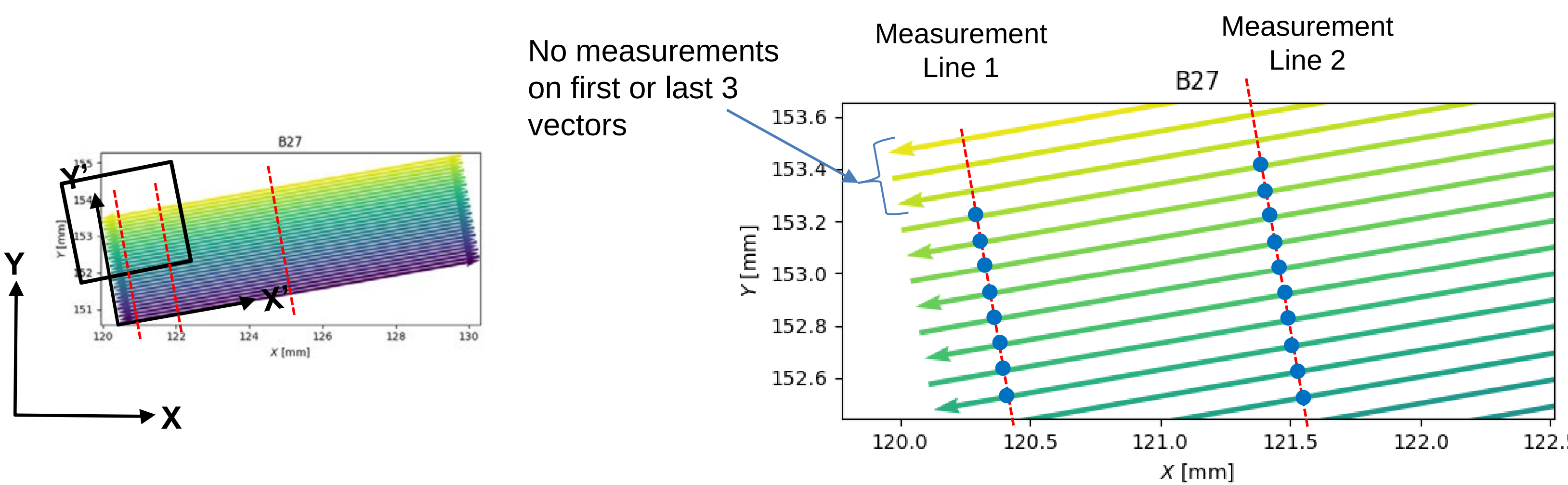


Fig. 5: Schematic of Measurement Locations for a X-Y 2D Pad

- Detailed measurement locations provided in \Challenge2\Challenge 2 Answer Template.xls

Requested Predictions

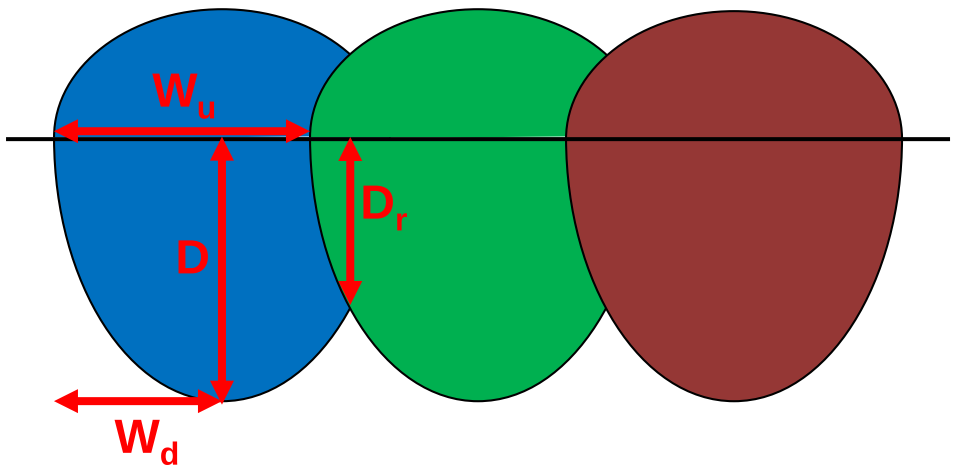


Fig. 6: Schematic of X-Y 2D Pad Meltpools
with Desired Measurements
(applicable to all samples, except B21 & B25)

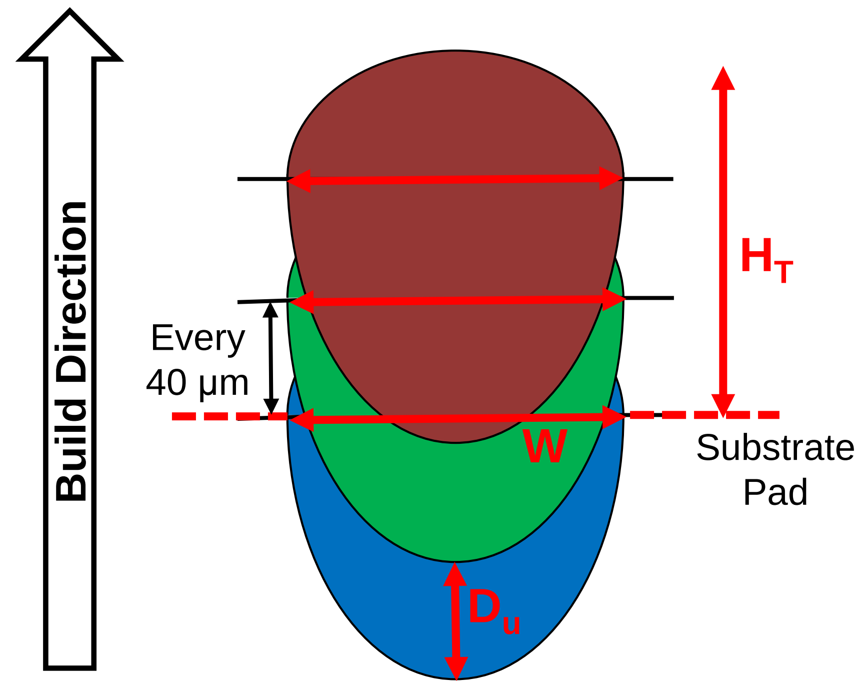


Fig. 7: Schematic of X-Z 2D Pad
Meltpools with Desired Measurements
(applicable to B21 & B25)

- 4 measurements per meltpool in X-Y 2D pads, which should be averaged over the central 18-24 meltpools along each evaluation line (ignore the outer 3 meltpools on each end of line)
- 2 measurements per meltpool in X-Z 2D pads, which should be averaged over lowest 9 meltpools along each evaluation line (ignore top meltpool) & 1 global measurement of total height above substrate pad

Data for Model Calibration

- Layer thickness = 40 µm for all single tracks
- Length = 20 mm for all single tracks
- Gaussian laser spot diameter (4σ) = 0.1 mm (from manufacturer datasheet)

Track Id	Power	Speed	Top-Down Width [µm] µ, σ	Cross-section Width [µm] µ, σ	Cross-section Max. Width [µm] µ, σ	Cross-section Depth [µm] µ, σ	Cross-section Height [µm] µ, σ
B10	300	1230					
B11	300	1230					
B12	290	953					
B13	370	1230					
B14	225	1230					
B15	290	1588					
B16	241	990					
B17	349	1430					
B18	300	1230					
B19	349	1058					
B20	241	1529					

Download Data Package for Calibration Values

Table 1: Single Track Calibration Measurements

- Tabulated processing conditions for calibration items listed in \Challenge2\CalibrationData\Build B Calibration Item Conditions.xlsx
- .cli files located in \Challenge2\CalibrationData\Single Track Descriptions
- Single track measurements in \Challenge2\CalibrationData\Build B Summary Measurements.xlsx

Data for Model Calibration

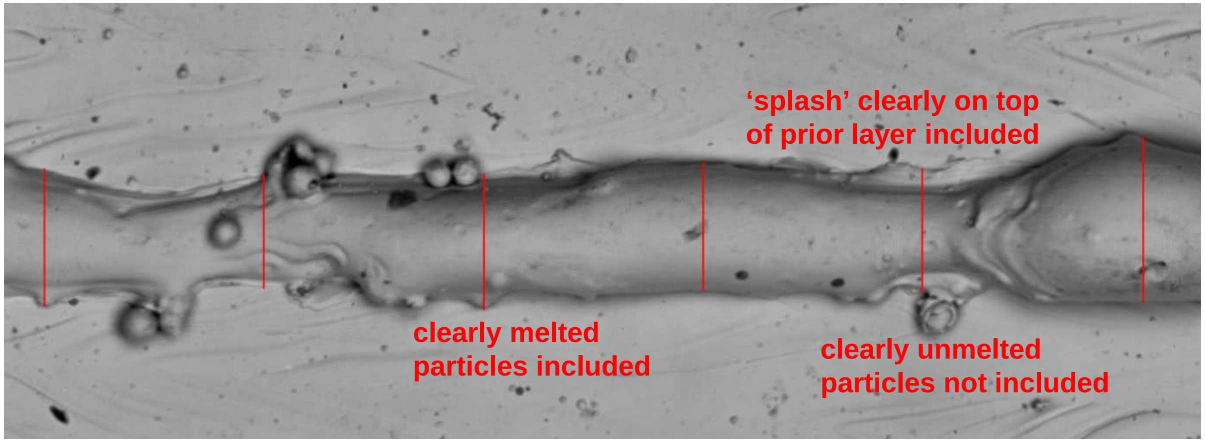


Fig. 8: Top-down BSE image with red lines representing width measurements

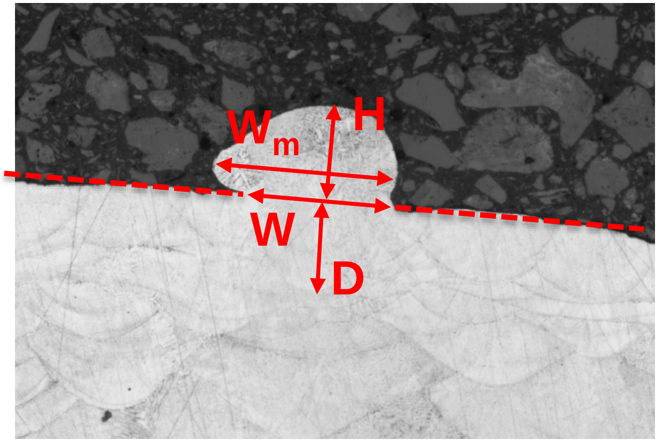


Fig. 9: Cross-section OM image with height, width, max width & depth shown

- Single tracks independently measured by 2 members of AFRL team
- All measurements taken from central 10mm of tracks
- Top-down measurements made on back-scattered electron (BSE) image
  - 20 locations, spaced by ~200 µm
- Cross-section measurements made on etched, optical microscopy (OM) images
  - 10 locations, spaced by ~100 µm
  - Width W defined as width of meltpool at location of previous layer
  - Max width W_m defined as widest section of meltpool (above or below previous layer)
  - Depth D defined as deepest point of meltpool below previous layer
  - Height H defined as highest point of meltpool above previous layer

- Raw top-down images located in \Challenge2\CalibrationData\BSE Top View Images
- Raw cross-section images located in \Challenge2\CalibrationData\OM CrossSection Images

Data for Model Calibration

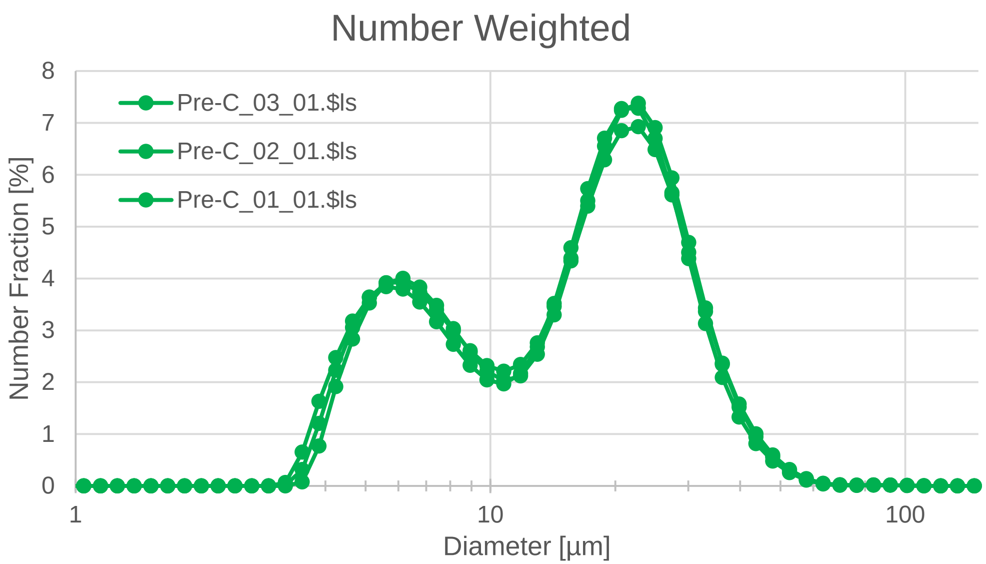


Fig. 10: Powder particle size distribution after build was completed

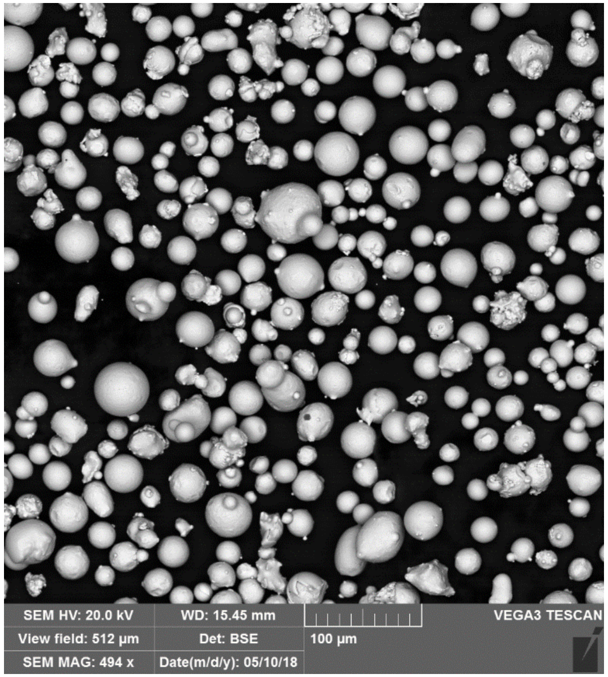


Fig. 11: BSE image of powder particles after build was completed

- 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 \Challenge2\CalibrationData\Powder Size.xlsx
- Powder morphology images located in \Challenge2\CalibrationData\Powder Images

Data for Model Calibration

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 2: 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

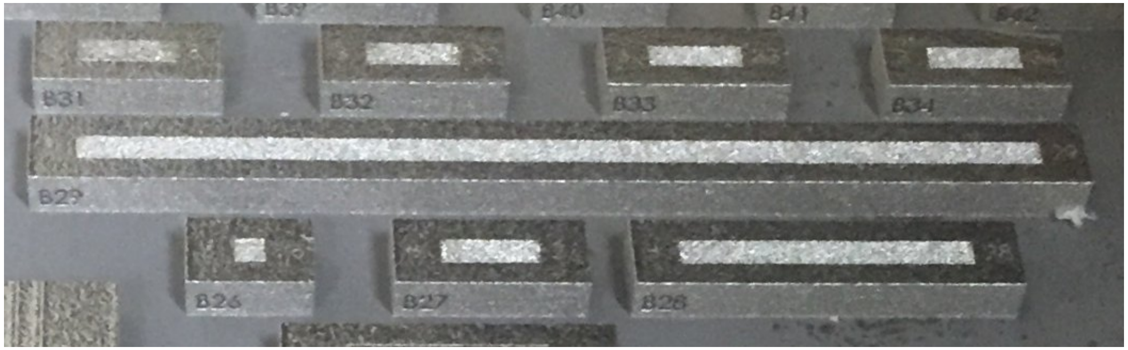


Fig. 12: Image of 2D pads showing their isolation in the build

Pad ID	Dimensions (mm)	Height (layers)	Power	Speed (mm/s)	Hatch Spacing (mm)	Layer Thickness (mm)
B21	5 x 1 track	10	300	1230	N/A	0.04
B25	5 x 1 track	10	241	1529	N/A	0.04
B26	3 x 3	1	300	1230	0.10	0.04
B27	10 x 3	1	300	1230	0.10	0.04
B30	20 x 20 (triangle)	1	300	1230	0.10	0.04
B31	10 x 3	1	300	1230	0.075	0.04
B34	10 x 3	1	300	1230	0.125	0.04
B35	1 x 3, 9 x 3	1	300	1230	0.10	0.04
B38	15 x 3	1	290	953	0.10	0.04

Table 6: Geometries and Process Conditions of Challenge Items

- Tabulated processing conditions for challenge items listed in \Challenge2\InputData\Build B Question Item Conditions.xlsx
- .cli files of 2D pads located in \Challenge2\InputData\Challenge Item Path Descriptions
- Locations of evaluation listed in \Challenge2\Challenge 2 Answer Template.xls

Input Data for Challenge Questions

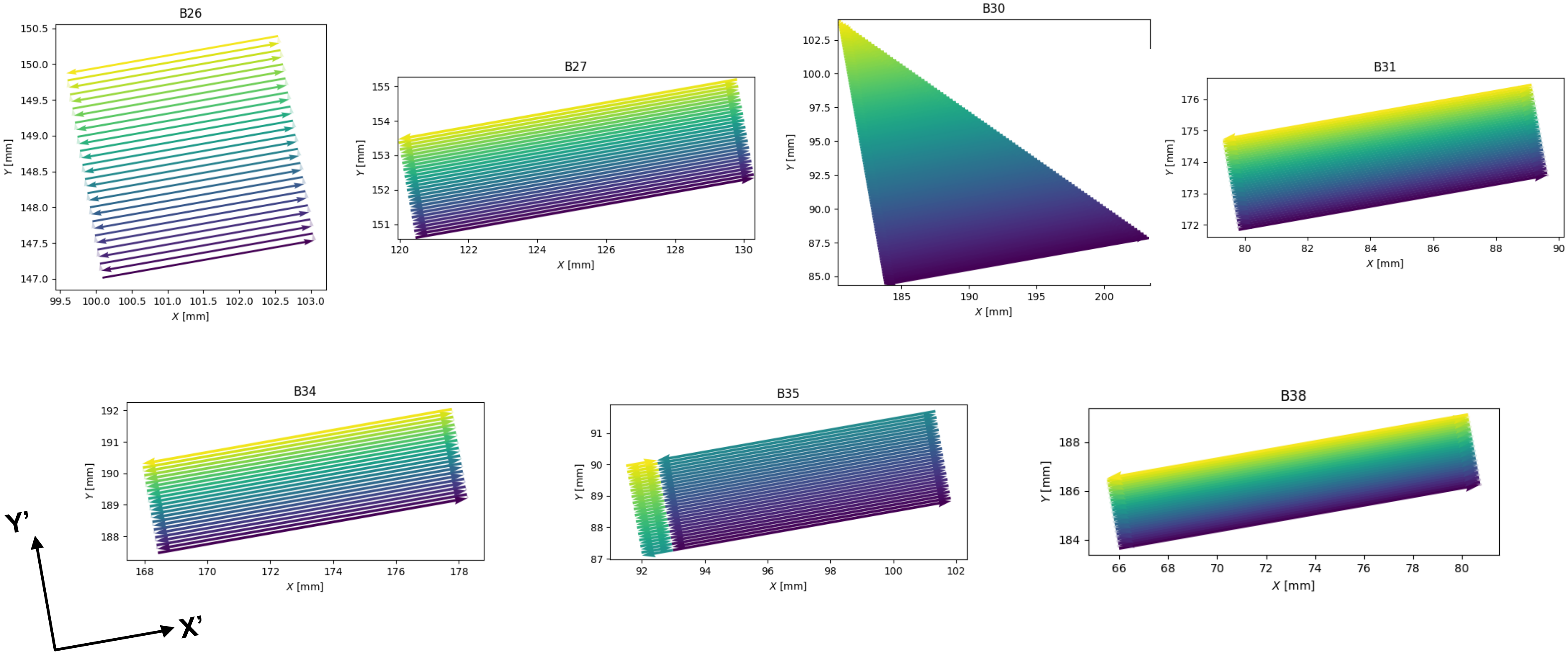


Fig. 13: Image of all X-Y 2D pads showing their scan path (X-Z pads not shown)

*** See Slide 4 for Coordinate System Description ***

Answer Format

	Measurement Line 1					Measurement Line 2					Measurement Line 3				
Pad ID	X' Pos. [mm]	W [μm] μ, σ	D_u [μm] μ, σ	H_T [μm]		X Pos. [mm]	W [μm] μ, σ	D_u [μm] μ, σ	H_T [μm]		X' Pos. [mm]	W [μm] μ, σ	D_u [μm] μ, σ	H_T [μm]	
B21	0.25					2.5					4.75				
B25	0.25					2.5					4.75				
Pad ID	X' Pos. [mm]	W_d [μm] μ, σ	W_u [μm] μ, σ	D [μm] μ, σ	D_r [μm] μ, σ	X' Pos. [mm]	W_d [μm] μ, σ	W_u [μm] μ, σ	D [μm] μ, σ	D_r [μm] μ, σ	X' Pos. [mm]	W_d [μm] μ, σ	W_u [μm] μ, σ	D [μm] μ, σ	D_r [μm] μ, σ
B26	0.1					1.5					X	X	X	X	X
B27	0.1					1.5					5				
B30	0.1					X	X	X	X	X	X	X	X	X	X
B31	0.1					1.5					5				
B34	0.1					1.5					5				
B35	0.1					0.5					1.5				
B38	0.1					1.5					7.5				

Table 7: Answer Submission Template (See slide 10, Figs. 6-7 for measurement definitions)

- Predictions for each measurement line and each specimen are worth same value
- Grades will consist of accumulating points based on accuracy, precision of predictions:

  For averages (μ): +/- 5 μm = 9 pts; +/- 10 μm = 3 pts; +/- 20 μm = 1 pt

  For standard deviations (σ): +/- 3 μm = 4 pts; +/- 6 μm = 2 pts; +/- 12 μm = 1 pt

- Answer sheet template located in \Challenge2\Challenge 2 Answer Template.xls

Supplemental Data

Thermophysical Properties from General Electric – America Makes

*Note powder is from different lot of same alloy

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 3: 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 4: Densities of Powder Compared to As-Built Solid

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 5: 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 \Challenge2\SupplementalData\Supplemental AM IN625 Data.pdf

Supplemental Data

Download Data Package for Supplemental Values

Fig. 14: Single Track Measurements for various Ni Superalloys

- Melt pool widths from additional source (General Electric - AmericaMakes) for multiple IN alloys (625, 718, 718+)
- Data not collected by AFRL and from different AM machine platform (SLM 250)

- Tabulated thermophysical property data located in \Challenge2\SupplementalData\Supplemental AM IN625 Data.pdf