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

Challenge Problem 2:

Microscale Process-to-Structure

Released August 2019

Integrity ★ Service ★ Excellence

Table Of Contents

AFRL

General Problem Statement

Predict selected aspects of meltpool geometry for single layer, multitrack scan pads at specified locations (red dashed lines in Fig. 1)

- Predict geometric dimensions (slide 17) along specified line
- Report average (μ) and standard deviation (σ) across all geometric dimensions in each measurement plane

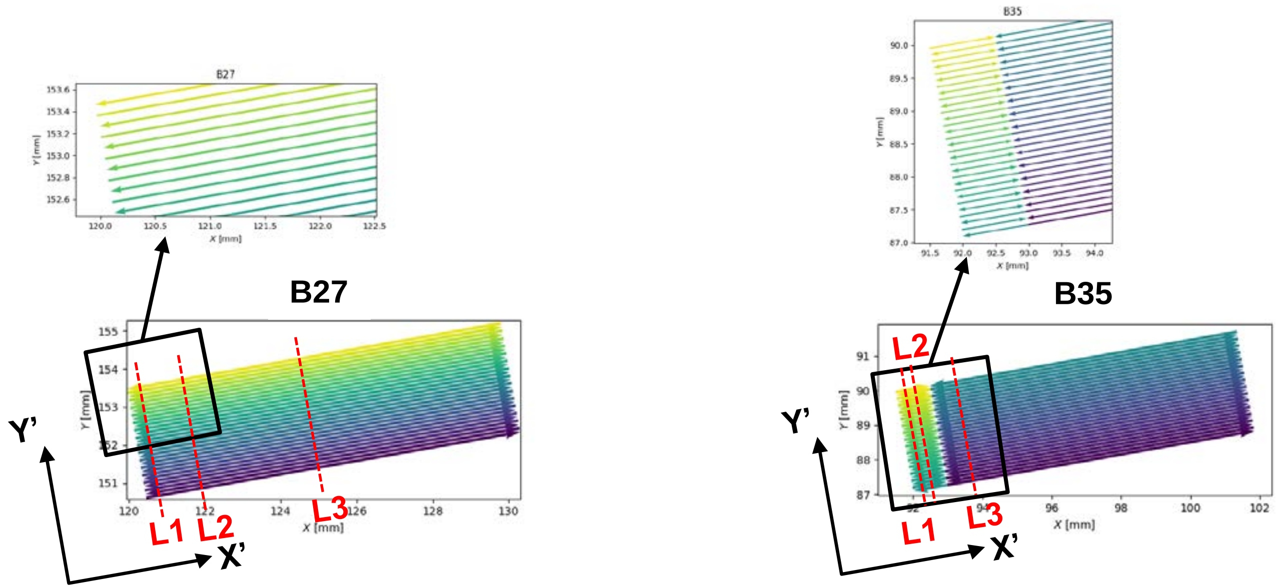


Fig. 1: Example Schematic of X-Y 2D Pad Scan Paths (B27 & B35)

- 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

General Process Overview

- Samples were printed on an EOS M280 Laser Powder Bed Fusion system (LPBF) in 2017
- Commercially available IN625 gas atomized powder was used as stock (slide 15 for material data provided by suppler)
- Substrate blocks were printed on top of the build plate using nominal conditions and ‘top-skin’ parameters were applied on the final 3 layers prior to single vector scans depositions (slide 9)
- Single vector scans (used for calibration data) and challenge problem multitrack scan pads were built on top of separate substrate blocks
- No post build heat treatment was performed

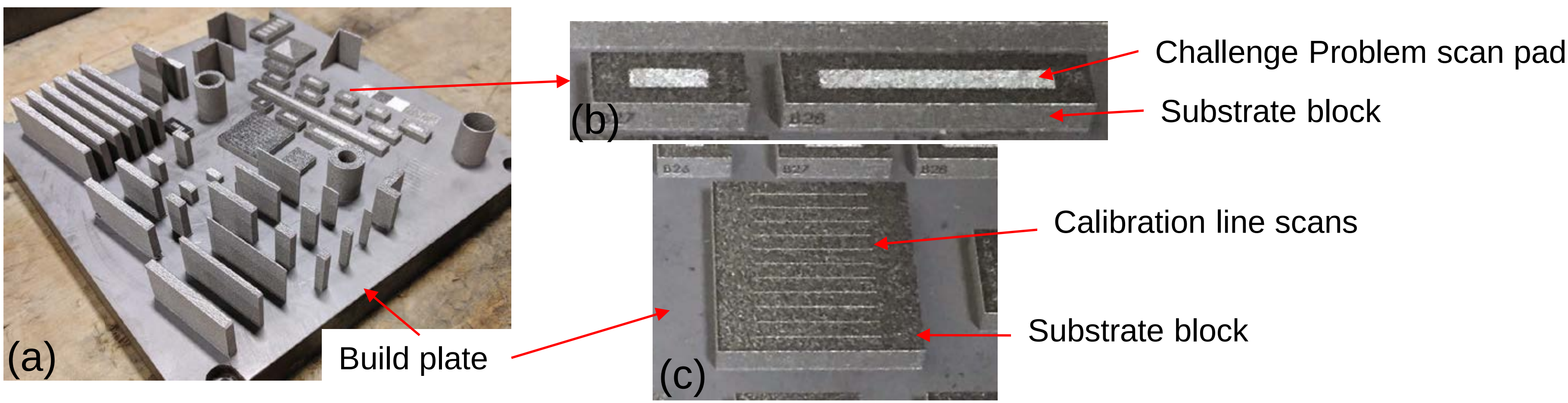


Fig. 2: Example of (a) full build plate and examples of an as-printed (b) challenge problem scan pad sample and (c) calibration line scans

Background Information

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)*. 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).

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

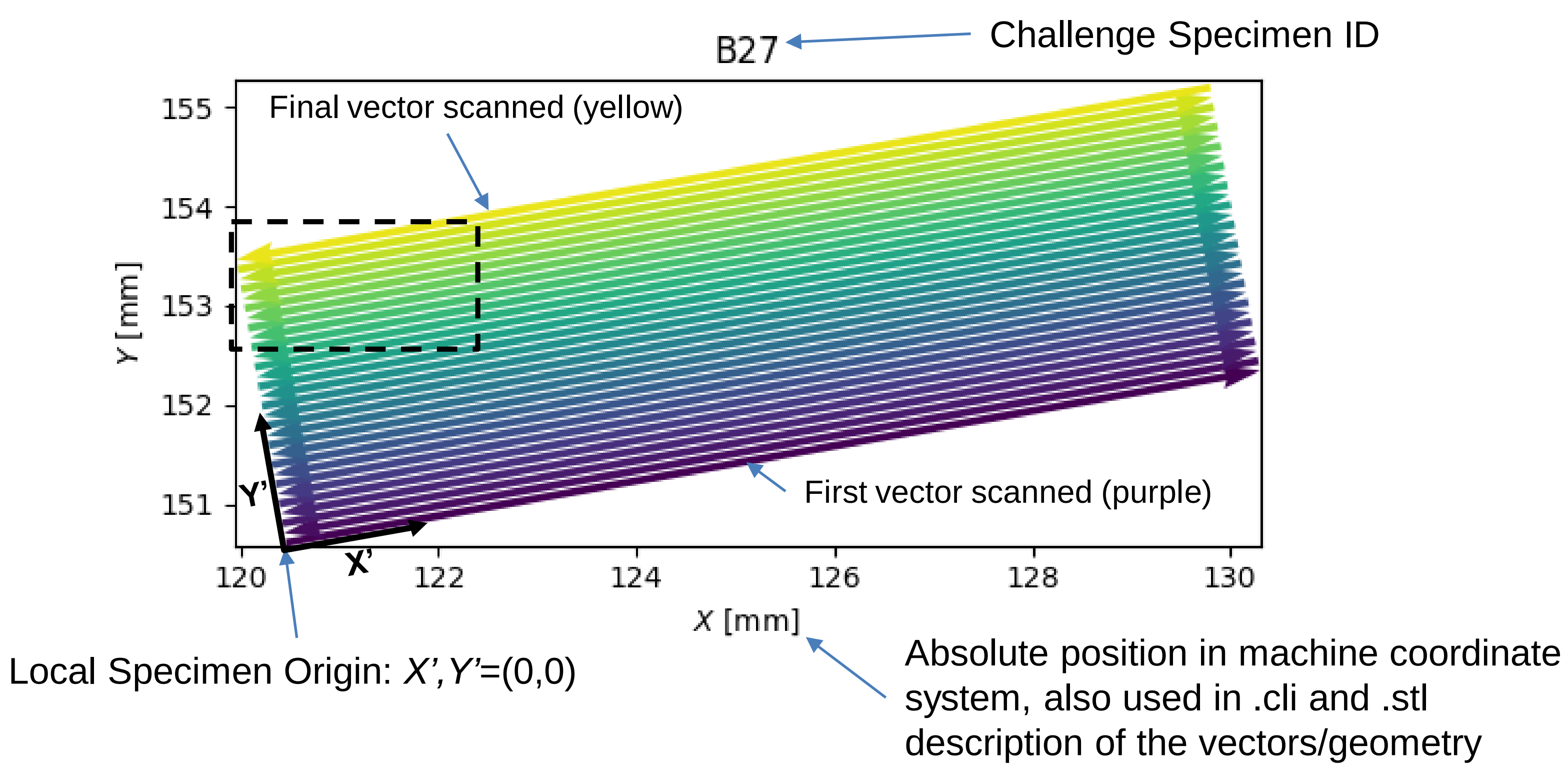
Locations where the meltpool geometry is to be predicted are described in a *specimen centered* coordinate system denoted as *X',Y',Z'* uniquely defined for each specimen on which measurements are to be made. In general, *Z'* is parallel to *Z*, and *X'* and *Y'* are rotated 10 degrees in the counter-clockwise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



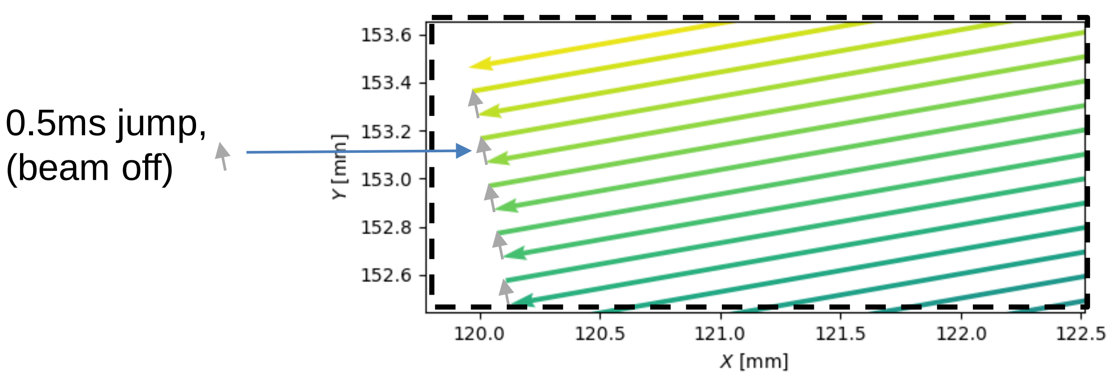


Fig. 3: Coordinate system of single layer, multitrack scan pads

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. The first vector processed (track 1) is moving parallel to +*X'*, the second would be parallel to -*X'*. Subsequent vectors alternate in a similar fashion.

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 in the *X'* and *Y'* directions. The blocks are directly printed onto a standard plain carbon steel base plate, approximately 30 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. Specimens B21 and B25 continue to layer 135. 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

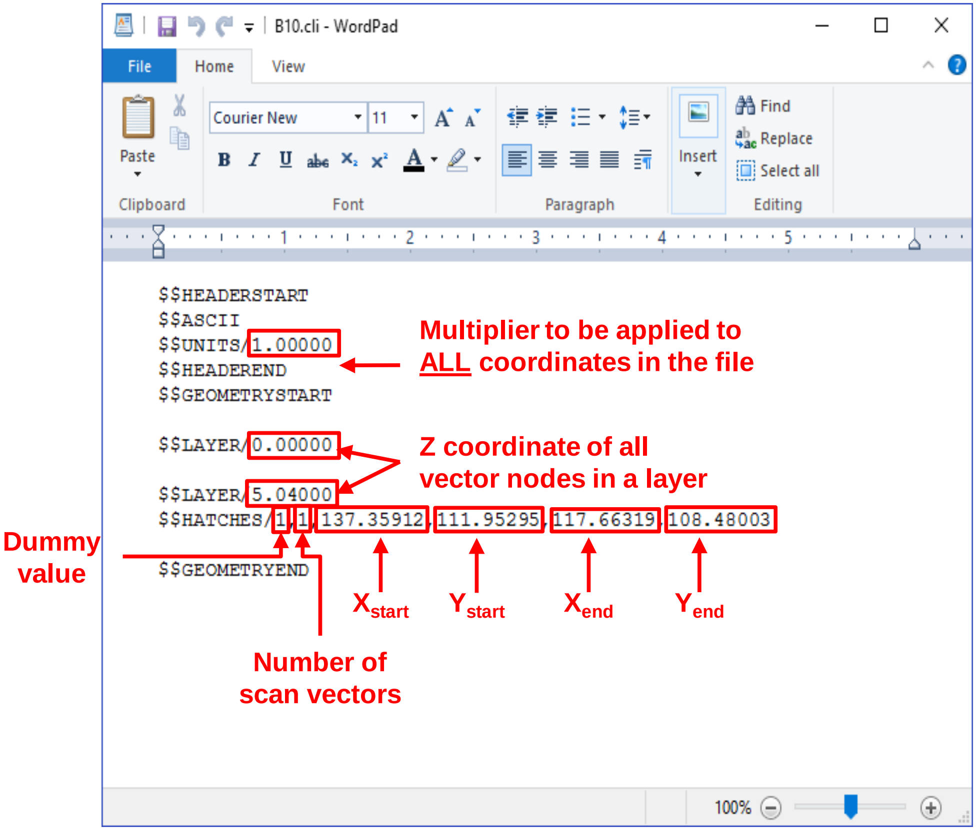


Fig. 4: Annotated CLI File for Single Track Calibration Item B10

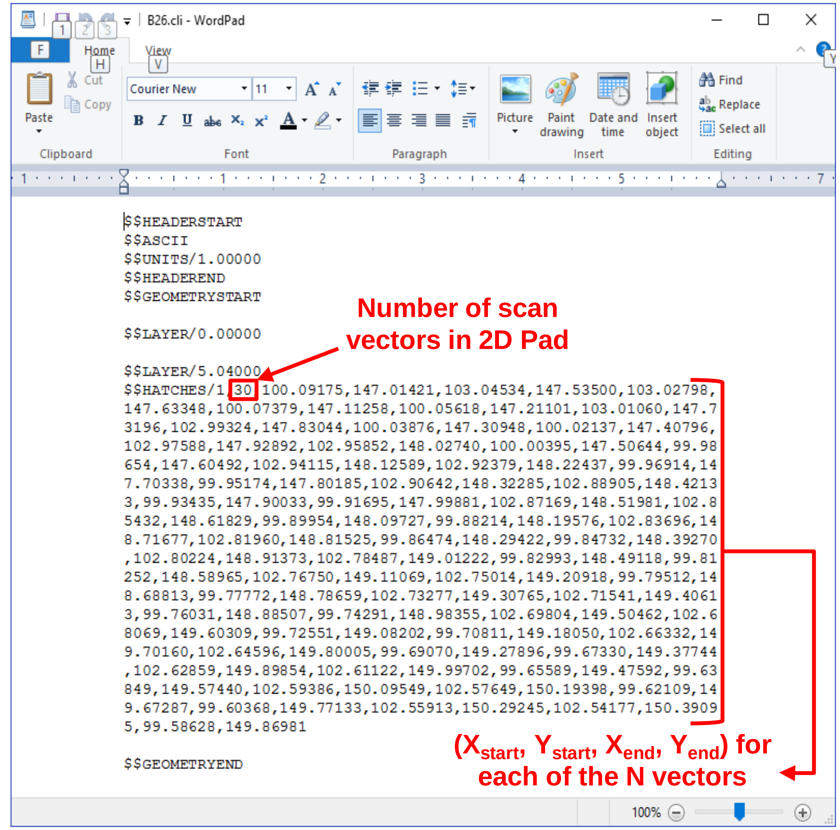


Fig. 5: Annotated CLI File for Challenge Item B26

Unofficial website detailing .cli format - http://www.hmilch.net/downloads/cli_format.html
(The website is a non-federal site. AFRL has not developed, vetted or endorsed the site or the technical data. The site location was provided for your information and convenience. If you visit the website, you are subject to the privacy, copyright, security, and information quality policies of that website.)

Calibration Data

Data for Model Calibration

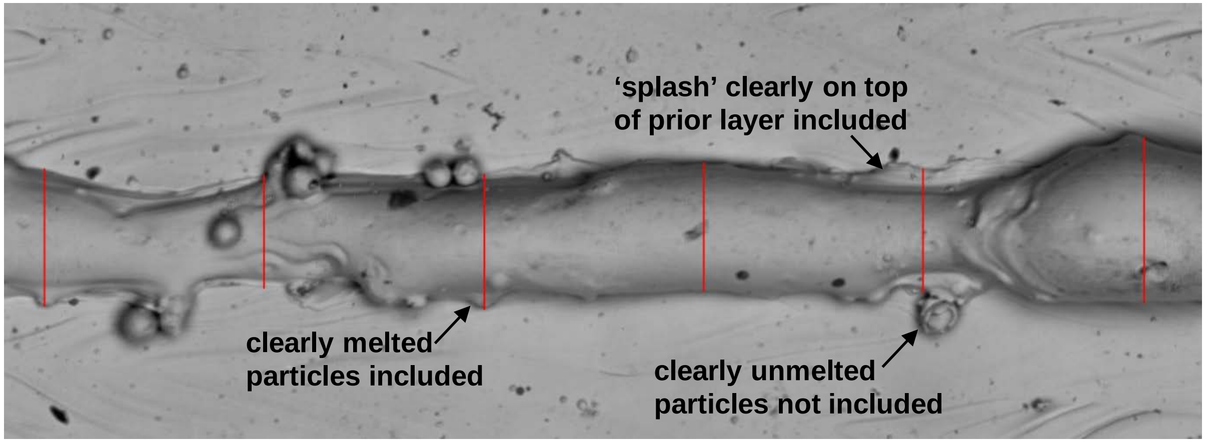


Fig. 6: Top-down BSE image with red lines representing width measurements

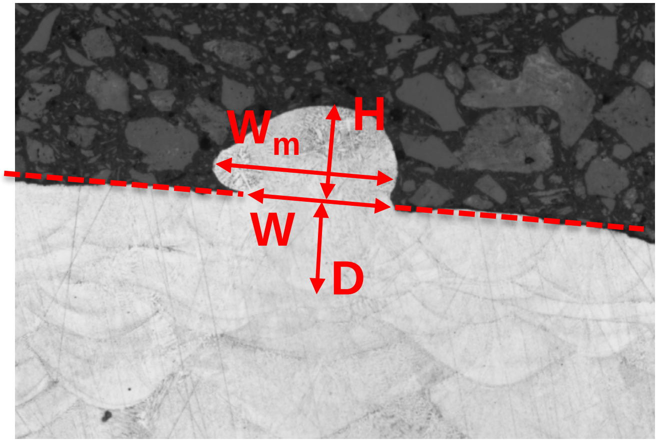


Fig. 7: Cross-section OM image with height, width, max width & depth shown

- 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

- 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	112.0, 11.1	86.9, 10.4	98.3, 13.4	26.9, 5.4	62.2, 18.3
B11	300	1230	112.0, 11.9	89.5, 11.8	97.4, 15.5	25.0, 6.1	60.3, 14.9
B12	290	953	127.6, 7.0	125.2, 6.6	128.3, 8.1	75.9, 7.6	66.0, 15.5
B13	370	1230	122.9, 8.4	130.1, 6.7	130.1, 6.7	72.0, 7.4	68.1, 9.2
B14	225	1230	96.0, 13.9	107.1, 9.9	109.4, 11.5	52.3, 9.0	65.7, 21.8
B15	290	1588	97.9, 14.0	112.9, 9.6	115.6, 9.8	54.3, 9.0	59.1, 12.3
B16	241	990	112.0, 13.0	110.8, 7.9	117.1, 12.7	42.5, 6.6	61.2, 11.9
B17	349	1430	110.7, 11.3	109.4, 10.7	111.4, 8.6	58.5, 4.6	60.1, 15.9
B18	300	1230	112.7, 12.7	109.7, 8.7	113.0, 12.0	46.9, 9.3	68.8, 25.9
B19	349	1058	129.9, 7.0	130.1, 7.1	134.4, 14.1	84.0, 8.9	63.5, 17.8
B20	241	1529	89.3, 12.8	83.5, 7.0	87.1, 11.2	20.1, 7.1	56.3, 18.1

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

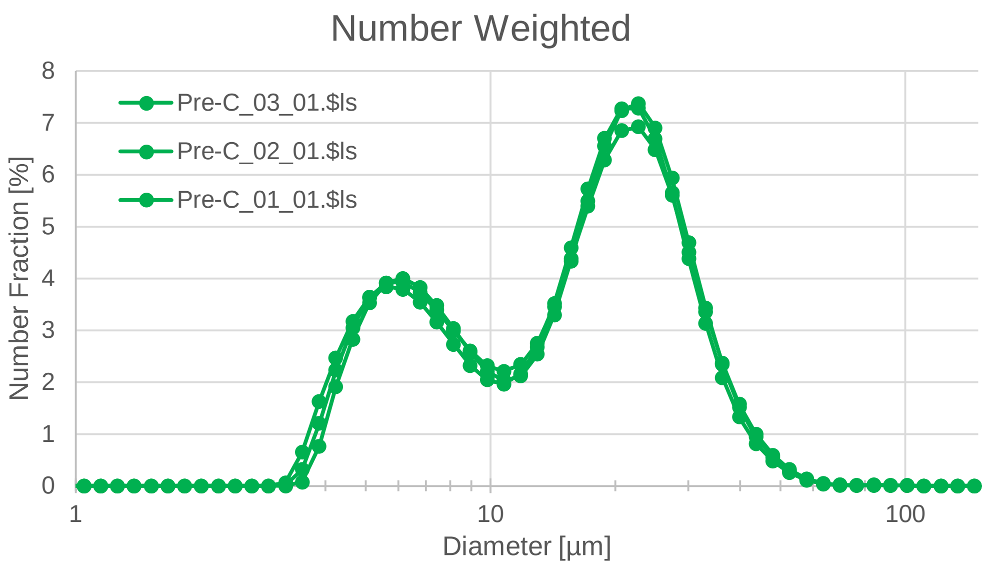


Fig. 8: Powder particle size distribution after build was completed

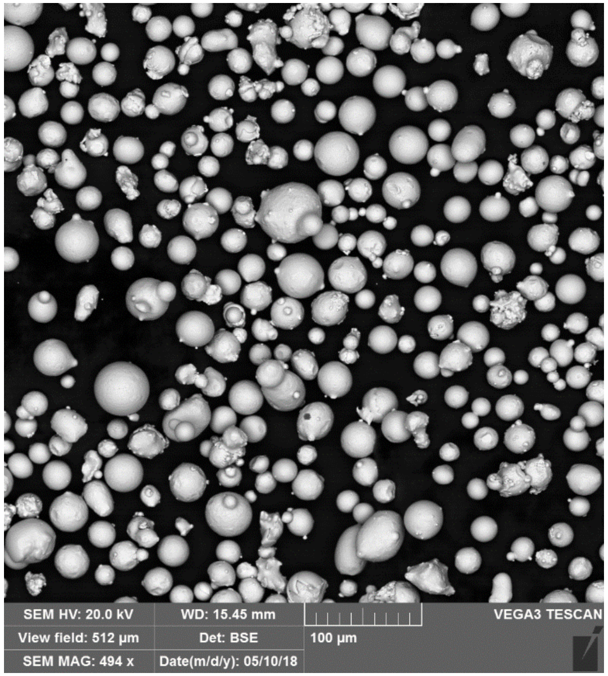


Fig. 9: BSE image of powder particles after build was completed

- 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	<0.004	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 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

Description of Desired Predictions

Detailed Prediction Locations

For each of the *X'-Y'* single layer multitrack scan pad challenge item, one to three "measurement planes" are defined in the answer template at the end of this document, and examples are shown as red dashed lines below. These planes are orthogonal to the *X*' axis, and are defined in terms of their *X'* coordinate (recall the *X',Y'* coordinate system is unique to each specimen). Printed specimens were imaged and analyzed within ±15µm of the 'measurement plane' defined in the answer template.

Various measurements of the meltpool dimensions (described in detail on slide 18) should be collected for each scan vector where it intersects the measurement plane, excluding the first 3 vectors (lowest *Y'* values) and the last 3 vectors (highest *Y'* values). The meltpool dimensions should be collected for all other vectors that cross the measurement plane, and the mean and standard deviation of this population should be reported for the collection of even numbered and odd numbered vectors at each measurement plane in the answer template on slide 24.

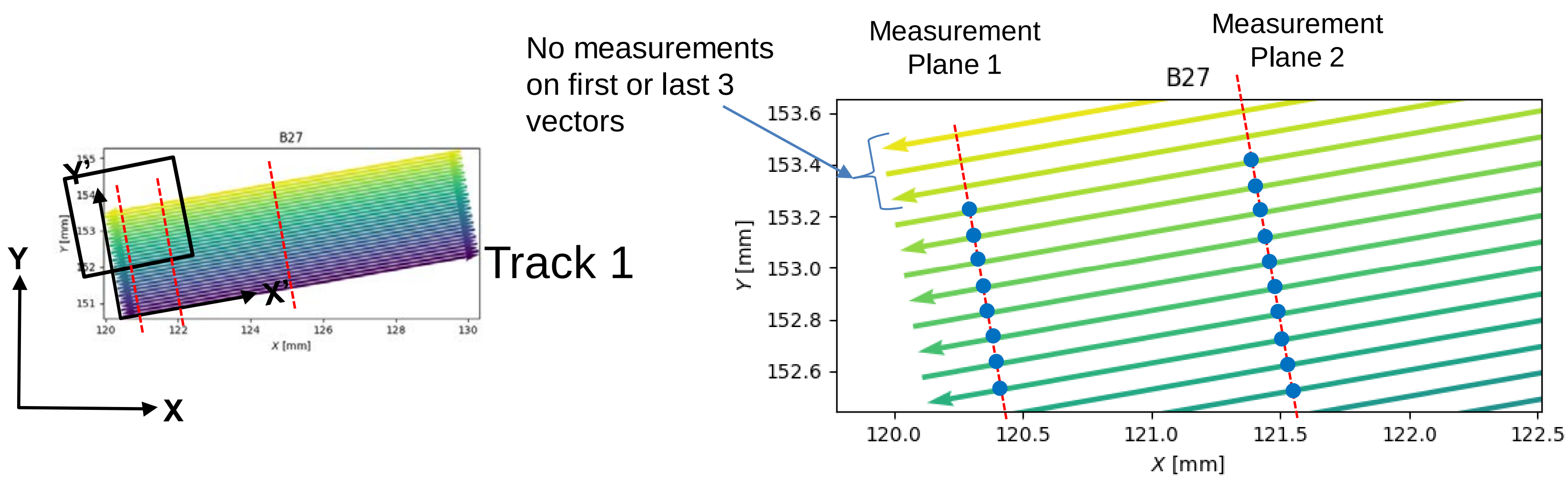


Fig. 10: Schematic of Measurement Locations for a X'-Y' 2D Pad

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

Requested Predictions: X-Y 2D pads

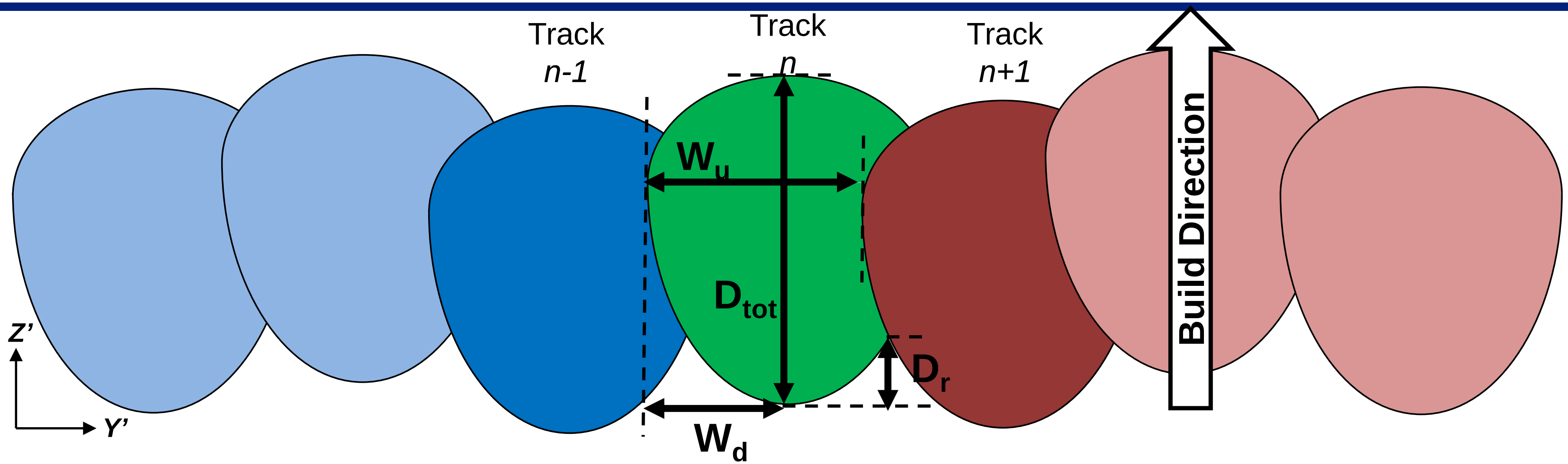


Fig. 11: Schematic image of a measurement plane for one of the *X-Y* 2D Pad Meltpools with Desired Measurements (applicable to samples B26, B27, B31, B34, B35, B38)

- For each pad, tracks are numbered 1 to N, where 1 is the first track deposited in time, and N is the last. In all cases measurements begin on track 4, and end on track N-3.
- At each measurement line (schematic in Fig 10., and specific *X'* positions listed in Table 4 on slide 24) for each track *except the first three and last three*, measure the following:
  - W_u: distance measured parallel to the *Y'* direction extending from the lowest *Y'* for any part of track *n* to the lowest *Y'* value along the interface between track *n* and the next subsequent track it intersects with (i.e. typically *n+1* or *n+2).* In case there is no overlap with a subsequent track, record the distance from the lowest to the highest *Y'* value for track *n.* In either case, these extrema in *Y'* may not occur at the same *Z'* value.
  - W_d: distance measured parallel to the *Y'* direction from the lowest portion of track *n* in the *Z'* direction to the lowest *Y'* value of track *n*.
  - D_{tot}: distance measured along the Z' direction from lowest to highest points in *Z'* . In the case of multiple local maxima in the *Z'* direction, use the value with a *Y'* value closest to the absolute minima.
  - D_r: distance measured along the *Z'* direction from the lowest point of track *n* in *Z',* to the intersection of melt pool boundaries for track *n* with track > *n* (i.e. *n+1* or *n+2).* If there is no intersection with an adjacent track in the direction toward *n+1*, set D_r=D_{tot} for that track.
- Report the average and standard deviation of each quantity listed in Table 4 for the even numbered tracks, and the odd numbered tracks

Pad ID	Total tracks	Start track	Ending track
B26	30	4	27
B27	30	4	27
B31	40	4	37
B34	24	4	21
B35	30	4	27
B38	30	4	27

Requested Predictions: Single Track Walls

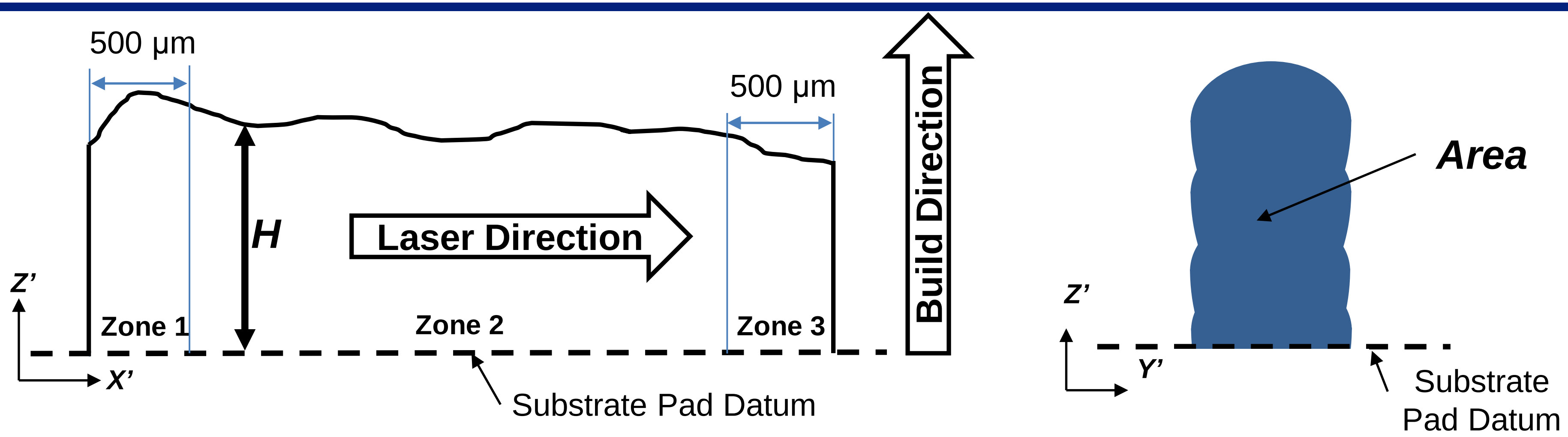


Fig. 12: Schematic of X-Z 2D Pad Meltpools with Desired Measurements (applicable to B21 & B25)

- Additionally, single track wall specimens B21 and B25 consist of 10 consecutive 40µm thick layers each with a single 5mm long vector directly on top of the preceding layer's vector, and processed with the laser moving in the same direction on each layer.
- For each of the 3 measurement zones shown in Fig. 12, report the average and standard deviation of:
  - Height *H* above the Substrate Pad Datum
  - Total cross-sectional *Area* for the entire portion of the wall above the Substrate Pad Datum, as observed in an *Y'Z'* plane, orthogonal to the scan vector
- Notes:
  - The Substrate Pad Datum is a plane coincident with the top surface of the substrate prior to deposition of the tracks
  - Beam motion is always in the +*X'* direction for all layers, Zone 1 is the first 500µm, Zone 2 is the central 4mm, and Zone 3 is the final 500 µm
  - Cross section area validation data will be measured from cross-sections collected approximately every 200µm in each zone. There will be a minimum of 3 sections collected within Zones 1 and 3, and approximately 20 cross in Zone 2
  - Height validation data will come from a side view covering the full wall at approximately 1µm pixel size. Standard deviation of the height will be determined by the variation of the top surface profile about the mean within each zone
  - Processing conditions are on slide 21

Input for Challenge Questions

Input Data for Challenge Questions

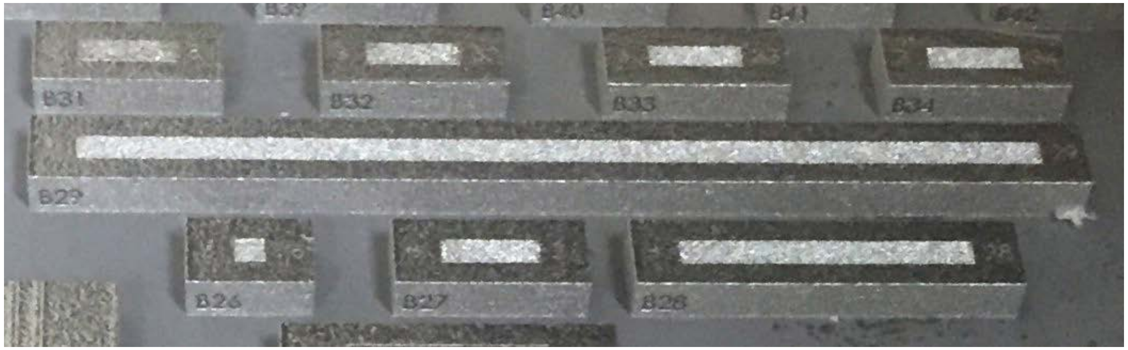


Fig. 13: Image of 2D pads showing their isolation in the build

Pad ID	Dimensions (mm)	Height (layers)	Power (W)	Speed (mm/s)	Hatch Spacing (mm)	Layer Thickness (mm)	Total tracks in each layer
B21	5 x 1 track	10	300	1230	N/A	0.040	1
B25	5 x 1 track	10	241	1529	N/A	0.040	1
B26	3 x 3	1	300	1230	0.10	0.040	30
B27	10 x 3	1	300	1230	0.10	0.040	30
B31	10 x 3	1	300	1230	0.075	0.040	40
B34	10 x 3	1	300	1230	0.125	0.040	24
B35	1 x 3, 9 x 3	1	300	1230	0.10	0.040	30
B38	15 x 3	1	290	953	0.10	0.040	30

Table 3: 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

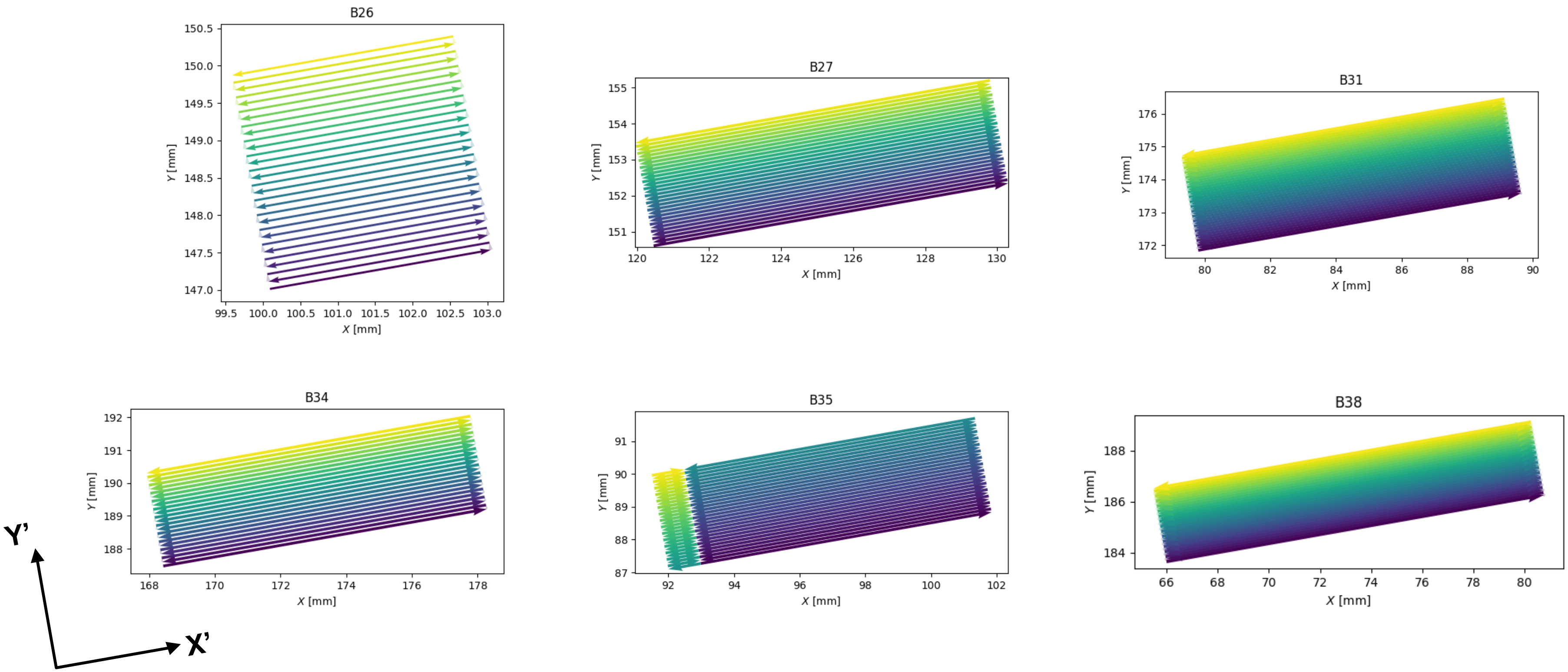


Fig. 14: Image of all 2D pads showing their scan path (substrate pads not shown)

*** See Slide 6 for Coordinate System Description ***

Challenge Question and Scoring

Answer Format

Pad ID..	Measurement Plane	X' Position [mm]	Track #	W_d Mean [µm]	W_d StdDev [µm]	W_u Mean [µm]	W_u StdDev [µm]	D Mean [µm]	D StdDev [µm]	D_r [µm] Mean	D_r StdDev [µm]
B26	1	0.1	Even								
B26	1	0.1	Odd								
B27	1	0.1	Even								
B27	1	0.1	Odd								
B31	1	0.1	Even								
B31	1	0.1	Odd								
B35	1	0.1	Even								
B35	1	0.1	Odd								
B38	1	0.1	Even								
B38	1	0.1	Odd								
B26	2	1.5	Even								
B26	2	1.5	Odd								
…	…	…	…								
…	…	…	…								

Table 4: A portion of the answer submission template for X-Y 2D pads. Report average and standard deviation for the even and odd track populations of tracks 4 through N-3 as described on slide 18. (See slides 17-18 for measurement definitions)

Pad ID	Measurement Zone	X' Start [mm]	X' End [mm]	Area Mean [µm^2]	Area StdDev [µm^2]	HT Mean [µm]	HT StdDev [µm]
B21	1	0.0	0.5				
B25	1	0.0	0.5				
B21	2	0.5	4.5				
B25	2	0.5	4.5				
B21	3	4.5	5.0				
B25	3	4.5	5.0				

Table 5: Answer submission template for single track walls. (See slides 17& 19 for measurement definitions)

- Full answer sheet template located on tabs in \Challenge2\Challenge 2 Answer Template.xls

Scoring

- Predictions for each measurement line and each specimen are worth same value

- Grades will consist of accumulating points based on accuracy and precision of predictions:
- For items B21, B25, B26, B27, B31, B34, B35, B38,

  for each mean value in Table 4: +/- 0.5 σ = 9 pts;
  +/- 1.0 σ = 3 pts;
  +/- 1.5 σ = 1 pt

  for standard deviation in Table 4: +/- 0.10 σ = 4 pts;
  +/- 0.25 σ = 2 pts;
  +/- 0.50 σ = 1 pt

  where σ is the empirically determined standard deviation for the measurement condition

- Responses must be returned within the document “Challenge 2 Answer Tempalte.xlsx” in units are described in column headers. ***Answers returned in any other format will not be scored***.
- In the case of a tie between two or more entries with the same overall point score, the entries will be ranked according to the sum of absolute errors for predictions on item B27.

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

Supplemental Data (non-AFRL data)

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 5: 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 6: 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

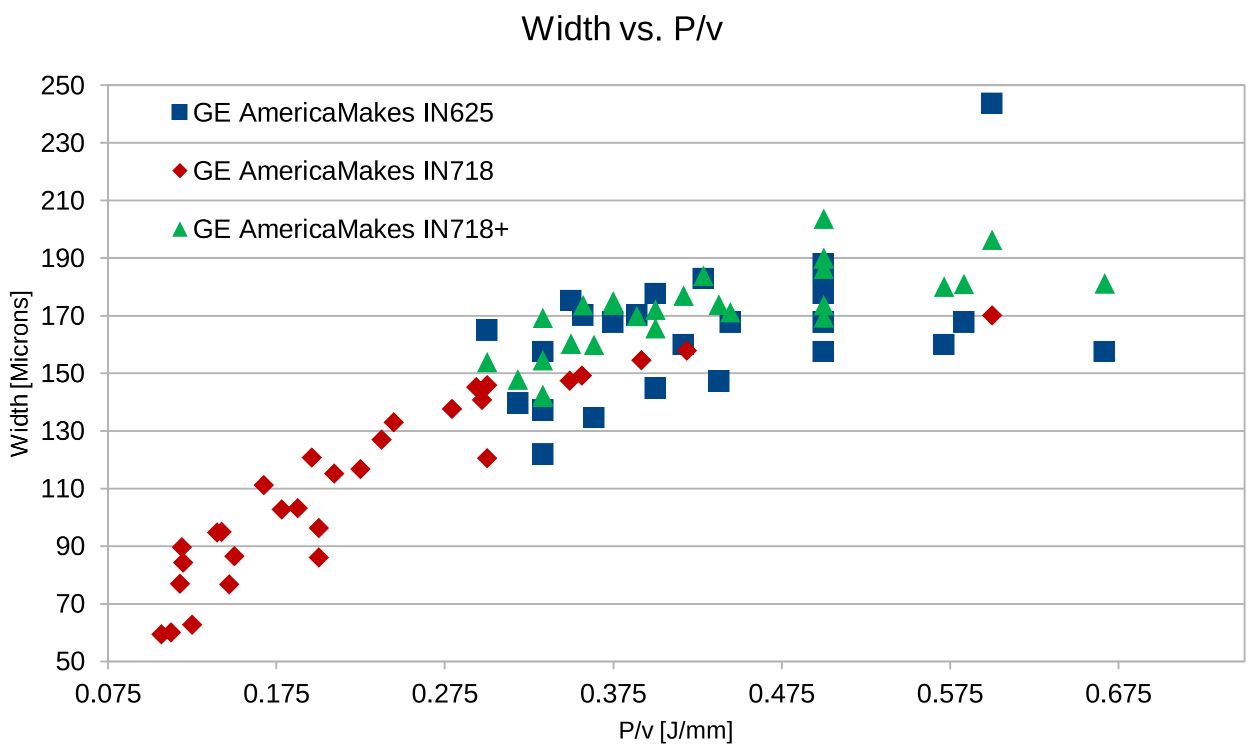


Fig. 15: Single Track Measurements for various Ni Superalloys

- 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