AMB2025-04 Benchmark Measurements and Challenge Problems: Laser hot-wire directed energy deposition (DED) 3D builds of nickel-based superalloy 718 test objects.

Figure 1 shows the general geometry of the build. The laser weld head has three beams concentric around the wire feed. Challenge-associated measurements will include residual stress/strain components, baseplate deflection after unbolting from build machine, and baseplate temperatures during the build. The laser power was be kept constant during the build but the feed rate and travel speed was varied to produce a good part geometry. Laser calibration data, wire and baseplate material composition, extensive build information including the programmed changes in feed rate and travel speed (G-code), and some thermocouple data are being provided. We will not provide material property data.

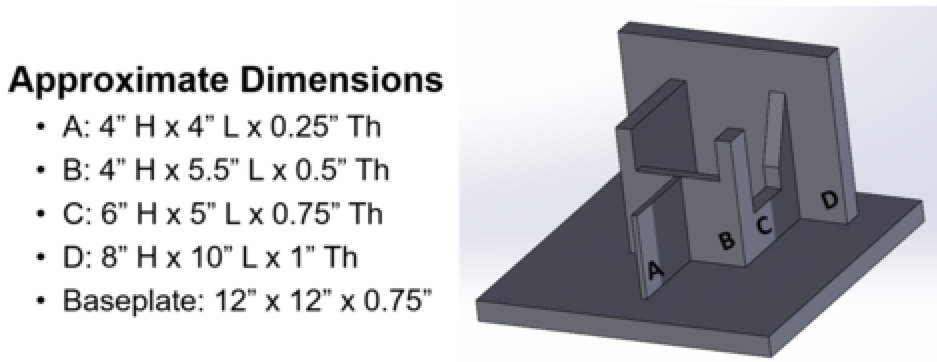

Figure 1: Approximate geometry of AMB2025-04 test objects.

Challenge Problems AMB2025-04

- **Temperature history prediction (CHAL-AMB2025-04-THP01):** Predict the temperature history at one thermocouple location located on bottom surface of the baseplate
- **Residual Elastic Stresses (CHAL-AMB2025-04-RS01):** Residual elastic strain components at select locations internal to build, corresponding to neutron diffraction measurements**.**
- **Residual Elastic Strains (CHAL-AMB2025-04-RS02):** Residual elastic strain components at select locations internal to build, corresponding to energy dispersive diffraction measurements**.**
- **Baseplate Deflection (CHAL-AMB2025-04-BD):** Deflection of the baseplate with no heat treatment

AMB2025-05: Single bead-thickness walls and individual laser hot-wire alloy 718 beads with variations in laser power and travel speed with fixed wire feed rate. This set of benchmarks includes two distinct sets of measurements. First, single-bead thickness walls are built using the same process parameters and feedstock material as the 3D builds (AMB2025-04). Challenge-associated measurements include grain-size histograms along different directions.

Second, individual laser hot-wire 718 beads are produced using variations in laser power and travel speed with fixed wire feed rate. Challenge-associated measurements include single-track geometry from cross sections both perpendicular and parallel to the bead direction and single-track surface topography along with average grain size measurements. Laser calibration data, wire and baseplate material composition (both alloy 718), process parameters and track path information (G-code), and some thermocouple data are being provided. We will not provide material property data.

Challenge Problems AMB2025-05

- **Average grain size (CHAL-AMB2025-05-MS01):** Distributions of direction-specific grain sizes from specified regions in the stair step walls.
- **Melt pool transverse geometry (CHAL-AMB2025-05-MP01):** Predict the width and depth of the melt pool for each set of processing parameters of the single bead depositions.

Build Information

All builds were performed using a Mazak Laser Hot Wire VC 500A/5XHWD machine at the Oak Ridge National Laboratory Manufacturing Demonstration Facility.

CAD will be supplied for the stair step thin wall, AMB DED specimen, and baseplate fixturing. G-code will be supplied for the stair step thin wall and AMB DED specimen. Changes to the layer height, time between layers due to consumable changeout, wire feed rate, total layers per section, hot wire power, and laser power can be found in the AMB2025-04and05 Print Tracker Excel Spreadsheets. Laser power measurements using a Primes Cube are also found in the excel spreadsheet.

<u>G-code</u>

The g-code will be provided for the stair step thin walls and the AMB DED geometry. The g-code commands are as follows:

- G0 W701 = laser on
- G0 W#700 = laser off
- G0/G1 = move
- X & V are coordinates

<u>Fixturing</u>

CAD is provided of the fixturing setup (Kurt - Machine Vise: 6.0000" Jaw Width, 6" Jaw Opening, Horizontal, Single Station, Stationary Base | MSC Direct).

The jaw was torqued to 108 Nm for each build.

<u>Baseplate</u>

Each baseplate was Nickel alloy IN718 with the following dimensions:

- 305 mm x 305 mm x 19.05 mm

Part layout on baseplate

Each AMB DED specimen was centered on one baseplate as shown below in Fig. 2. The supplied CAD file will have the build properly centered on the baseplate.

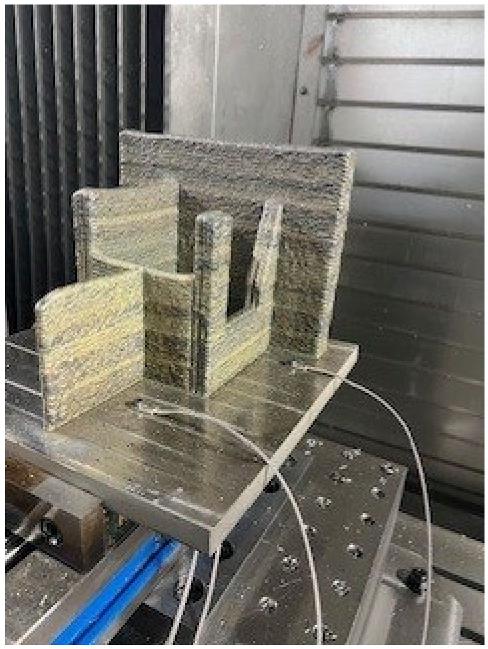

Figure 2: Geometric layout of each AMB DED specimen.

All three-stair stepped thin walls were deposited on one baseplate as shown below in Fig. 3.

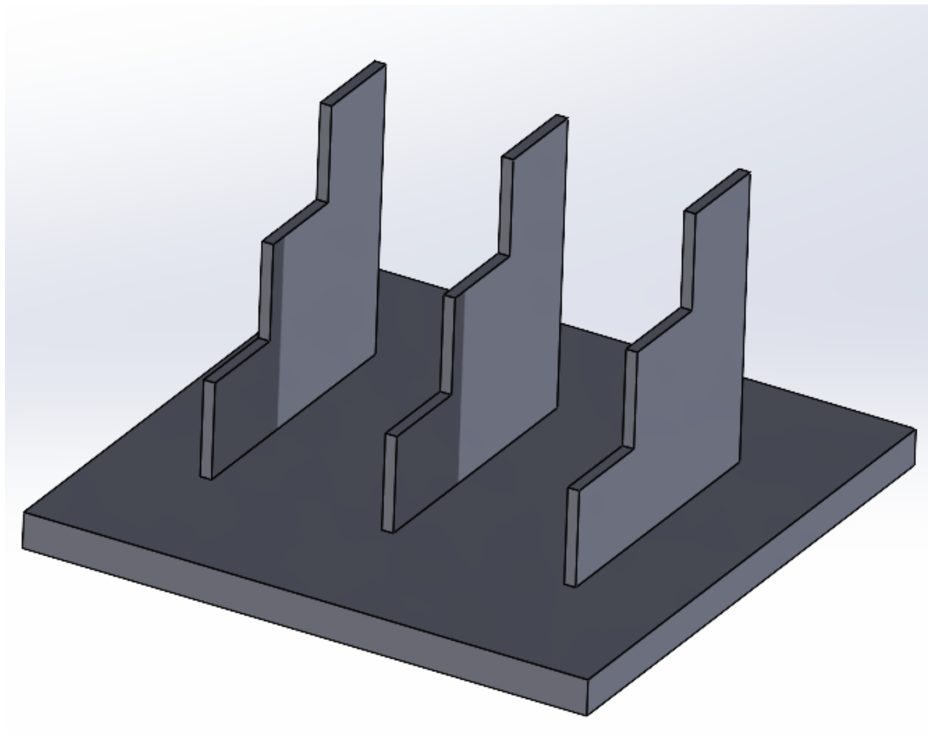

Figure 3: Geometric layout of each stair step thin wall specimen.

Three single track beads with a length of 152 mm were deposited on one baseplate for each set of processing parameters. Five different sets of processing parameters were used for a total of 15 beads. The geometric layout can be seen below in Fig. 3.

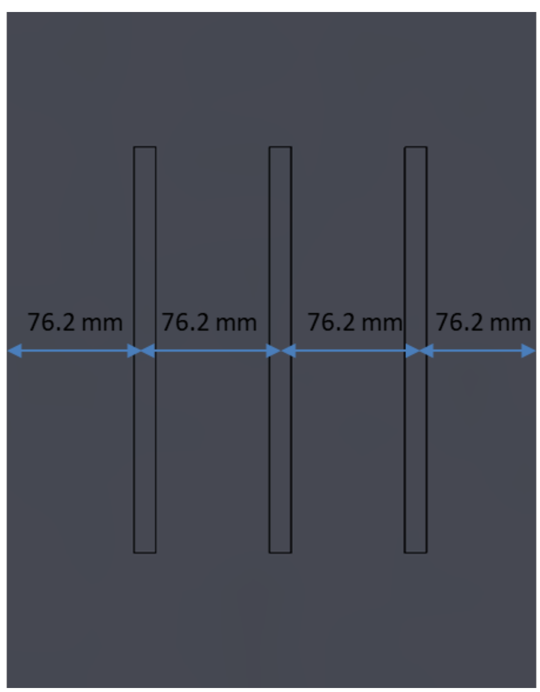

Figure 4: Geometric layout of the bead on plate depositions.

Wire feedstock material

All IN718 builds were conducted using wire from a single lot.

Sample Cutting

Prior to insertion on the x-ray and neutron beamlines, the substrate and post were trimmed for beam access with a wire EDM as shown in Fig. 5.

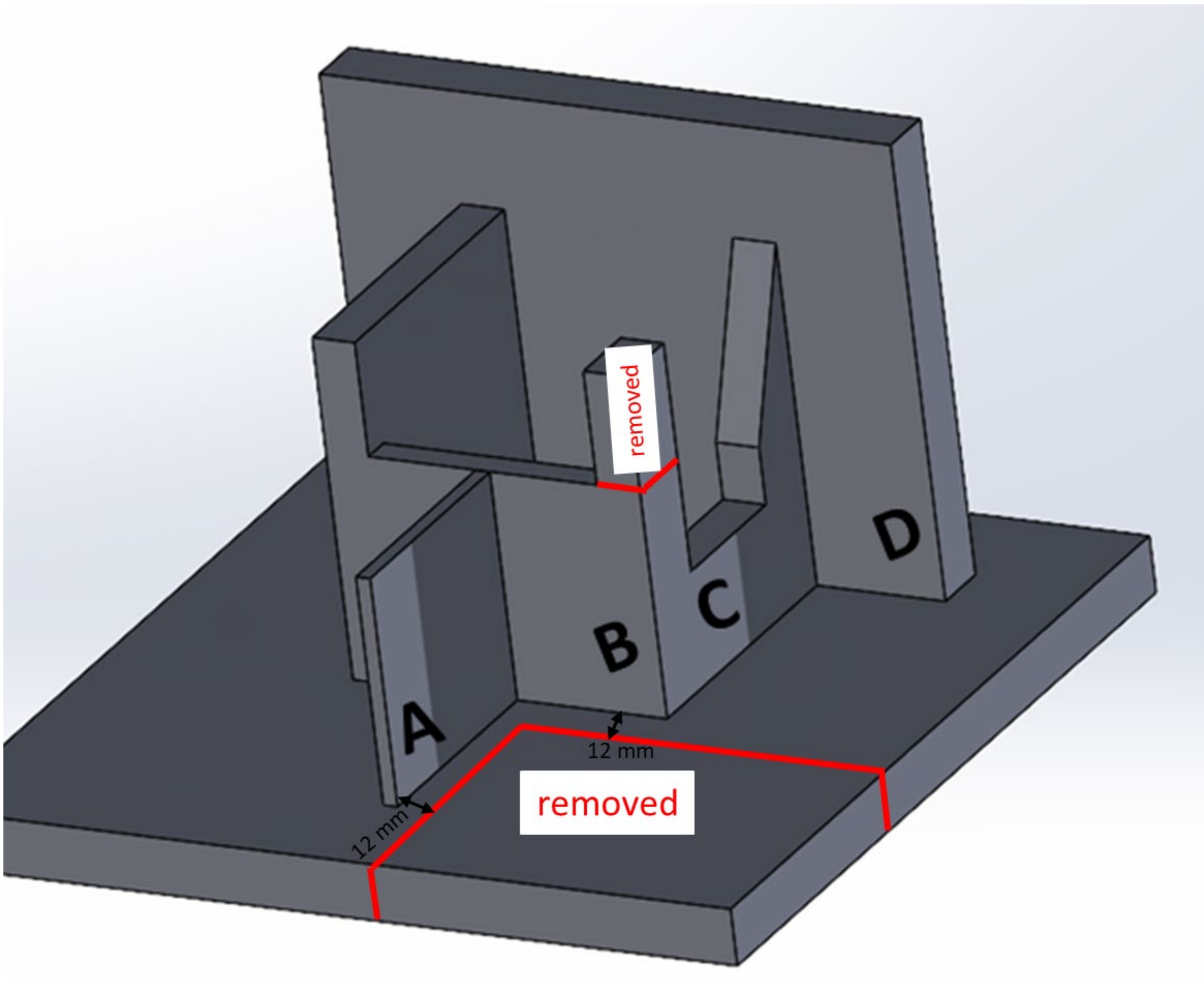

Figure 5: Geometric description of wire-EDM cuts made to AMB DED geometry.

Measurement Description

The AMB2025-04/5 benchmark measurements include in situ phenomena during the build process and several different types of ex situ characterization measurements including residual strain and stress measurements, part distortion, and 2D microstructure characterization. The measurement methods include:

In situ measurements during the build

- Use of in situ thermocouples to measure the location-dependent temperature history of the baseplate at various locations.

Ex situ measurements

- Residual strain and stress measurements using synchrotron X-ray diffraction and neutron diffraction
- Distortion measurements comparing baseplate geometry before and after deposition
- 2D cross sections measured using a combination of SEM and optical microscopy

Temperature History

All baseplates were outfitted with multiple thermocouples on the top and bottom surfaces of the baseplates using the coordinates as shown in Fig. 6.

Thermocouple Locations

X (mm)	Y (mm)	Z (mm)
152.4	152.4	0
228.6	152.4	0
149.4	262.4	19.05
148.4	42.4	19.05
147.4	117.4	19.05

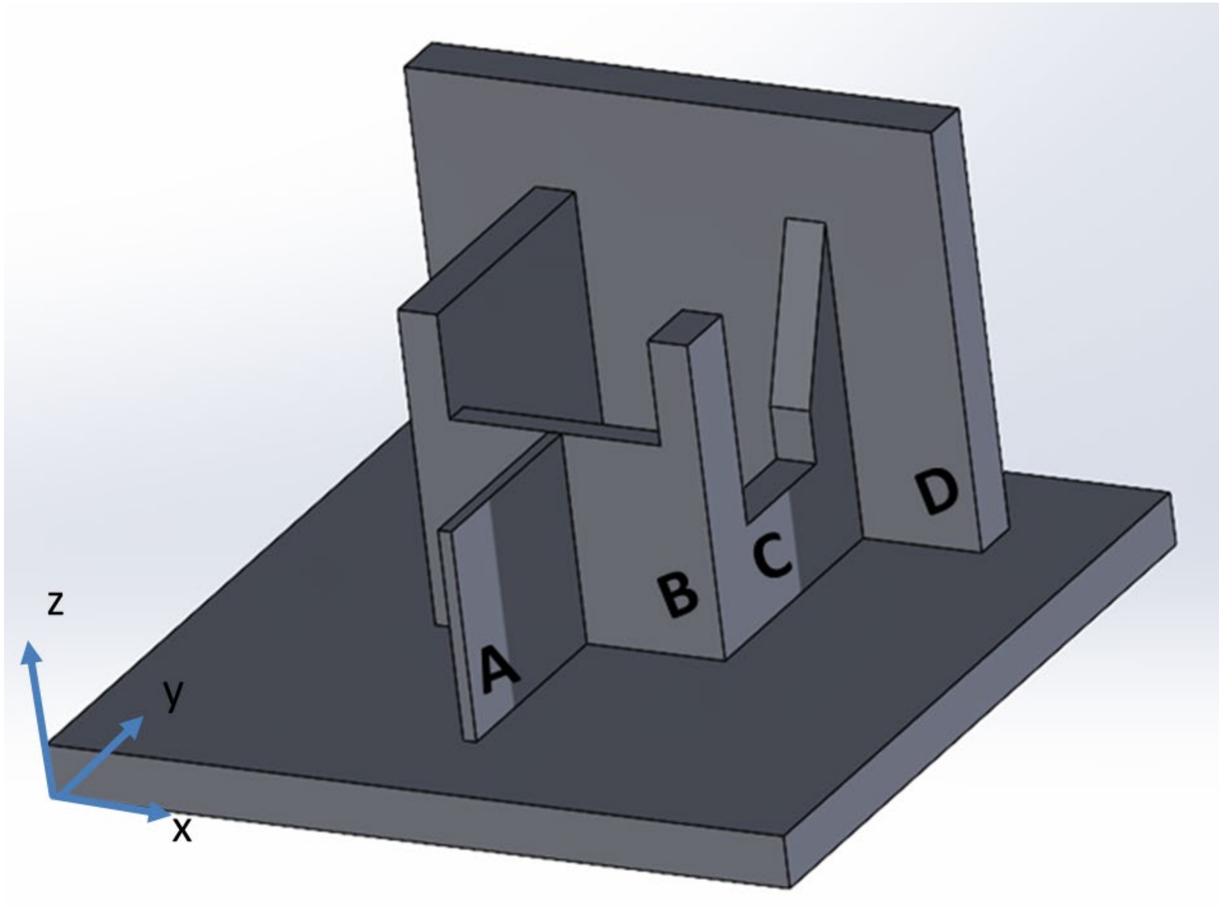

Figure 6: Schematic describing the coordinates of the thermocouple locations.

Residual Strain and Stress

Residual elastic strain (RS) within as-built IN718 parts was measured using synchrotron X-ray diffraction at the structural materials beamline at the Cornell High Energy Synchrotron Source (CHESS) and neutron diffraction on the HB-2B High Intensity Diffractometer for Residual Stress Analysis (HIDRA) instrument at Oak Ridge National Laboratory's High Flux Isotope Reactor (HFIR). The x-ray and neutron diffraction RS measurements were conducted on nominally identical parts, AMB2025-04-LHWDED-01 and AMB2025-04-LHWDED-02. The synchrotron X-ray and neutron unstrained lattice parameter measurements were conducted using small rectangular prism specimens.

Synchrotron X-ray energy dispersive diffraction

Residual strains in the longitudinal direction (X or Y, along wall) and the build direction (Z)) were measured using energy dispersive diffraction (EDD) at the 1A3 beamline at CHESS. The coordinate reference systems for these measurements are shown in Figure 12. The detector was calibrated using a CeO2 reference material (NIST 674b standard). A strain-relieved part of the build cut to a 2 mm thick slice along the build direction from the stand-out post adjoining walls

B and C, was used as the reference d0 specimen. Residual strains were measured at points located on walls A, C and D.

Neutron diffraction

Neutron diffraction residual strain measurements typically require much larger gauge volumes and data acquisition times than corresponding elastic strain measurements using synchrotron X-ray diffraction. However, neutrons are considerably more penetrating than typical high-energy X-rays and can conduct measurements along three orthogonal axes, providing improved access to stress states.

The neutron diffraction measurements at HIFR used a 311 reflection to probe the 311 lattice spacings averaged over the measurement volumes in the X, Y, and Z directions. As with the synchrotron X-ray RS measurements, the gauge volume is defined by the intersection of the incident beam and the diffracted beam. For these neutron measurements, the 2q angle is 90°. The values used for the (311) reflection were 1/E=5.299 TPa^-1 and -nu/E=-1.4527 TPa^-1 which were calculated from the single crystal constants using the Kroener model. They amount to E=188.7 GPa and nu=0.274 for the (311) reflection.

Baseplate Distortion

After being built, the part remains on the build plate which is distorted. Due to the unique clamping setup in the Mazak, each corner was unrestrained during the build. As such, one corner of the baseplate was clamped down to a measurement table with the orientation shown in Figure 7 to measure the baseplate deflection of the other three corners with a FARO laser scanner.

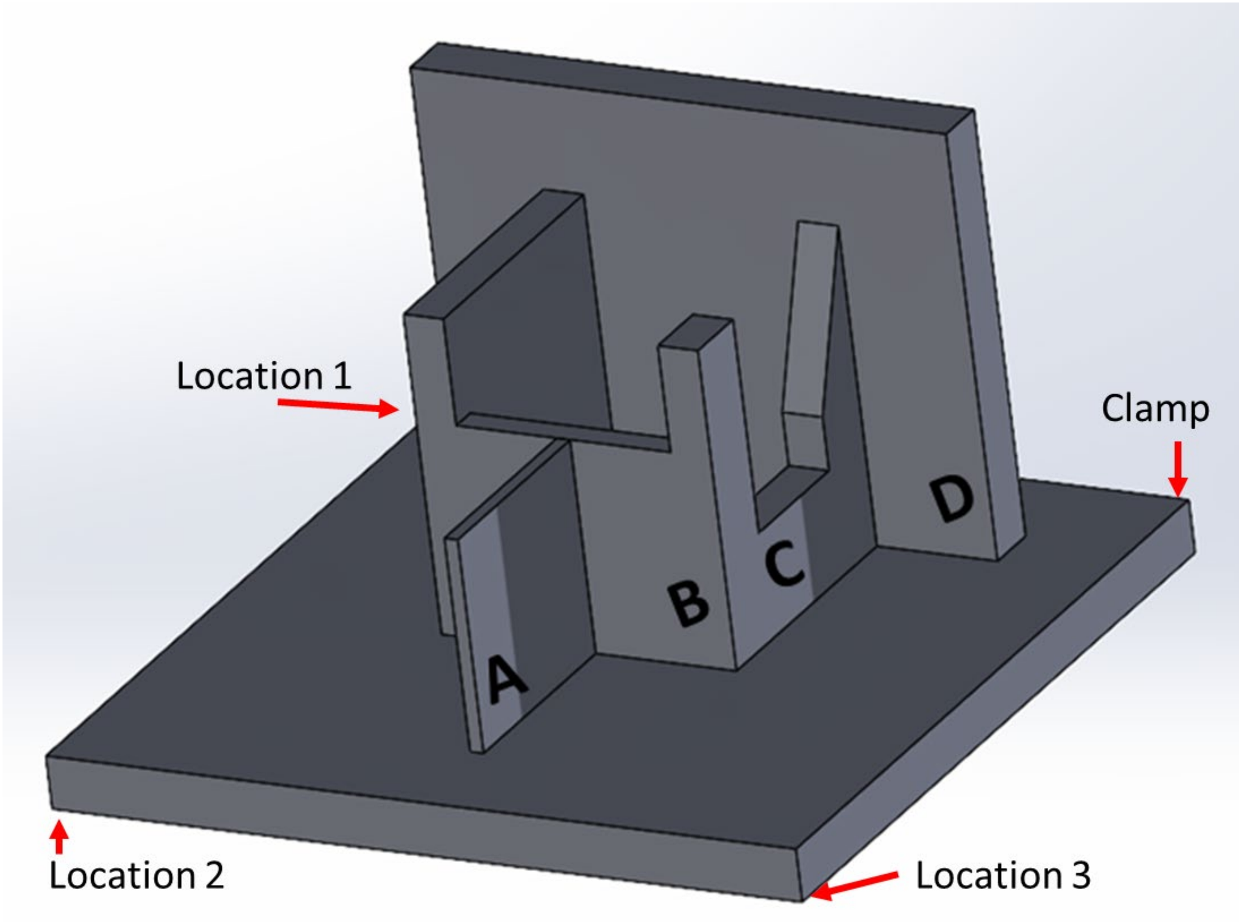

Figure 7: Schematic detailing the orientation in which the build was clamped and scanned.

<u>Transverse Cross Sections Bead on Plate</u>

Eight 2D transverse cross sections at the center through the bead on plate deposition were examined using backscattered SEM and/or optical microscopy with etching to characterize the size of the melt pool boundary. These eight measurements were sectioned at 0.5 mm increments from the center of the bead on plate deposition. The eight measurements were then averaged to approximate the size of the melt pool in the steady state condition.

The measurement location is shown in Figure 8.

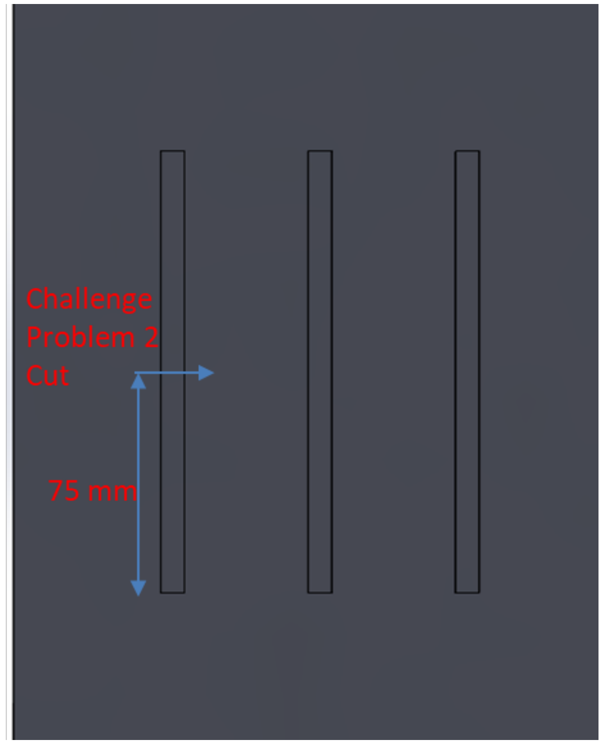

Figure 8: Schematic detailing the location of the transverse cross section cut and measurement

2D Microstructure

Backscattered SEM techniques were used to measure area-weighted mean caliper diameter of the grains in the 2D cross section along longitudinal and build direction in a 5 mm x 5 mm area in the center of each stair step.

The measurement locations are shown in Figure 9.

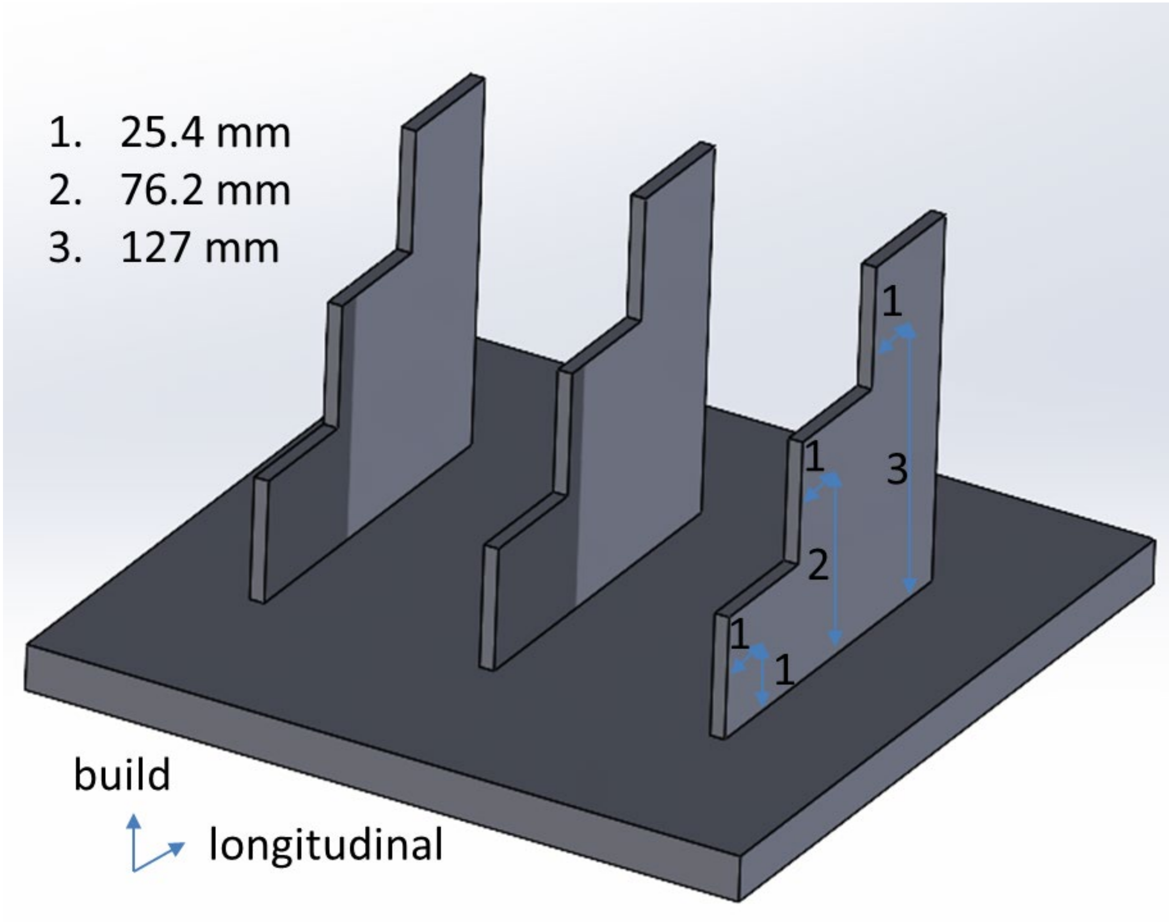

Figure 9: Schematic detailing the measurement locations for average grain size.

Description of Benchmark Challenge Problems

CHAL-AMB2025-04-THP01 – Temperature History Prediction

Modelers are asked to predict the temperature history measured by a thermocouple at (X: 76.2 mm, Y: 76.2 mm, Z: 0 mm) location for the stair step build at a sampling rate of 0.2 Hz. The coordinate system describing the location of the thermocouple is shown in Fig. 10. The grading criteria will be root mean square error.

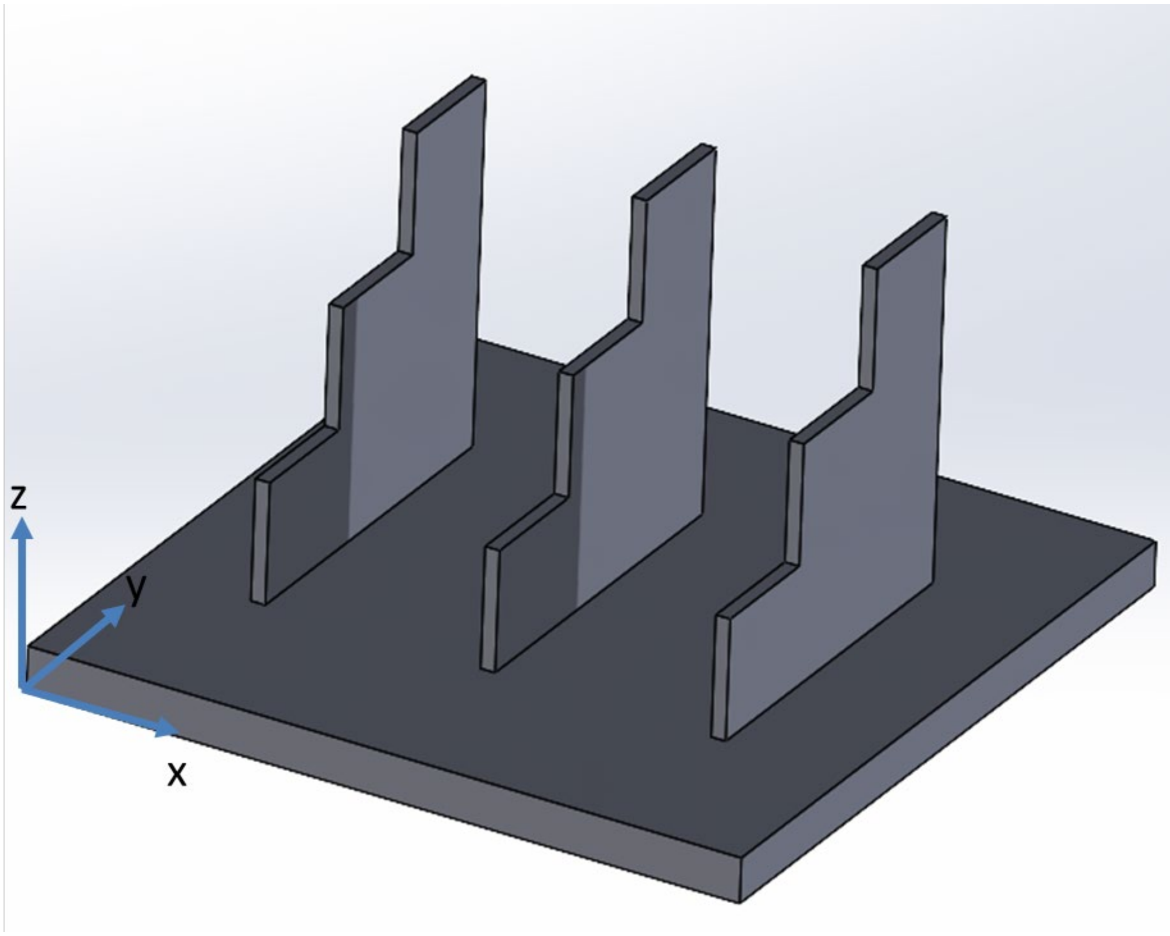

Figure 10: Schematic showing the coordinate system describing the location of the thermocouple.

<u>CHAL-AMB2025-04-RS01 – Residual Elastic Stresses</u>

This challenge problem is associated with predicting the residual stress in the as-built material. This challenge problem will only focus on the results obtained via neutron diffraction as shown in Figure 11. The sampled volume was centered on the midplane of each wall, with the associated coordinate systems shown at each scan location. Elastic strains were measured at each location wherein the stress was calculated. In the submission template, columns 1, 2, 3 provide the coordinates of each measurement, while columns 4, 5, 6 are the locations where the predicted XX, YY, and ZZ stresses should be input. There are three different coordinate system origins, one for each wall. Participants may use any method they like to predict the stresses at the specified sample coordinates, but it is important to note that the measured values we will be comparing with are volume averages as described in the measurement description. The grading criteria will be root mean square error.

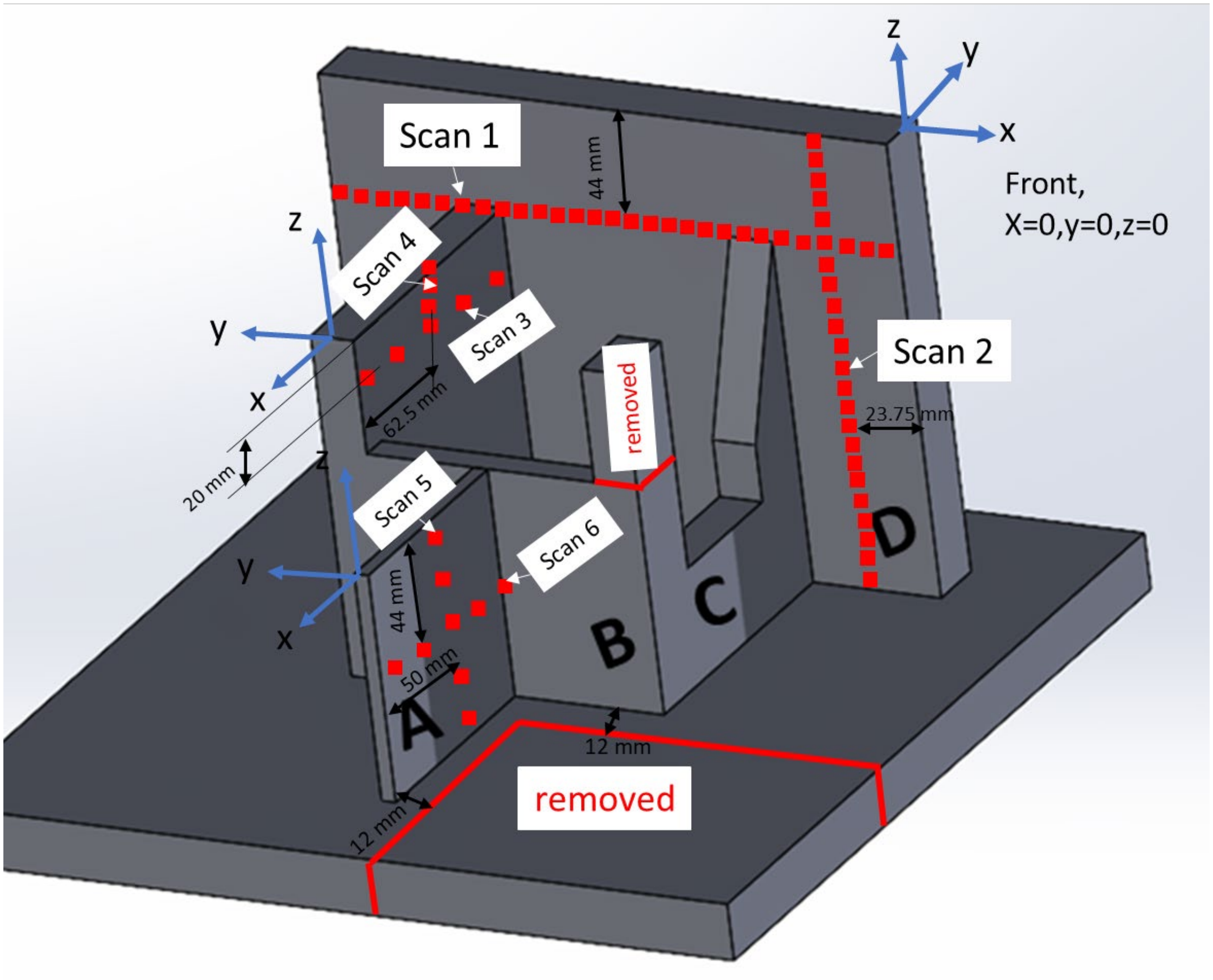

Figure 11: Schematic detailing the locations and coordinates of the residual elastic strain measurements

<u>CHAL-AMB2025-04-RS02 – Residual Elastic Strains</u>

This challenge problem is associated with predicting the residual elastic strains in the as-built material. This challenge problem will only focus on the results obtained via energy dispersive diffraction as shown in Figure 12. The sampled volume was centered on the midplane of each wall, with the associated coordinate systems shown at each scan location. Elastic strains were measured at each location. Similar to CHAL-AMB2025-04-RS01, there are three different origins, one for each respective wall. In the submission template, columns 1, 2, 3 provide the X, Y, and Z coordinates of each measurement, while columns 4 and 5 are the locations where the predicted strain tensor components should be entered. Participants may use any method they like to predict the strains at the specified sample coordinates, but it is important to note that the measured values we will be comparing with are volume averages as described in the measurement description. The grading criteria will be root mean square error.

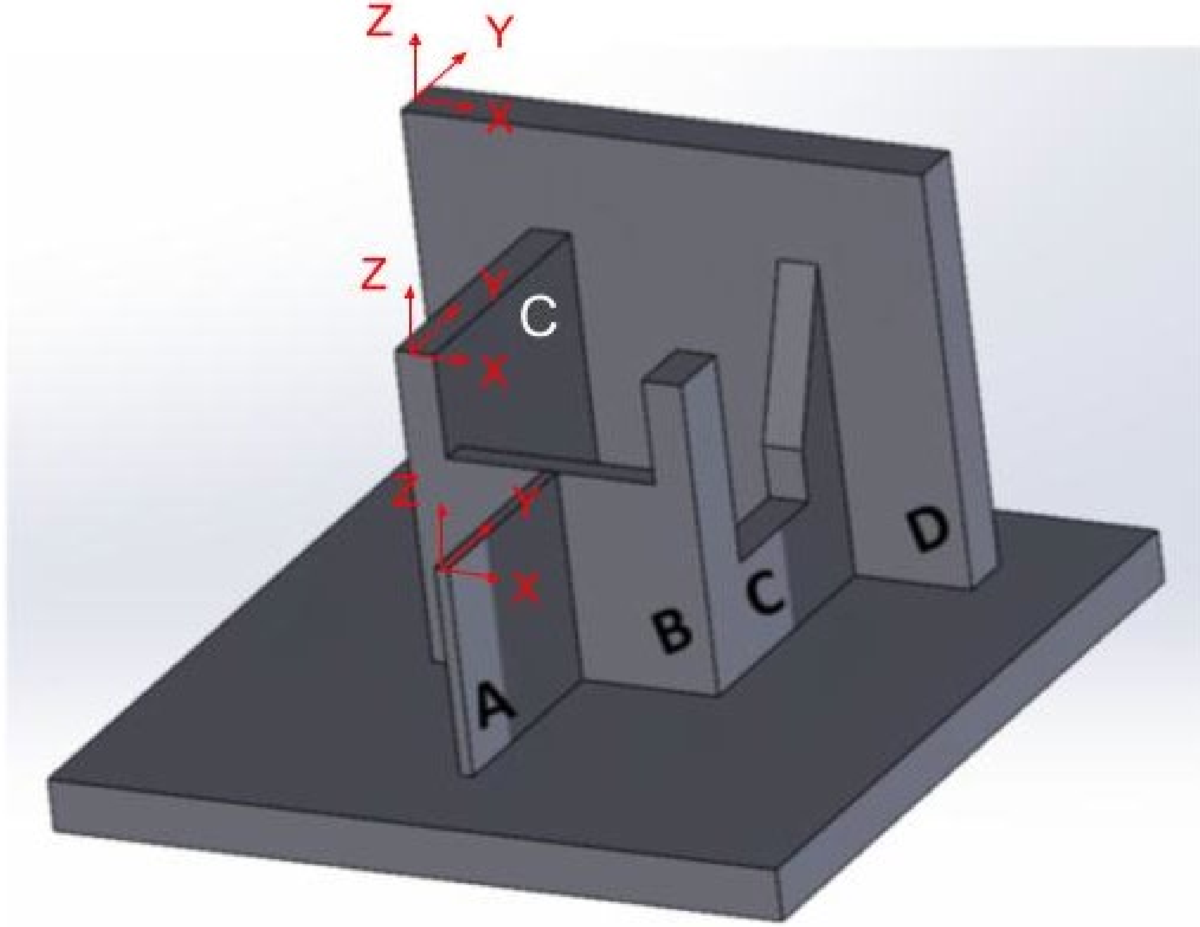

Figure 12: Schematic detailing the origins of the coordinates for the residual elastic strain measurements

CHAL-AMB2025-05-BD – Baseplate Deflection

This challenge problem is to predict the vertical deflection of the three unclamped corners on the underside of the baseplate relative to the clamped corner as shown in Figure 7. The part was clamped down on a measurement table. The grading criteria will be root mean square error.

CHAL-AMB2025-05-MS01

This challenge problem is associated with predicting the area-weighted mean caliper diameter of the grains in the 2D cross section along longitudinal and build direction in a 5 mm x 5 mm area in the center of each stair step, as shown in Figure 9. The grading criteria will be root mean square error.

CHAL-AMB2025-05-MP01 – Melt pool geometry

This challenge problem is associated with predicting the width and depth of the melt pool geometry measured at the center of the bead as shown in Fig. 8 for each of the processing parameter conditions of the bead on plate depositions. The melt pool boundary can be defined as any material that exceeds or is equal to the solidus temperature, 1100 ºC.

Links to Submission Templates and Calibration Data Files

The submission templates for the associated challenges problems are listed below:

- CHAL-AMB2025-04-BD.csv
- CHAL-AMB2025-04-RS01.csv
- CHAL-AMB2025-04-RS02.csv
- CHAL-AMB2025-04-THP01.csv
- CHAL-AMB2025-05-MP01.csv
- CHAL-AMB2025-05-MS01.csv

The build data (g-code and print tracker information) associated with the AMB2025-04 builds are listed below:

- NIST_Bench_S5_P1.eia
- NIST_Bench_S5_P1_1V2.eia
- NIST_Bench_S5_P2.eia
- AMB2025-04-LHWDED-02-PrintTracker.xlsx

The print tracker and thermocouple data associated with the AMB2025-05 bead on plate depositions are listed below:

- AMB2025-05-SB-1-Thermocouple.xlsx
- AMB2025-05-SB-2-Thermocouple.xlsx
- AMB2025-05-SB-3-Thermocouple.xlsx
- AMB2025-05-SB-4-Thermocouple.xlsx
- AMB2025-05-SB-5-Thermocouple.xlsx
- AMB2025-05-SB-PrintTracker.xlsx

The build data (g-code and print tracker information) associated with the AMB2025-05 stair step builds are listed below:

- AMB2025-05-TW-PrintTracker.xlsx
- NIST_Stair_S3.eia

Disclaimer:

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the US government, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose