ENABLING MODELERS TO TEST THEIR SIMULATIONS AGAINST RIGOROUS, HIGHLY CONTROLLED ADDITIVE MANUFACTURING BENCHMARK (AM BENCH) MEASUREMENT DATA

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ABSTRACT

The Additive Manufacturing Benchmark Test Series (AM Bench) is a National Institute of Standards and Technology (NIST) led organization that provides a continuing series of additive manufacturing (AM) benchmark measurements, challenge problems, and conferences with the primary goal of enabling modelers to test their simulations against rigorous, highly controlled AM benchmark measurement data. The series includes AM Bench 2018, 2022, 2025, and a future 2028 [1]. All AM Bench data are permanently archived for public use. While AM Bench covers a wide range of materials and measurements, each series had some form of single-track or multi-track laser scan experiments with in-situ thermography, surface topography, and melt pool cross-sections for metals-based laser powder bed fusion (PBF-LB/M) additive manufacturing.

Machine performance and parameter uncertainty were quantified for these experiments to support modelers with uncertainty quantification. Relationships between melt pool cross-sectional measurements with laser parameters, gas flow, scan geometry, skywriting time, and powder layer thickness were established. This includes location specific, repeat cross-sections. An uncertainty analysis on cross-section melt pool measurands was performed to allow for model validation. Each iteration of AM Bench has provided new takeaways in terms of process insight, measurement needs, and modeling sensitivity and accuracy.

1 AM BENCH

AM Bench was founded by Dr. Lyle Levine in response to a 2015 National Academies workshop highlighting the need for benchmarking AM modeling and simulation tools [2]. AM Bench relies on its 154 collaborators across 30 institutions in industry, academia, and government to contribute to its benchmark measurements, data management systems, and conference organization. The first AM Bench conference and benchmark measurements were completed in 2018 with three sets of benchmarks focused on PBF-LB for metals and polymers and one set of benchmarks on polymer material extrusion. AM Bench 2018 received 46 challenge problem submissions. The second round, completed in 2022, saw the series grow to seven benchmarks on PBF-LB/M, thermoplastic material extrusion, and vat photopolymerization with 136 submissions. The third round in 2025 included nine benchmarks covering PBF-LB/M, wire-fed laser directed energy deposition (DED-LB), and vat photopolymerization with 86 submissions. The AM bench data are permanently archived and available online [1]. AM Bench datasets averaged 1,670 unique user downloads per month over the last year from May 2025 to 2026. Planning for the fourth round, AM Bench 2028, is underway. In addition to traditional benchmarks, a portion will include three coupled benchmarks with a strong connection to the aviation industry through partnership with the Computational Materials for Qualification and Certification (CM4QC) Steering Group [3].

One theme across the iterations of AM Bench has been single-track laser scan and multi-track laser scan experiments to benchmark PBF-LB/M models. The melt pool is the building block for PBF-LB/M. While the process is typically described as layer-by-layer, each layer is line-by-line or track-by-track. Single-track and multi-track laser scan measurements provide well-controlled boundary conditions, are more approachable for high fidelity modelers than full component builds, and are complimentary to full component benchmarks using the same laser process conditions. The AM Bench single-track and multi-track benchmarks are summarized in TABLE 1. Early experiments were single tracks on bare plates at different laser power and scan speeds [4]. The next iteration also used bare plates and included the laser spot diameter as a variable for single tracks and a multi-track rectangle scanned in two different directions [5]. The different scan directions revealed that the melt pool depth decreased when the scan direction and gas flow direction were parallel compared to anti-parallel or perpendicular relationships [5]. The most recent iteration included bare plates and powder layers with different laser turnaround times (i.e., skywriting times) for a typical (5 mm × 5 mm) and thin (1 mm × 5 mm) rectangular area. The introduction of powder was intended to bridge the gap between bare plate experiments and real parts. The two geometries and turnaround times were intended to capture the natural variation in PBF-LB/M under "constant" process parameters.

TABLE 1. Single line and single layer benchmarks through prior AM Bench years. P – laser power, v – laser scan speed, D_g – laser spot diameter. IN625 – nickel superalloy 625, IN718 – nickel superalloy 718.

Year	Powder	Geometry	Laser Parameters	Alloy
2018	No	Single-track	P, v	IN625
2022	No	Single-Track & Multi-track	P, v, D_g, scan direction	IN718
2025	Yes	Multi-track	Layer thickness, skywriting time	IN718

2 PBF-LB/M MACHINE PARAMETERS

A critical part of AM Bench experiments is rigorous machine characterization. AM Bench 2025 multi-track experiments were conducted on the Fundamentals of Laser-Matter Interaction (FLaMI) testbed, a very accurate, well characterized, and highly configurable laser processing testbed at NIST [6]. The AM Bench 2025 multi-track experiments used a laser power of 285 W ± 7 W, laser scan speed of 960 mm/s ± 6 mm/s, and a laser spot diameter (Gaussian fit, 4σ) of 72 µm ± 3.5 µm. The uncertainties are Type B, Type B, and Type A standard uncertainties (k = 1), respectively. A hatch spacing (spacing between tracks) of 110 µm was used for multi-track experiments. These represent nominal settings for a PBF-LB commercial machine printing IN718. The galvanometer on the FLaMI testbed achieved a minimum laser turnaround time (i.e., skywriting time) of 0.75 ms for the combination of scan speed and hatch spacing. A slower laser turnaround time of 5 ms was also used for bare plate multi-track experiments, which resulted in less heat buildup and more consistent melt pool morphologies between the two pad geometries. Results from this experiment are shown here for brevity. The skywriting time is not a traditional user parameter but rather typically set by the machine manufacturer to minimize build time and maintain position accuracy based on the performance of the galvanometer. The materials were IN718 plate and IN718 powder. Powder was hand-spread using a metal razor blade and shims on the edge of the plate with a powder layer thickness (PLT) of 80 µm and 160 µm. The PLT was defined as the gap between the top of the shims and plate surface. We estimated an expanded uncertainty of ± 5 µm (p = 95 %) for the gap thickness. More details are provided through the experiment description on the AM Bench website for the AMB2025-06/07 challenge [1]. The next sections present melt pool cross-section methods, results, and uncertainty for these experiments.

3 PBF-LB/M MELT POOL CROSS-SECTION MEASUREMENTS

The laser tracks were cross-sectioned perpendicular to the scanning direction and metallographically prepared, including etching, to reveal the material that was melted and solidified (referred to as the melt pool). Various measurands can be defined to describe the melt pool characteristics. There is no standard for measuring melt pools despite the commonplace measurement. Example micrographs and measurement schematics are shown in FIGURE 1, and the symbols are defined in TABLE 2. The measurands may differ between a single-track and a multi-track cross-section. In particular the width measurement is only a half-width measurement for multi-tracks because of remelting from the subsequent tracks.

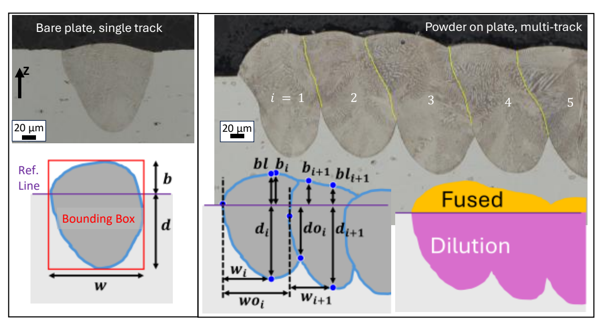

FIGURE 1. Example optical micrographs of melt pool cross-sections with schematics showing measurands for single-track and multi-track experiments. See TABLE 2 definitions. Melt pool boundaries were drawn for illustrative purposes. The distance measurands only require the determination of specific points or lines and do not require tracing the melt pool. Image segmentation using the Segment Anything Model was used to determine the fused and dilution areas. See Ref. [1] for details.

TABLE 2. Measurand definitions for single and multi-track cross-sections. "i" is the track number for multi-track experiments.

Single / Multi	S	Definition
Single, Multi	d, d_i	Depth: maximum vertical distance below original surface.
Single, Multi	b,b_i	Bead height: maximum vertical height above original surface.
Single	w	Width: maximum horizontal distance.
Multi	w_i	Width (trailing half-width): distance from the trailing edge to the depth centerline.
Multi	do_i	Overlap depth: vertical distance below original surface at melt pool intersection.
Multi	wo_i	Overlap width: vertical distance between trailing edges of consecutive melt pools.
Multi	bl_i	Bead height: vertical distance above original surface at depth centerline.

Single tracks are most simply measured using a bounding box. The depth and bead height are referenced to the original plate surface. The original plate surface is rotated to be horizontal prior to measurement through image rotation. Multi-track experiments have additional measurands that describe the track-to-track relationship. Mult-track cross-sections are more challenging to measure because the contrast between intersecting melt pools can be rather weak. A selection of measurement results from AM Bench 2025 is shown in FIGURE 3 with plots of bead height, depth, and width versus track number for different PLT. Data comes from three repeat cross-sections in the center of the two multi-track experiments (5 mm and 1 mm). The melt pool width was indeterminate (not measured) for most of the tracks for the 1 mm multi-track experiment. There are significant differences between the melt pool morphology for the 5 mm and 1 mm as shown by the segmented images of the last track (track number 45).

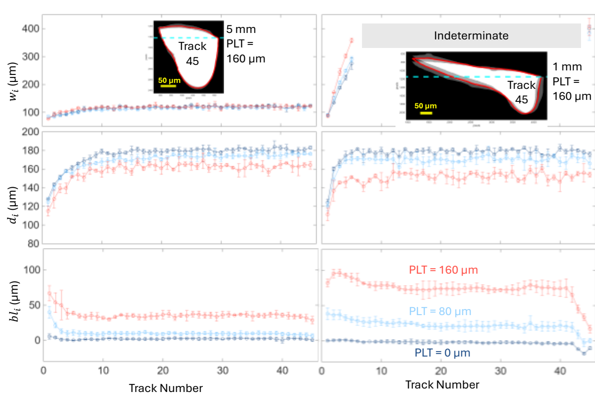

FIGURE 2. Melt pool measurements of width, depth, and bead height for a cross-section in the middle of 45 track areas with different PLT (left column) 5 mm x 5 mm area, (right column) 1 mm x 5 mm area. Data points are the mean ± std. dev. of three repeats. Images show the segmented final track melt pool cross-section (see FIGURE 1 for additional interpretation).

4 UNCERTAINTY ANALYSIS

For a multi-track experiment, it is desirable to calculate the uncertainty on a per track basis given that trends with track number exist. Significant effort was made to make repeat measurements where the cross-section position was at the same location for three samples since the results also depend on the location within the multi-track. This was achieved using fiducial markers on the plates created by the process laser and grinding with a handheld jig that allowed for viewing and alignment of the sample. This process yielded a position uncertainty of ± 75 µm (p = 95 %).

We considered four terms in the uncertainty analysis: microscope resolution (Type B), user variability (Type B), repeatability (Type A), and variation along the track length (Type B). The optical resolution was estimated at 0.5 µm (k = 1). The user variability in measuring the melt pool was estimated at ± 10 pixels or 1.74 µm (k = 1). The three repeats showed a low standard deviation, σ. The uncertainty term for repeatability was calculated as the standard error (k = 1) of the mean: 1.32*$\sigma/\sqrt{3}$. Variation along the track length, excluding the initial start and end, in this case is considered over a very short length of 150 µm based on the uncertainty in cross-section position, and it was estimated at 5 % of the mean. For bead heights, the variation was 5 % with a minimum value of 1 µm since the bead height values for bare plate experiments are very close to zero. The 5 % value for melt pool width is reasonable based on prior work that measured variation on the order of a few percent for bare plate line scans [7]. The 5 % value for melt pool depth was verified as a conservative estimate for various conditions with longitudinal cross-sections along separate 10 mm long single-track and multi-track experiments. FIGURE 3 shows an example result from these separate experiments using IN625 powder on plate on a commercial PBF-LM machine with similar laser parameters to that of the AM Bench experiments. The variation in the melt pool depth along the track length was calculated over 150 µm increments along the track from 0.425 mm to 9.575 mm (excluding the first and last 0.5 mm). The relative standard uncertainty was calculated using two methods: the coefficient of variation (standard deviation divided by the mean, assumes a gaussian distribution) and the semi-range divided by $\sqrt{3}$, normalized by the mean (i.e., (max – min) / (mean·$2\sqrt{3}$), assumes a rectangular distribution). This yielded median relative standard uncertainties of ~1.5 % with maximum values near 5 %.

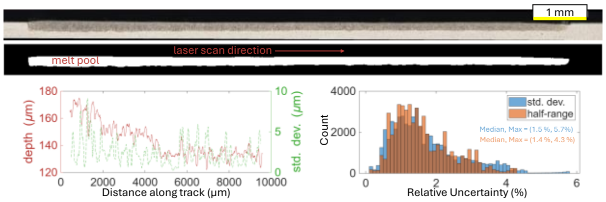

FIGURE 3. Cross-section of 10 mm long track along the scan direction for a multi-track geometry with IN625 powder on plate: optical micrograph (top), segmented image (middle), depth and standard deviation (std. dev.) vs. distance along the track (bottom left), histograms of the relative standard uncertainty calculated using the two methods described in the main text.

The four terms were combined in quadrature and expanded by a factor of 2 to produce the combined, expanded uncertainty: U (k = 2, p = 95 %). FIGURE 4 shows relative U normalized by the means for bare plate and powder on plate (PLT = 160 µm). A 10 % relative uncertainty is the minimum, and it appears consistent between pad geometries for bare plate experiments. The relative uncertainty increases slightly and shows more scatter from track-to-track for powder-on-plate experiments. This is largely due to an increase in the standard deviation from repeat measurements (n = 3). We reason the increase in relative uncertainty is due to increased process variation with powder and not related to the measurement method. Uncertainties for the other melt pool measurands and experimental conditions were also calculated, and these are available with the benchmark dataset.

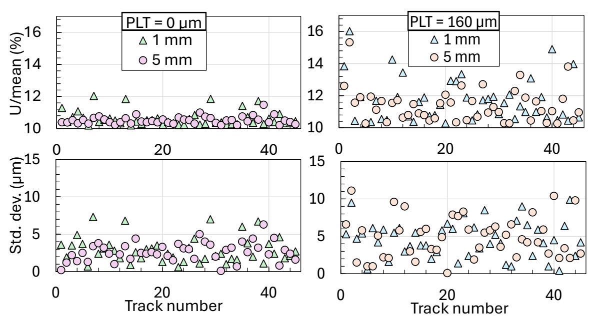

FIGURE 4. Relative uncertainty (U/mean) and standard deviations (std. dev.) for melt pool depth vs. track number for bare plate (PLT = 0) and powder-on-plate (PLT = 160 µm) experiments. Data includes 5 mm × 5 mm and 1 mm × 5 mm multi-track geometries (pads).

5 SUMMARY

Melt pool cross-section geometry benchmark data for multi-track bare plate and powder-on-plate experiments was generated with a relative uncertainty in melt pool depth on the order of 10 % (p = 95 %). The benchmark data includes machine parameter uncertainties for laser power, laser scan speed, laser spot diameter, and powder layer thickness. These AM Bench datasets enable model validation for different scenarios: under direct variation of laser parameters and indirect variation caused by part geometry and laser path planning (i.e., scan direction and skywriting time). Additionally, the datasets include a comparison between bare plate and powder-on-plate to make better informed decisions on validation protocols.

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