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Measurements of melt pool geometry and cooling rates of individual laser traces on IN625 bare plates

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Abstract

The complex physical nature of the laser powder bed fusion (LPBF) process warrants use of multiphysics computational simulations to predict or design optimal operating parameters or resultant part qualities such as microstructure or defect concentration. Many of these simulations rely on tuning based on characteristics of the laser-induced melt pool, such as the melt pool geometry (length, width, and depth). Additionally, many of numerous interacting variables that make LPBF process so complex can be reduced and controlled by performing simple, single track experiments on bare (no powder) substrates, yet still produce important and applicable physical results. The 2018 Additive Manufacturing Benchmark (AM Bench) tests and measurements were designed for this application. This paper describes the experiment design for the tests conducted using LPBF on bare metal surfaces, and the measurement results for the melt pool geometry and melt pool cooling rate performed on two LPBF systems. Several factors, such as accurate laser spot size, were determined after the 2018 AM Bench conference, with results of those additional tests reported here.

Keywords

Laser powder bed fusion; Selective laser melting; Thermography; Melt pool length; Cooling rate

1. Introduction

This paper describes the experiment design, and measurement results of melt pool geometry (length, width, and depth), as well as cooling rate measurements for comparison to numerical process simulations pertaining to bare metal scans. These tests were part of several types of benchmark tests and measurements for the 2018 Additive Manufacturing Benchmark Tests (AM Bench), and given the indicator AMB2018-02 on the AM-Bench website [1]. Single-track experiments were chosen to reduce the number of experiment variables and ensure broad utility among modelers. Additionally, these tests are conducted on bare substrates without powder to further reduce the number of variables (e.g., powder

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size distribution, or powder layer height), and reduce potential variability due to secondary physical phenomena (e.g., powder denudation, or track instability); though it has been shown that melt pools formed on bare plate and single layers of powder share similar lengths and cooling rates [2]. The experiments were conducted on two different LPBF systems; the Additive Manufacturing Metrology Testbed (AMMT) [3], and an EOS M270¹ commercial build machine (CBM).

2. Experiment Setup

2.1. Sample Preparation & Test Parameters

Nickel-based superalloy 625 (IN625) substrates are used in this study. They measure 24.5 mm × 4.5 mm, and 3.2 mm thick. The substrate surface is prepared with 320 grit random orientation polishing to create a flat, optically diffuse surface with surface features much smaller than the melt pool scale (approximately 10's of μm). Substrates were held in the AMMT and CBM systems by four pins in a fixture. Figure 1 presents an illustration of the fixturing method. This setup was introduced in prior work [4], and designed to ensure minimal contact is made on the substrate, which minimizes conductive heat loss. The fixture and pins are made of aluminum alloy.

Surface roughness of the substrates was measured using laser confocal microscope on three sample areas between the laser scan tracks (approximately 0.3 mm × 1.5 mm, avoiding any scan track topography). Arithmetic mean height areal parameter values ranged from $S_a = 0.44 \mu\text{m}$ to $0.53 \mu\text{m}$, and root mean square height parameter values from $S_q = 0.64 \mu\text{m}$ to $0.73 \mu\text{m}$.

Scan parameters (laser power and scan speed), are identified by 'Case', with the following parameter values: Case A laser power and speed are 150 W and 400 mm/s, Case B are 195 W and 800 mm/s, and case C are 195 W and 1200 mm/s. Figure 2 shows the track numbering and scan parameter case. Initial AMMT thermal imaging was collected at an integration time of 100 μs (here referred to as AMMT-100 μs). Due to the potential effect of motion blur on the 100 μs thermal images described in Section 2.2, a second, limited set of tests were conducted at an integration time of 20 μs (AMMT-20 μs). and compared to the AMMT-100 μs scans to ensure that they were executed under nominally similar conditions.

Laser spot size is set through different mechanisms on the CBM and AMMT. The CBM uses an f-theta lens to create a flat scanning field, and an adjustable defocusing lens after the laser collimator to adjust spot size. The AMMT uses a dynamic linear translating z-lens (LTZ) to perform a flat-field correction [3]. This LTZ is mounted and aligned on a second linear stage, which adjusts the static laser focus position and spot size. CBM spot size was presumed to be set based on the manufacturers specifications, and AMMT spot size was measured *in-situ* by attenuating the laser beam after the laser collimator and directly scanning on a charge-coupled device (CCD) array. For the AMMT, 4-sigma diameter ($D4\sigma$) was 170 μm (full-width half max (FWHM) of 100 μm) and the CBM laser spot ($D4\sigma$) was

¹Certain 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 National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

100 μm (FWHM of 59 μm). Spot size and additional machine parameters pertinent to the conditions inside the build chamber are provided in Table 1.

2.2. Melt Pool Imaging Thermography Systems

The thermography setup for *in-situ* measurements on the CBM and AMMT varied in several significant ways. However, both systems incorporate a staring configuration that views the melt pool as it scans through the camera field of view. Also, the essential method for calibration, measurement, and analysis of the resulting melt pool images proceeded using similar methods. Figure 3 shows both thermography experiment setups, with description of pertinent components. Table 2 provides a comparison of pertinent technical parameters for both imaging systems.

Since the cameras view their respective surfaces at an angle, the projected pixel size on the build surface (or instantaneous field of view, iFoV) is different in the horizontal and vertical direction in camera image. That is, while each camera pixels are square, the true dimensions on the build surface are different in the horizontal and vertical directions. Equivalent iFoV in the vertical image direction is scaled by $r/\cos(\theta)$, with r being the horizontal scale in μm per pixel, and θ being the viewing angle the camera makes with respect to the build surface normal.

The CBM camera is calibrated using a commercial spherical cavity, variable temperature blackbody source, with a circular foil aperture slightly larger than the field of view to avoid stray light which can erroneously increase the signal. The AMMT camera is calibrated using a custom, light emitting diode (LED) driven integrating sphere, with interchangeable apertures. Both have calibrations tied to the primary standards at NIST. Figure 4 shows the calibration ranges for each of the three samples shown in Figure 2.

Note that the calibration ranges shown in Figure 4 do not equate to the true measurable temperature ranges. Since the emittance of the physical surface shifts the measurable range of the true temperature [5], each of the calibration ranges indicated in Figure 4 do in fact enable observation of the melt pool solidification boundary assumed to be 1290 $^{\circ}\text{C}$ in this paper. The calibration procedure essentially maps digital signals measured by the camera (S_{means}) to the setpoint temperature of the calibration blackbody source (T_{bb}) by fitting a nonlinear function F to $S_{means} = F(T_{bb})$. The Sakuma-Hattori equation [6] is used and described in the next section, and closely approximates a spectrally-integrated Planckian radiation function, but is invertible in closed form. The contribution of the calibration on measurement uncertainty is discussed in Section 4.

AMMT-100 μs thermal images were collected at 8-bit digital dynamic range (256 DL), whereas the 20 μs thermal imaging (AMMT-20 μs) was collected at 12-bit digital dynamic range (4096 DL). Thermal calibrations for the AMMT camera were conducted at 12-bit dynamic range setting, therefore the AMMT-100 μs data had to be upconverted by multiplying the signal value by $2^4 = 16$. The contribution of the digital sampling and digital upconversion AMMT-100 μs to measurement uncertainty is discussed in Section 4. CBM images were collected at 14-bit digital dynamic range (16 384 DL).

2.3. Calculation of Melt Pool Length and Cooling Rate

Once thermal images of the melt pool are collected, several processing steps are conducted to convert the camera signal to a temperature that corresponds to the solidification temperature and measure the melt pool length and cooling rate from the profile line taken from the center of the melt pool. First, this section will provide some detail on the difference between radiance temperature (or, apparent temperature), true temperature, and emissivity to provide background on how the line profile data are obtained. Similar publications from the authors provide more detail [4,5]. In addition, description of the image analysis for extracting melt pool length is provided.

The relationship between measured signal from the camera (S_{meas}), measured in DL, radiance temperature (T_{rad}), true temperature (T_{true}), and emissivity (ϵ), is defined by the Measurement Equation:

$$S_{meas} = F(T_{rad}) = \epsilon F(T_{true}) \quad (1)$$

Radiance temperature is equivalent to a true temperature if $\epsilon = 1$ (which is approximated when conducting a thermal calibration of the camera against a blackbody calibration source). F is the Sakuma-Hattori calibration function as mentioned before, which relates measured signal [DL] to radiance temperature [$^{\circ}\text{C}$] or [K]. Often, a $(1-\epsilon)$ term representing reflected ambient temperature sources is added to the measurement equation [5]. However, this factor has minimal consequences to measurement of temperatures vastly higher than the ambient surroundings, such as in LPBF melt pool thermographic measurements. The Sakuma-Hattori equation and its inverse are given in Equations (2) and (3):

$$F(T) = \frac{C}{\exp\left(\frac{c_2}{AT+B}\right) - 1} \quad (2)$$

$$F^{-1}(S) = \frac{c_2}{A \ln\left(\frac{C}{S} + 1\right)} - \frac{B}{A} \quad (3)$$

The term c_2 is the second radiation constant (14 388 $\mu\text{m}/\text{K}$) and the coefficients A , B , and C are fit coefficients determined through least-squares regression. For thermographic measurements of laser-induced melt pools, a solidification boundary of the melt pool (freezing point) may be distinguished by a discontinuity or inflection point in the temperature vs. time ($T(t)$) data or temperature vs. length ($T(x)$) profile, assuming laser scan speed is constant. This freezing point is identified by the minimum of the second derivative of $T(x)$, as demonstrated in [4]. This definition follows similar methods used in fixed-point thermometry, in which the solidification point is defined as the inflection point between the solidus and liquidus regions of a melting curve [7].

If the freezing point (nominally the solidus) temperature is known or well-approximated, the effective emittance of that point can be extracted from Equation (1) using Equation (4) as

mentioned in the AMB2018-02 test description [1]. We assume this value, T_{freeze} is 1290 °C for IN625.

$$\epsilon_{freeze} = \frac{S_{meas}}{F(T_{freeze})} \quad (4)$$

Although 1290 °C is an assumed value, it will be shown that this has minimal effect on the melt pool length measurement but does affect the cooling rate measurement. In reality, the solidification temperature is likely affected by undercooling due to the high cooling rates and nonequilibrium solidification [8].

Once calculated, ϵ_{freeze} can then be used to convert the measured camera signal or radiance temperature in Equation (1) into ‘true’ temperature using Equation (5). Essentially, this scales the measured radiance temperature field (nonlinearly) such that the detected solidification boundary in the thermal images equate to the assumed solidification temperature of 1290 °C. Although this is valid for the solidification point, it is assumed that ϵ_{freeze} is applicable at temperatures above and below the solidification point, or over the range that cooling rate is measured.

$$T_{true} = F^{-1}\left(\frac{S_{meas}}{\epsilon_{freeze}}\right) \quad (5)$$

Laser scans for experiments described here are essentially horizontal within the field of view of the camera, therefore melt pool temperature profiles may be extracted by selecting a horizontal row of pixels at the melt pool center. In the case of non-horizontal scans (not described in this paper) this method is inadequate, therefore we developed a more universal algorithm for extracting the melt pool temperature profile along its length.

First, an approximate melt pool shape is determined by locating an approximate solidification boundary. The principle axis of this shape, determined from the second central moment, then defines the profile line $T(x)$ along which further melt pool length and cooling rates are calculated. The following algorithm is used to define melt pool profile data. Step 1 to 4 describes the method for identifying the estimated melt pool boundary and extraction of the length profile line $T(x)$ for melt pools that are not horizontally aligned in the thermographic image. Step 5-9 uses the $T(x)$ to calculate the melt pool length and cooling rate:

1. Determine the **approximate solidification** point by selecting a line of pixels (horizontal, diagonal, or otherwise) along the approximate centerline of the melt pool, creating a profile line, and locating the solidification inflection point (in $S(x)$) on the profile line determined by minimum the second derivative.
2. Calculate the solidification **approximate emittance** using the assumed freezing temperature (1290 °C for IN625) and Equation (4).
3. Find the approximate **melt pool shape** by thresholding (binarizing) the image to values within ± 5 DL of the approximate solidification point.

4. For this binarized melt pool shape, calculate the centroid, and major and minor axis orientations based on the shape central moments.
5. Use the major axis to define the melt pool **profile line** (signal vs. x , or $S(x)$)
6. Convert the profile line signal values to **radiance temperature** vs. x ($T_{rad}(x)$) using Equation (1).
7. Determine the solidification point T_{freeze} using the minimum of the second derivative of $T_{rad}(x)$.
8. Determine effective emittance of this point, ϵ_{freeze} , from Equation (4), and the true temperature profile $T_{true}(x)$ from the right hand side of Equation (1).
9. Calculate the front of the melt pool as the intersection of $x_{front} = T^{-1}(T_{freeze})$, and the lower cooling rate point $x_{low} = T^{-1}(T_{low})$, from the true temperature profile $T_{true}(x)$.

Figure 5 demonstrates an example measurement of one video frame from the CBM and AMMT-20 μ s measurements, respectively. Note that although the colorbars and resultant radiance temperature make the CBM melt pool apparently much larger than the AMMT melt pool, this is largely due to the different calibration ranges, where CBM camera is capable of measuring and displaying lower temperatures. Additionally, note that the calculated solidus emittance differs between the two figures. Although this calculated emittance is not a robust metrological value, it does have physical relationship to the normal spectral emittance of the metals, which are known to have higher normal spectral emittance at the near-infrared (such as the AMMT camera) compared to the short-wave infrared (such as the CBM camera) [9,10]. However, when scaled via the calculated solidus emittance, the solidification points in the melt pool temperature profiles match the assigned solidus temperature of 1290 °C. Also note that the CBM had smaller laser spot size compared to the AMMT, therefore higher volumetric laser energy density, which can explain the greater measured melt pool length shown in Figure 5, and measured depth described in the next section.

Melt pool length and cooling rates are calculated from the ‘true’ temperature profiles in the spatial domain $T_{true}(x)$. Melt pool length L_x , is determined by locating the solidification inflection point via the minimum of the second derivative of the $T(x)$ profile line [4], resulting in the point x_{freeze} , and measuring the length to the front of the melt pool at the intersection of $T(x) = T_{freeze}$ (determined using linear interpolation between points) resulting in the point x_{front} . This provides for the length measurement L_x , where the subscript x indicates measurement in the spatial domain:

$$L_x = |x_{front} - x_{freeze}| \quad (6)$$

Cooling rate measurements, as described in Section 3.1.2 of the AMB2018-02 test description website [1], are in units [°C/s] and measured as the difference between assumed solidus point ($T_{freeze} = 1290$ °C) and a selected lower temperature T_{low} and its respective spatial point x_{low} . The time-rate change is then calculated using the known constant scan speed $v = x / t$.

$$\dot{T}_x = \frac{v(T_{freeze} - T_{low})}{|x_{freeze} - x_{low}|}$$

A cooling rate temperature range of 1290 °C to 1190 °C was selected for the two thermal imaging systems. Due to the different calibration range of the CBM camera, which can measure lower temperatures, broader range of 1290 °C to 1000 °C is also provided for comparison.

It should also be mentioned that the location of the solidification point, based on the 2nd derivative of T(x), minimally differs between the T_{rad} and T_{true} curves in Figure 5, indicating that the accuracy of the assumption in T_{freeze} = 1290 °C has minimal effect on the length measurement. However, it can also be seen in Figure 5 that the slopes of the T_{true}(x) and T_{rad}(x) profiles do differ. This indicates that the cooling rate measurement depends on the scaling from T_{rad}(x) to T_{true}(x), which in turn depends on T_{freeze} and the assumption that it is applicable at temperatures below the solidification point. Additionally, T_{freeze} depends on the assumed value of T_{freeze} = 1290 °C. For these and other reasons, cooling rate measurements are only provided for comparison, but not recommended for reference or calibration of AM models, as described in Section 3.

2.4. Melt Pool Transverse Cross-Sections Measurements

Each of the three samples in Figure 2 were cross sectioned through the middle of the laser traces, mounted, and polished using typical metallurgical sample preparation procedures. The samples were etched with aqua regia for 20 s to 30 s and then examined and photographed with a Zeiss LSM800¹ confocal laser scanning microscope. The measurement mode of the microscope software was used to draw a bounding rectangle at the melt pool depth and width boundaries.

The measurement results for melt pool width and depth presented on the AM-Bench measurement results website were made from the AMMT-100 μs sample [11]. Similar measurements were later taken on the CBM sample, as detailed here. Melt pool depth and width measurements of all 10 traces on the AMMT-100 μs sample and CBM sample were acquired using three different imaging conditions: (1) 50x objective, bright field (BF), Z-Stack, (2) 50x objective, reflected light dark field mode (DF), Z Stack, and (3) 50x Objective, DF, photograph at autofocus position. An enhanced depth of focus image (EDF) was compiled from each of the image stacks (ZStk) and saved as tagged image file format (TIFF) files as well as the native file format of the microscope. Example BF, Z-stack measurements for the CBM and AMMT-100 μs samples of each scan Case (A, B, and C) are shown in Figure 6. The AMMT cases all demonstrated conduction mode track formation. The CBM-generated tracks exhibited slight keyhole or keyhole transition shape in Cases B and C, likely due to the smaller laser spot size compared to the AMMT. Additionally, the CBM Case A cross-sections showed relatively elevated humping, likely due to more dynamic fluid flow within the melt pool, and again caused by the smaller laser spot size and increased laser energy density.

Melt pool cross-section geometry results were later obtained for the AMMT-20 μs samples, although they utilized only one imaging technique. These were all measured using 50x objective, reflected light brightfield mode, although images were collected with a 3 pixel x 3 pixel binning mode, which resulted in image scaling per pixel of 0.186 μm .

3. Results

Table 3 provides a compilation of process parameters and measurement results for each scan track of each sample in Figure 2. For thermography-based measurements (effective emittance, melt pool length, and cooling rate), the sample population N is the number of video frames in Table 3. For microscopy-based measurements (cross-section width and depth) this is the number of measurements per track ($N = 3$). The $\pm 1\sigma$ indicated is the standard deviation of the measurements for each individual track, whether it is number of video frames or number of microscopy measurements. Note that this does not imply a standard uncertainty, but an indication of the variance about the average values presented. These individual track measurements are compiled into a summary, later in this section in Table 4.

Melt pool cross-section geometry measurements, topography, grain shapes, dendritic microstructure, etc. presented elsewhere in this special issue [12–14] were all made on the AMMT-100 μs tracks listed in Table 3. To ensure the physical scan tracks for the AMMT-20 μs and AMMT-100 μs cases were created under the same conditions (namely, laser power, scan speed, and laser spot size), melt pool cross-section geometry for these two samples are compared in Figure 7. The similar resultant cross-section geometry indicates these were indeed created under the same conditions.

Since scan conditions were similar for the AMMT-100 μs and AMMT-20 μs cases, melt pool depth and width measurements made from cross-section microscopy could be combined for these two datasets. The melt pool geometry measurement results are compiled to give unified reference values for each scan condition case (A, B, C), and each machine (CBM or AMMT), and are presented in Table 4 and plotted in Figure 8.

Since the values in Table 4 are based on mean values, it also provides the uncertainty of the mean, u_{mean} . The sample population (N) for melt pool length measurements was based on the total number of thermal video frames of all videos taken for that class. Similarly, the class mean for melt pool length defined as the average of all combined video frames for that class (e.g., the class mean for CBM Case A lengths is the average of $N = 53+27+49$ total measurements), and standard uncertainty of the mean taken as $U_{\text{mean}} = \sigma / (N)$. For any measurements where $N < 30$, $u_{\text{mean}} = z \cdot \sigma / (N)$, where z is taken from the student's t table for a confidence interval of 68.3%. Errorbars in Figure 8 represent $\pm u_{\text{mean}}$.

Melt pool cooling rate measurements were significantly different for the CBM and AMMT cases, although the trends comparing the A, B and C cases were similar for both machines. For the AMMT-100 μs cases, the measurements at the lower temperature point, T_{low} in Equation (6), are likely affected by motion blur from the longer 100 μs integration time. The effect of this motion blur on the temperature profile $T(x)$ is not as simple as calculating a

blur length based on integration time and scan speed, $x_{blur} = (100 \mu\text{s}) \cdot v$. This has a minimal effect on the melt pool length measurement, but does affect T_{low} , therefore cooling rate values for the AMMT 100 μs cases should not be referred to, and are noted as such in Table 3. In addition, the limited calibration range of the AMMT-20 μs measurements may have resulted in the lower temperature point, T_{low} , occurring where the calibration curve in Figure 4 is insensitive, and may be affected by sensor nonlinearity. For these reasons, cooling rate measurements are only given as exemplar measurement results, but not recommended for reference or calibration of AM models.

Still, the CBM and AMMT-20 μs cooling rate values cases are an order of magnitude different or more, primarily stemming from the different $D4\sigma$ laser spot sizes of 100 μm and 170 μm , respectively. The melt pool lengths of the CBM sample were significantly longer than for the AMMT-20 μs sample, which coincide with the deeper melt pool depths shown in Figure 6 and Table 4, and the longer lengths are indicative of lower cooling rates.

4. Measurement Uncertainty

4.1. Unit Conversions

A preliminary compilation of the components of measurement uncertainty for melt pool length are described here. Nevertheless, the following analysis, and compiled uncertainty budget in Table 5 compares different factors in measurement uncertainty for the AMMT and CBM systems.

To combine the individual contributing components of measurement uncertainty, they must be converted to the same unit as the measurand (unit of length [μm] for melt pool length). Components of uncertainty given in terms of signal, $u(S)$ in units of [DL], such as digitization errors, camera noise, etc. are converted to temperature $u(T)$ in [$^{\circ}\text{C}$] by taking the partial derivative of the inverse calibration equation $F^{-1}(S)$ from Equation 3.

$$u(T) = \frac{\partial F^{-1}(S)}{\partial S} u(S) \quad (8)$$

The differential term is determined by partial differentiation of the inverse calibration Equation (3), with respect to S :

$$\frac{\partial F^{-1}(S)}{\partial S} = \frac{c_2 C}{AS(C + S) \ln^2\left(\frac{C + S}{S}\right)} \quad (9)$$

For melt pool length, this is evaluated at the solidification point. Furthermore, components of uncertainty defined in temperature units $u(T)$, such as calibration uncertainty, or those converted from signal $u(S)$, are converted to units of length $u(x)$ in [μm] utilizing reciprocal of the partial derivative of the true temperature profile $T(x)$:

$$u(x) = \left(\frac{\partial T(x)}{\partial x} \right)^{-1} u(T) \quad (10)$$

Values for dT/dx are based on the first derivative, in the spatial domain, of the true temperature profile $T(x)$, evaluated at the freezing point (e.g., $dT_{true}(x_{freeze})/dx$). If components of uncertainty defined in units of length are defined in pixels, these are converted to units of [μm] using the iFoV in Table 2.

4.2. Measurement Uncertainty – Melt Pool Uength

Equation (6) described the measurement of melt pool length from the thermal profile $T(x)$. Since the profile line is relatively steep at the front of the melt pool (dT/dx is relatively high), the intersection of the length measurement at x_{front} is more precise than determining the location of x_{freeze} . Additionally, uncertainties in temperature $u(T)$, converted to uncertainty in length $u(x)$ via Equation (10) are reduced with higher dT/dx . Therefore, it is assumed that $u(x_{front}) \rightarrow 0$, and uncertainty in the melt pool length measurement is solely derived at the freezing point x_{freeze} :

$$u(L_x) = u(x_{freeze}) \quad (11)$$

The following lists those components of uncertainty that are accounted for in the uncertainty budget. Components of uncertainty due to thermal camera calibration, $u_1(T)$, stems from the curve fit procedure (in units of $^{\circ}\text{C}$) and defined here as the root mean square error (RMSE) of the curve fit. The calibration uncertainty for the AMMT-100 μs was 0.34°C , for AMMT-20 μs was 2.2°C , and for CBM was 8.1°C .

The component of uncertainty due to signal digitization, $u_2(S)$, is assumed to be ± 1 DL with uniform probability distribution, resulting in a standard uncertainty of $1/\sqrt{3} = 0.58$ DL.

The AMMT-100 μs case was originally collected at 8-bit (256 DL) dynamic range, and was upconverted to 12-bit (4096 DL) digital range, resulting in a 16x loss in precision (± 8 DL). An added component of uncertainty is provided assuming uniform probability distribution, of $U_3(S) = 8/\sqrt{3}$ [DL].

Signal noise, or the temporal noise of flicker of the thermal camera pixels for both AMMT and CBM was typically ± 1 DL. Assuming uniform probability distribution results in $U_4(S) = 1/\sqrt{3} = 0.58$ DL

Uncertainty due to spatial pixilation is assumed to be ± 1 pixel, with uniform probability. This is converted to [μm] using the iFoV in Table 2, resulting in $u_5(x) = \text{iFoV}/\sqrt{3}$ μm .

Motion blur and optical blur are mathematically complicated, and their incorporation into measurement uncertainty in thermal or other imaging-based metrology is not standardized. Optical blur stems from the inherent resolution limits of optical system, which depend on many factors, but primarily depend on the measured wavelength and numerical aperture (i.e., the Airy disk diameter, or diffraction limit [15]). Motion blur depends on the relative speed

of an object or scene with respect to the integration time or shutter speed. Mathematically, both optical blur and spatial blur affect a ‘perfect’ image through convolution of a 2D spatial filter. How this convolution affects the image depends on the convolution filter kernel, as well as the *specific image or scene*. In other words, the measurement uncertainty stemming from blur will depend on the ‘perfect’ image being measured. As yet, no closed form or simple formulation is known to exist that can be generally applied to determine the contribution of blur to a dimensional measurement on a varying set of images or video.

A conservative, Type B estimate is provided here for motion blur ($u_6(x)$) and optical blur ($u_7(x)$). Uncertainty in length measurement due to motion blur is assumed to be equal to $2x$ the blur length, calculated as $\delta x = 2 v \cdot t_{int}$ where v is the scan speed and t_{int} is the integration time. The measured point is assumed to exist within δx with uniform probability, resulting in $u_6(x) = v \cdot t_{int} / 3$. Optical blur is estimated as $u_7(x) = 2\sigma$ width of an assumed rotationally-symmetric gaussian point spread function, measured using knife edge technique described in ISO-12233 [16,17]. Optical blur is assumed to have a normal distribution.

Standard uncertainty of the mean was described prior to Table 4. The class mean for melt pool length defined as the average of all combined video frames for that class (e.g., the class mean for CBM Case A lengths is the average of $N = 53+27+49$ total measurements), and standard uncertainty of the mean taken as $u_8(x) = \sigma / (N)$. The sample population (N) for melt pool length measurements was based on the total number of thermal video frames of all videos taken for that class. For any measurements where $N < 30$, $u_8(x) = z \cdot \sigma / (N)$, where z is taken from the student’s t table for a confidence interval of 68.3%.

The ISO Guide to the Expression of Uncertainty in Measurement [18] gives the formula for combining uncertainties in the absence of correlations for the combined standard uncertainty, u_c . This requires that each component of uncertainty be converted to standard uncertainty with equivalent normal probability distribution). For those components that are given with a rectangular probability distribution of the range $\pm a$ (in units of that component of uncertainty), these are converted to their equivalent standard uncertainty by a factor of $2a / \sqrt{12}$, or $a / \sqrt{3}$ prior to unit conversion. Each component of standard uncertainty is converted to length units using Equation (8)–(10), then added in quadrature:

$$u_c^2(x) = \sum_n \left(\frac{\partial T(x)}{\partial x} \right)^{-2} u_n^2(T) + \sum_m \left(\frac{\partial T(x)}{\partial x} \right)^{-2} \left(\frac{\partial F^{-1}(S)}{\partial S} \right)^2 u_m^2(S) + \sum_l u_l^2(x) \quad (12)$$

$u_n^2(T)$ are the squares of those components defined in units of temperature [$^{\circ}\text{C}$] ($n = 1$), $u_m^2(S)$ are the squares of those components defined in units of signal [DL] ($m = 2$ to 4), and $u_l^2(x)$ are the squares of those components defined in units of length [μm] ($l = 5$ to 8).

Table 1 lists each component of standard uncertainty, the unit conversion factors, and the components converted to length units. Finally, the combined standard uncertainty is provided calculated using Equation (12), and expanded uncertainty assuming coverage factor $k=2$ [19].

Some components of uncertainty are assumed negligible. Variability in scan speed and resulting effects are neglected. The high speed cameras have very precise timing clocks (>1 MHz), and precise frame rates. cursory observation of the transit of the melt pool across image frames for both the CBM and AMMT cameras demonstrated that the scan speed, measured as the distance moved between frames divided by frame period, resulted in variability far less than one pixel width. Variability in integration time and resulting effects on measurement is similarly neglected due to the precise timing of the camera clocks.

4.3. Measurement Uncertainty - Cross-section width and depth

Uncertainty due to optical resolution limits in the microscope images are accounted for based on the Rayleigh criterion and illumination wavelength of the microscope. This was estimated to be 0.5 μm (Type B).

Uncertainty due to variability along the track stems from the fact that these measurements are based on a subset of transverse metallographic cross-sections, whereas the actual geometries of the track can vary in the longitudinal direction. This effect is minimized when performing laser scans on relatively smooth, bare metal surfaces when compared to single layers of metal powder. Ricker et al. [13] provides topological measurements in the longitudinal direction of the tracks. However, melt pool width or depth were not measured along the longitudinal direction. For width, Fox et al. measured variability along a track width on a 17-4 stainless steel plate, resulting in a 1σ variation of 1.8% [20]. This was conducted on 'as-received' surface, which is rougher than those used in this paper, likely contributing to a relatively more variation in track width. Based on this, a conservative estimate of 2% uncertainty in variability track width is accounted for (Type B).

Similarly, variability in track depth is not measured since longitudinal cross sections along the track length were not obtained. However, the authors believe this effect to vary less than 5%, with greatest variation for CBM track A since the cross sections in Figure 6 demonstrate it to have occurred near or at keyholing regime. King et al. [21] created longitudinal cross-sections, and noted a 15% variability in depth along 316L stainless steel scan tracks. However, an example track in King et al. had significantly higher volumetric energy density, defined as $E = P/V/A$ [J/mm^3], where P is laser power [W], V is scan speed [mm/s], and A is the area of the laser spot based on $D4\sigma$ diameter [mm^2]. This indicates that King et al. utilized $E = 124 \text{ J}/\text{mm}^3$, whereas CBM Case A utilized $48 \text{ J}/\text{mm}^3$. Although track depth fluctuations likely do not scale directly with energy density, and materials in AM-Bench and King et al. were different, this indicates track depth variability for CBM case A is likely much less than 15% in [21]. Conservative estimates of 5% of mean depth is assumed for all AMMT and CBM cases (Type B).

User variability in the track boundary selection in the microscopic images had an approximate ± 6 pixel repeatability for the $0.062 \mu\text{m}/\text{pixel}$ resolution images, and ± 2 pixel repeatability for the $0.186 \mu\text{m}/\text{pixel}$ images, resulting in user variability uncertainty of $\pm 0.372 \mu\text{m}$ (Type A) for all measurements.

The total number of measurements, N, and the experimental standard uncertainty of the mean, u_{mean} , are provided in Table 4. Since the number of measurements made of the

microscope images were $N < 30$, u_{mean} is scaled based on Student-t distribution to represent a 68.3% (1σ) confidence interval as described in the text prior to Table 4.

Since each component of uncertainty is already defined in units of length, no unit conversions are necessary, and the combined standard uncertainty of the width $u_c(w)$ or length $u_c(d)$, without correlations, is given as the sum of uncertainty components in quadrature:

$$u_c^2(w) = \sum_i u_i^2(w) \quad (13)$$

Expanded uncertainty, U , utilizes coverage factor $k=2$ [19]. Table 6 and Table 7 provide the uncertainty budgets for melt pool width and depth, respectively.

5. Discussion and Conclusions

This paper described the experiment setup and measurement results for the AMB2018-02 measurement challenges for melt pool geometry. These experiments consisted of LPBF tracks scanned on bare IN625 plates, *in-situ* melt pool length and cooling rate measurements via thermography, and ex-situ transverse cross-section geometry (width and depth) via optical microscopy. A summary of compiled results are provided in Table 4, and preliminary measurement uncertainty analysis provided in Table 5–Table 7. Cooling rates are provided, but to be considered as exemplar data, but not reference data.

Melt pool cross-section measurements, such as width and depth, as well as microstructural measurements (grain shapes and dendritic microstructure) provided for the 2018 AM-Bench challenges [1] were from the AMMT-100 μs tracks given in Table 4 [13,22]. However, due to motion blur in the thermographic system, melt pool length measurements should be taken from AMMT-20 μs tracks or the CBM tracks. It was found that cooling rate measurements were significantly different for the AMMT and CBM systems, likely stemming from differences in the imaging systems that affect temperature values much below the solidification point. It was shown in Figure 7 that the AMMT-100 μs and AMMT-20 μs tracks were fabricated under comparable conditions (laser power, scan speed, and laser spot size).

Melt pool length measurements using thermography have larger uncertainty than cross-section width or depth measurements taken via optical microscopy, primarily due to differences in spatial resolution. However, with thermography, greater number of measurements or image frames can be taken, which can elucidate transient variations. Variability in melt pool depth along the track are based on review of external publication [21], and likely depend on the melt pool formation mode (conduction or keyhole). Further work is necessary to better identify this variability, potentially with new methods for longitudinal track cross-sections, and how the measured variability may contribute to melt pool depth measurement uncertainty from more easily obtained transverse cross-sections.

6. References

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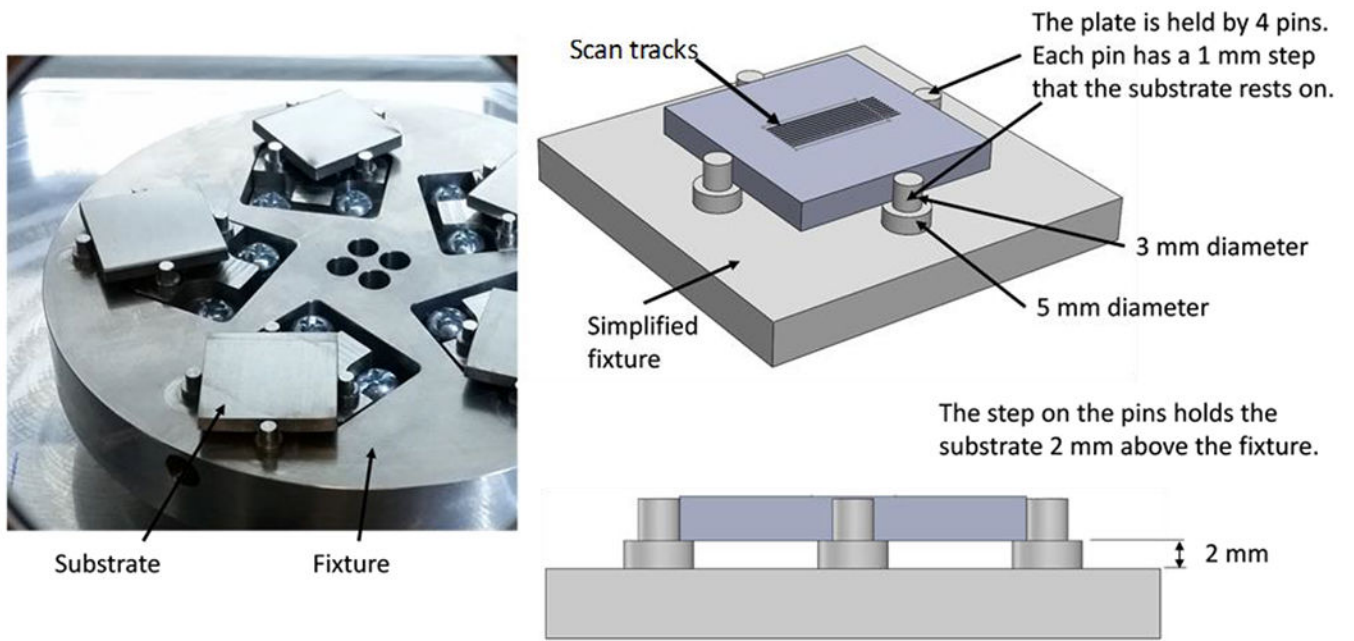


Figure 1: Illustration of the substrate as it is held in the fixture inside the CBM. AMMT had a similar holding system.

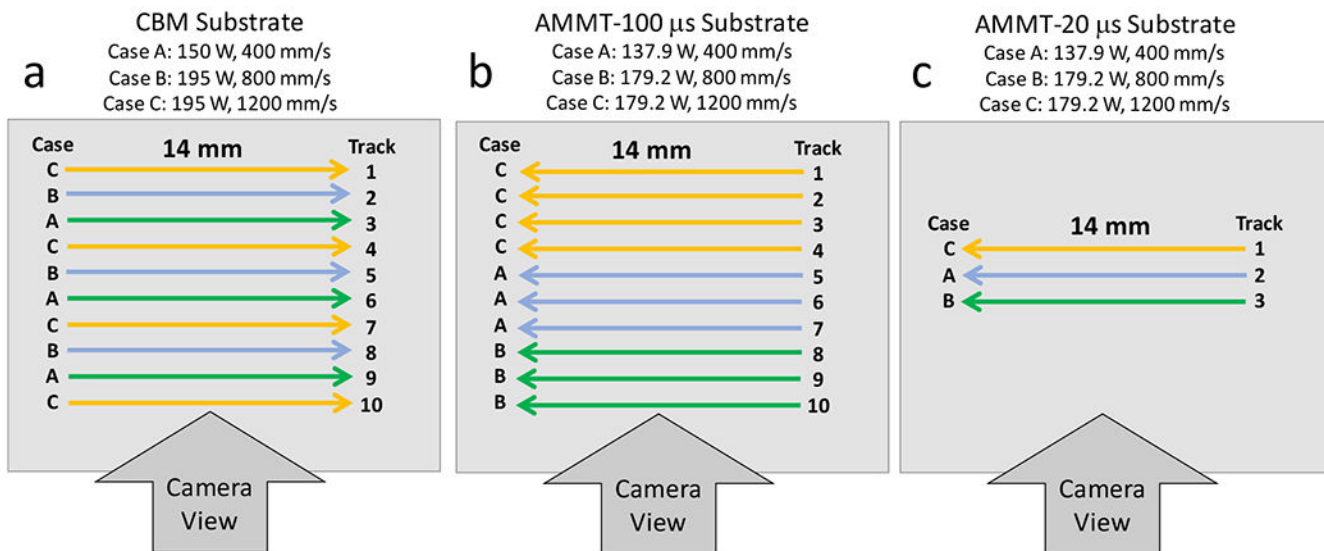


Figure 2: Track numbering and layout for each set of measurements: **a** CBM, **b** AMMT-100 μ s, **c** AMMT-20 μ s. Laser power values indicated are the applied laser power.

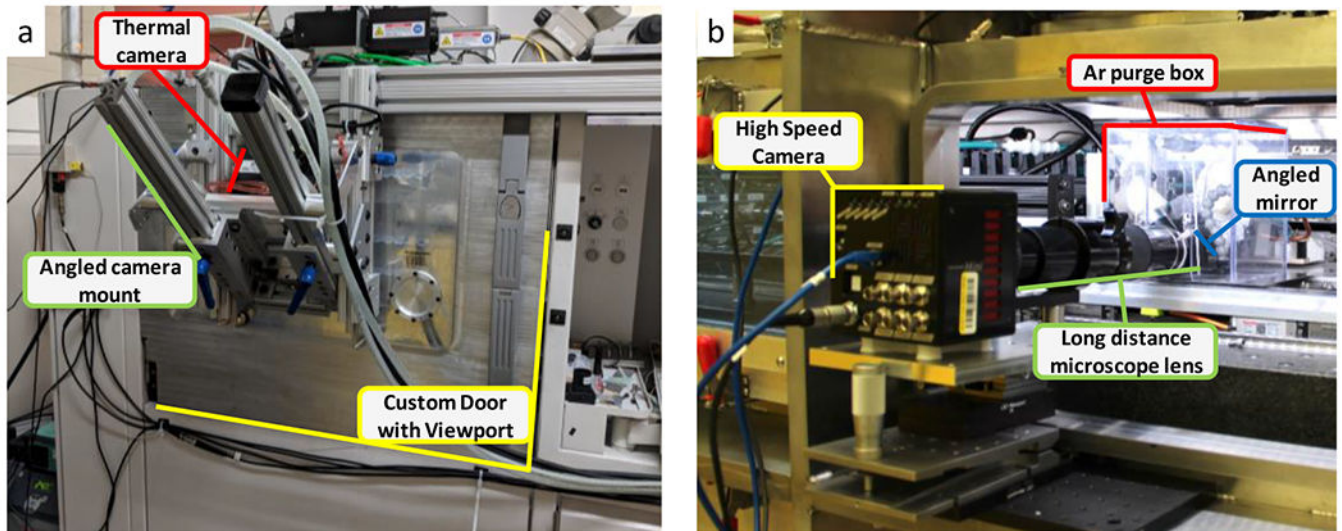


Figure 3:
Thermography setup for each machine: **a** CBM, using a mounting bracket to angle the camera and look through a custom door with viewport, **b** AMMT, using a long distance microscope and angled first-surface mirror mounted in an argon purge box.

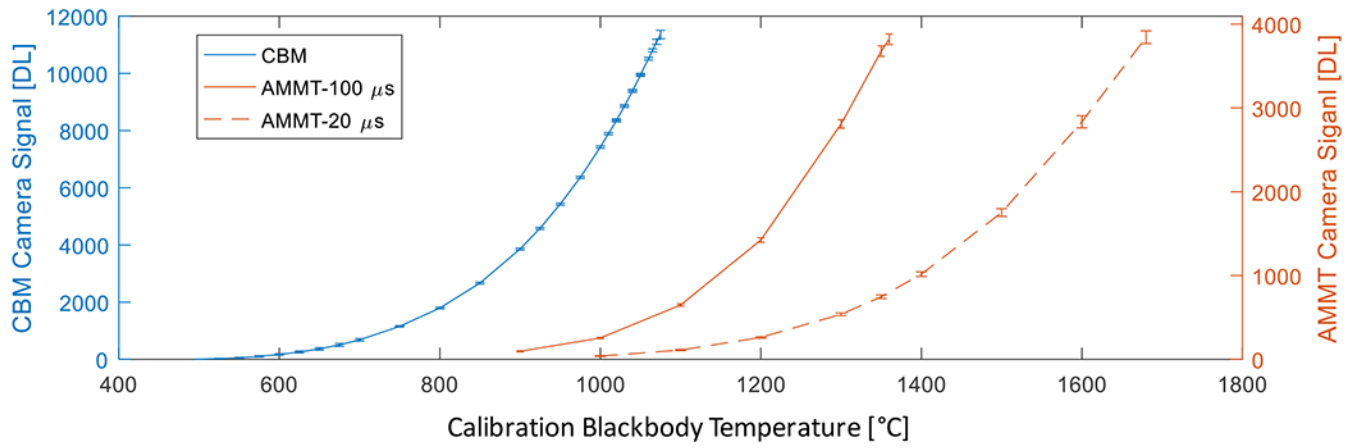


Figure 4: Thermal calibration points (with linear interpolated lines for clarity) for the CBM and AMMT thermal cameras. Error bars indicate $\pm 1\sigma$ standard deviation.

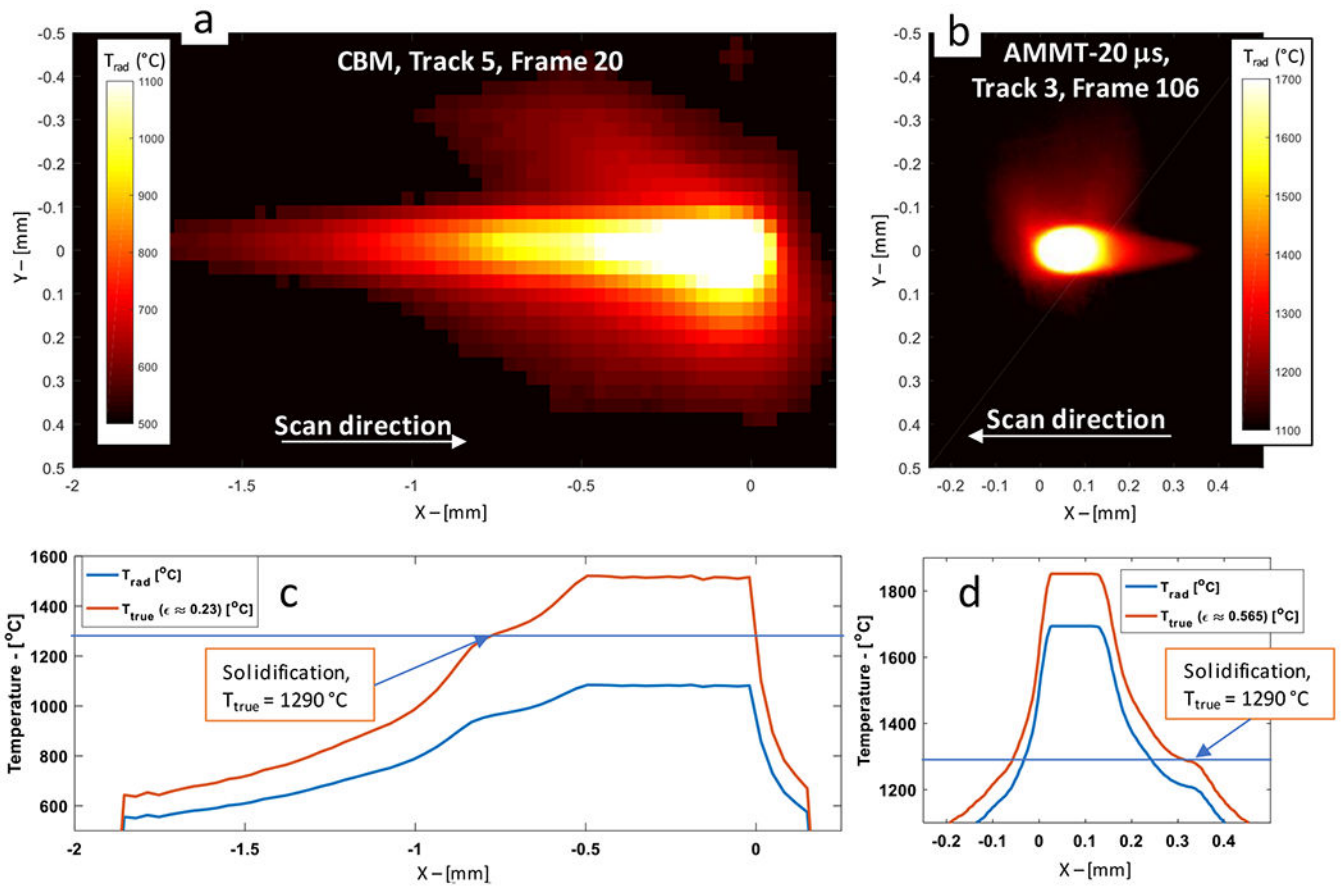


Figure 5:
 Example radiance temperature thermal video frames for **a** CBM, **b** AMMT-20 μ s. Example temperature profiles for, **c** CBM, **d** AMMT-20 μ s

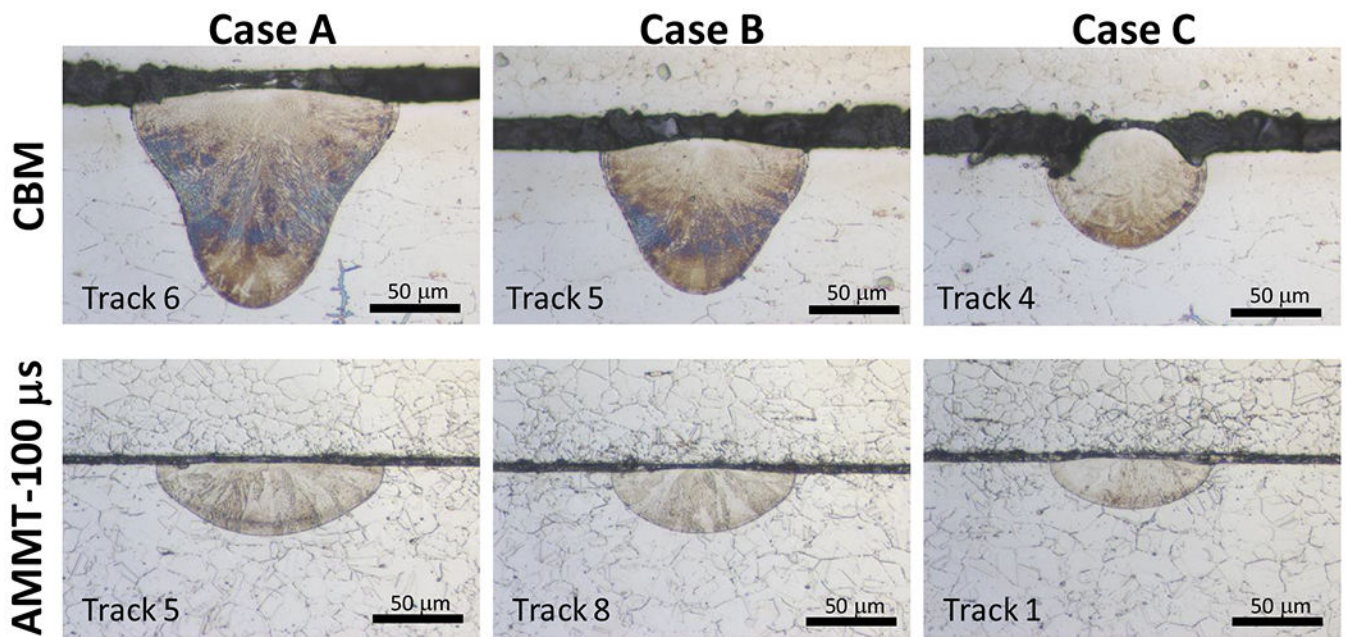


Figure 6:
Example brightfield, 50x, Z-stack melt pool cross-section on the CBM and AMMT-100 μs representing Cases A, B and C. Original images are 263 μm X 176 μm, and 0.062 μm per pixel.

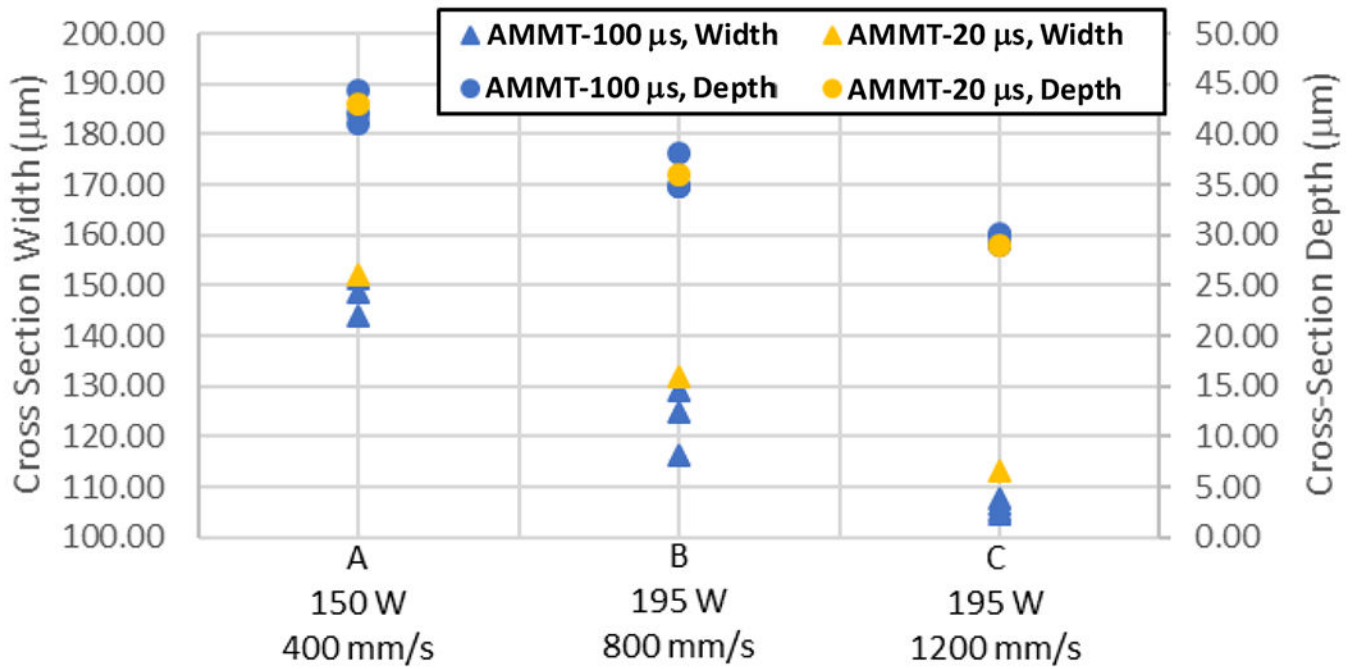


Figure 7: Comparison of tracks made on the AMMT at different thermal camera integration times (20 μs and 100 μs). Similar results indicate the scan tracks were made under similar conditions (specifically, laser power and laser spot size).

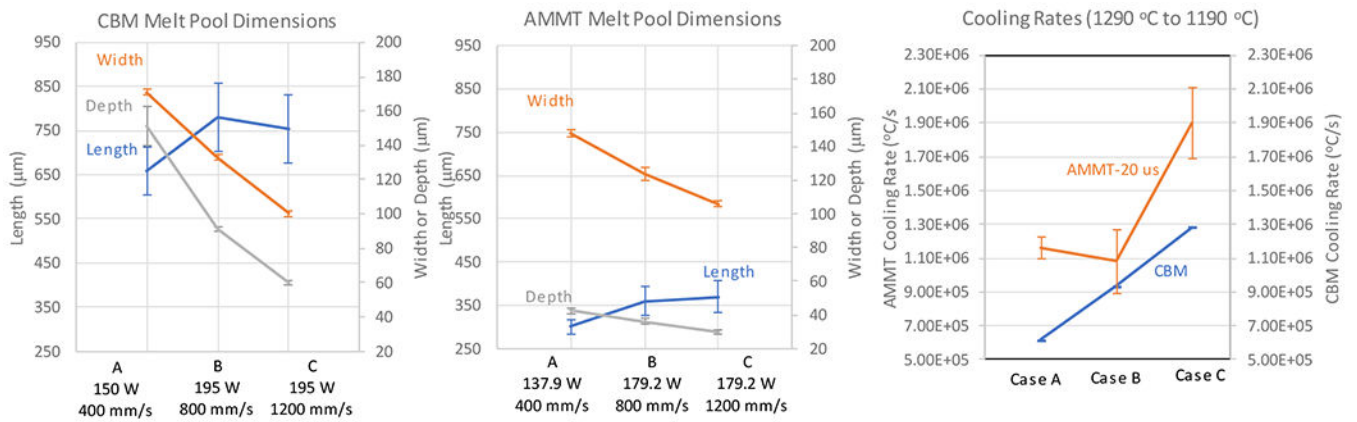


Figure 8: Compiled summary results for melt pool geometry measurements on CBM and AMMT. Note that laser spot size was different for CBM and AMMT. Error bars indicate $\pm 1\sigma$ of the standard uncertainty of the mean, u_{mean} . A complete uncertainty analysis is provided in Section 4.

Table 1:

Machine parameters for the CBM and AMMT systems.

	CBM	AMMT
Laser spot size	D4 σ diameter = 100 μm FWHM = 59 μm	D4 σ diameter = 170 μm FWHM = 100 μm
Inert gas	Nitrogen	Argon
Oxygen level	$\approx 0.5\%$	$< 0.08\%$

Table 2:

Infrared thermography specifications for the CBM and AMMT systems.

	CBM	AMMT
Imager Type	Cooled, Extended Range Indium Antimonide (InSb)	High Speed Si-based Complimentary Metal Oxide Semiconductor (CMOS)
Lens Type	50 mm short-wave infrared (SWIR) lens on 12.5 mm extension.	Long distance microscope (visible spectrum) with attached mirror.
Optical Filter Bandwidth	1350 nm to 1600 nm	850 nm \pm 20 nm
Integration Time	40 μ s	20 μ s or 98 μ s
Digital Dynamic Range	14-bit saturates at \approx 12 000 digital levels (DL)	12-bit (0 DL to 4095 DL)
Radiant Temperature Calibration Range (at integration time)	500 $^{\circ}$ C to 1050 $^{\circ}$ C (40 μ s)	1000 $^{\circ}$ C to 1650 $^{\circ}$ C (20 μ s) 900 $^{\circ}$ C to 1350 $^{\circ}$ C (100 μ s)
Frame rate	1800/s	10 000 /s
Window Size	360 pixels \times 128 pixels	1024 pixels \times 672 pixels
Field of View (FoV)	12.96 mm \times 6.82 mm	3.36 mm \times 2.20 mm
Detector Pixel Pitch	12 μ m	20 μ m
Magnification	0.33x	6x
Instantaneous FoV (iFoV) per pixel	36 μ m (horizontal)	3.28 μ m (horizontal)
Viewing Angle	46.3 $^{\circ}$ from surface normal (43.7 $^{\circ}$ from surface)	24 $^{\circ}$ from surface normal (66 $^{\circ}$ from surface)

Table 3: Test conditions and melt pool measurement results for CBM and AMMT cases A,B, and C used for AM-Bench reference values.

Machine	Track #	Case	Power (W)	Speed (mm/s)	Laser Spot Diameter (μm)	# Video Frames	Int. Time (μs)	Effective Emittance		Cooling rate 1290 °C to 1190 °C (°C/s)		Cooling rate from 1290 °C to 1000 °C (°C/s)		Cross Section (μm)		Cross Section (μm)	
								Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
CBM	3	A	150	400	100	53	40	0.225	0.011	6.21E+05	7.19E+04	5.59E+05	4.46E+04	173.82	0.35	154.40	0.58
CBM	6	A	150	400	100	27	40	0.237	0.010	6.58E+05	9.41E+04	5.84E+05	5.96E+04	168.94	0.21	129.77	0.80
CBM	9	A	150	400	100	49	40	0.232	0.009	5.81E+05	4.38E+04	5.35E+05	2.55E+04	170.24	2.25	170.41	2.41
CBM	2	B	195	800	100	25	40	0.205	0.012	9.00E+05	1.65E+05	9.33E+05	9.24E+04	134.96	0.20	89.50	0.17
CBM	5	B	195	800	100	25	40	0.230	0.013	9.51E+05	1.44E+05	9.57E+05	8.16E+04	132.16	0.34	91.13	0.38
CBM	8	B	195	800	100	9	40	0.229	0.009	9.53E+05	1.11E+05	9.57E+05	7.74E+04	131.94	0.08	93.13	0.35
CBM	1	C	195	1200	100	11	40	0.169	0.020	1.31E+06	4.71E+05	1.38E+06	3.21E+05	97.82	0.20	59.61	0.39
CBM	4	C	195	1200	100	13	40	0.204	0.015	1.17E+06	3.71E+05	1.43E+06	2.46E+05	102.04	0.46	60.75	0.52
CBM	7	C	195	1200	100	15	40	0.220	0.018	1.40E+06	3.71E+05	1.54E+06	3.23E+05	100.73	0.16	60.03	0.35
CBM	10	C	195	1200	100	13	40	0.194	0.024	1.25E+06	3.13E+05	1.34E+06	2.42E+05	99.68	0.38	60.33	0.35
AMMT	5	A	137.9	400	170	51	100	0.673	0.034	1.20E+07 ^c	5.66E+05	<i>b</i>	<i>b</i>	144.00	0.32	44.40	0.12
AMMT	6	A	137.9	400	170	55	100	0.667	0.044	1.45E+07 ^c	4.77E+06	<i>b</i>	<i>b</i>	151.30	0.07	41.00	0.19
AMMT	7	A	137.9	400	170	55	100	0.679	0.060	1.21E+07 ^c	7.15E+05	<i>b</i>	<i>b</i>	148.50	0.36	42.10	0.11
AMMT	8	B	179.2	800	170	27	100	0.575	0.065	1.97E+07 ^c	1.27E+06	<i>b</i>	<i>b</i>	116.40	0.19	38.20	0.18
AMMT	9	B	179.2	800	170	31	100	0.581	0.062	1.98E+07 ^c	1.82E+06	<i>b</i>	<i>b</i>	129.10	0.14	34.80	0.04

Machine	Track #	Case	Power (W)	Speed (mm/s)	Laser Spot Diameter (μm)	# Video Frames	Int. Time (μs)	Effective Emittance		Melt Pool Length (μm)		Cooling rate 1290 °C to 1190 °C (°C/s)		Cooling rate from 1290 °C to 1000 °C (°C/s)		Cross Section (μm)			
								Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
AMMT	10	B	179.2	800	170	31	100	0.583	0.032	415	10	1.90E+07 ^c	1.85E+06	<i>b</i>	<i>b</i>	124.90	0.20	34.90	0.15
AMMT	1	C	179.2	1200	170	21	100	0.519	<i>a</i>	444	13	2.90E+07 ^c	5.33E+06	<i>b</i>	<i>b</i>	104.40	0.19	29.00	0.08
AMMT	2	C	179.2	1200	170	22	100	0.519	<i>a</i>	435	16	2.78E+07 ^c	4.88E+06	<i>b</i>	<i>b</i>	107.70	0.19	29.20	0.04
AMMT	3	C	179.2	1200	170	22	100	0.519	<i>a</i>	445	14	2.76E+07 ^c	5.80E+06	<i>b</i>	<i>b</i>	106.60	0.07	30.00	0.00
AMMT	4	C	179.2	1200	170	16	100	0.519	<i>a</i>	455	11	2.83E+07 ^c	4.46E+06	<i>b</i>	<i>b</i>	105.40	0.22	30.20	0.15
AMMT	2	A	137.9	400	170	19	20	0.600	0.016	300	12	1.16E+06 ^c	2.68E+05	<i>b</i>	<i>b</i>	152.00	2.00	43.00	0.90
AMMT	3	B	179.2	800	170	10	20	0.565	0.017	359	20	1.08E+06 ^c	5.88E+05	<i>b</i>	<i>b</i>	132.00	2.00	36.00	0.90
AMMT	1	C	179.2	1200	170	7	20	0.519	0.031	370	10	1.90E+06 ^c	5.52E+05	<i>b</i>	<i>b</i>	113.00	1.00	29.00	0.90

^a Solidus could not be detected on these samples. An assumed emittance of 0.519 based on the equivalent AMMT-20 μs measurement is used.

^b Due to limited calibration range of camera on AMMT, temperatures below 1100 °C were too erroneous to use in cooling rate measurements

^c Due to limited calibration range for AMMT-20 μs, and motion blur for AMMT-100 μs, cooling rate values should not be used, but are printed here for reference.

Table 4:

Compiled summary results for melt pool geometry and cooling rate measurements on CBM and AMMT. Note that only length and cooling rate measurements from the AMMT-20 μs measurements are included (not AMMT-100 μs). Width and depth measurements incorporate both AMMT-100 μs and AMMT-20 μs measurements.

	Cooling rate (1290 °C to 1190 °C)			Class Length			Class Width			Class Depth		
	Mean	N	U_{mean}	Mean	N	U_{mean}	Mean	N	U_{mean}	Mean	N	U_{mean}
	°C/s		°C/s	μm		μm	μm		μm	μm		μm
AMMT-A	1.16E+06	19	6.15E+04	300	19	0.50	148	9	1.07	42	9	0.49
AMMT-B	1.08E+06	10	1.86E+05	359	10	3.69	123	9	1.87	36	9	0.56
AMMT-C	1.90E+06	7	2.09E+05	370	7	7.72	106	12	0.37	30	12	0.16
CBM-A	6.20E+05	129	6.16E+03	659	129	0.47	171	9	0.82	151	9	5.75
CBM-B	9.35E+05	59	1.82E+04	780	59	0.50	133	9	0.50	91	9	0.52
CBM-C	1.28E+06	52	5.29E+04	754	52	0.68	100	12	0.48	60	12	0.16

Table 5:

Uncertainty budget for melt pool length measurements.

	Components of Standard Uncertainty (Melt Pool Length)										Prob. Dist.	Analysis Type			
	AMMT-100 μs					AMMT-20 μs							CBM		
	Unit	Case A	Case B	Case C	Case A	Case B	Case C	Case A	Case B	Case C			Case A	Case B	Case C
Calibration, $u_1(\text{T})$	[°C]	0.34	0.34	0.34	2.2	2.2	2.2	8.1	8.1	8.1	8.1	8.1	8.1	Norm.	A
Signal Digitization, $u_2(\text{S})$	[DL]	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	Unif.	A
Signal Upsampling, $u_3(\text{S})$	[DL]	4.62	4.62	4.62	4.62	4.62	4.62							Unif.	A
Camera Signal noise, $u_4(\text{S})$	[DL]	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	Unif.	A
Spatial Pixelation, $u_5(\text{x})$	[μm]	1.89	1.89	1.89	1.89	1.89	1.89	1.89	1.89	1.89	20.78	20.78	20.78	Unif.	A
Motion Blur, $u_6(\text{x})$	[μm]	23	46	69	8	16	24	16	32	48	32	48	48	Unif.	B
Optical Blur, $u_7(\text{x})$	[μm]	2.90	2.90	2.90	2.90	2.90	2.90	28.80	28.80	28.80	28.80	28.80	28.80	Norm.	B
Standard Uncertainty of the Mean, $u_8(\text{x})$	[μm]	0.68	1.45	1.50	0.50	3.69	7.72	0.47	0.50	0.68	0.50	0.68	0.68	Norm.	A
Unit Conversion Factors															
Scan speed	[$\mu\text{m}/\text{s}$]	4.00E+05	8.00E+05	1.20E+06	4.00E+05	8.00E+05	1.20E+06	4.00E+05	8.00E+05	1.20E+06	4.00E+05	8.00E+05	1.20E+06		
$\frac{\partial T(x, freeze)}{\partial x}$	[°C / μm]	2.13	1.71	2.46	1.68	1.55	1.75	0.52	0.46	0.50	0.46	0.50	0.50		
$\frac{\partial F^{-1}(S, freeze)}{\partial S}$	[°C / DL]	0.0722	0.0722	0.0722	0.3623	0.3623	0.3623	0.0268	0.0268	0.0268	0.0268	0.0268	0.0268		
Components Standard Uncertainty, Converted into Length Units [μm]															
Calibration, $u_1(\text{x})$	[μm]	0.16	0.20	0.14	1.31	1.42	1.26	15.70	17.49	16.33	17.49	16.33	16.33		
Signal Digitization, $u_2(\text{x})$	[μm]	0.02	0.02	0.02	0.35	0.13	0.12	0.03	0.03	0.03	0.03	0.03	0.03		
Signal Upsampling, $u_3(\text{x})$	[μm]	0.16	0.19	0.14											
Camera Signal noise, $u_4(\text{x})$	[μm]	0.02	0.02	0.02	0.12	0.13	0.12	0.03	0.03	0.03	0.03	0.03	0.03		
Spatial Pixelation, $u_5(\text{x})$	[μm]	1.89	1.89	1.89	1.89	1.89	1.89	20.78	20.78	20.78	20.78	20.78	20.78		
Motion Blur, $u_6(\text{x})$	[μm]	13	27	40	5	9	14	9	18	28	18	28	28		
Optical Blur, $u_7(\text{x})$	[μm]	2.904	2.904	2.904	2.904	2.904	2.904	28.8	28.8	28.8	28.8	28.8	28.8		

	Components of Standard Uncertainty (Melt Pool Length)										Prob. Dist.	Analysis Type
	AMMT-100 μs			AMMT-20 μs			CBM					
	Case A	Case B	Case C	Case A	Case B	Case C	Case A	Case B	Case C			
Standard Uncertainty of the Mean, $u_8(x)$	[μm]	0.68	1.45	1.50	0.50	3.69	7.72	0.47	0.50	0.68		
Combined Standard Uncertainty, $u_c(x)$	[μm]	13.80	26.93	40.18	5.95	10.63	16.29	39.92	43.69	47.92		
Expanded Uncertainty, U (k=2)	[μm]	27.59	53.86	80.36	11.91	21.26	32.57	79.84	87.39	95.85		

Table 6:

Uncertainty budget for the melt pool width for the AMMT and CBM cases compiled in Table 4.

Components of Standard Uncertainty (Melt Pool Width)									
	Unit	AMMT			CBM			Prob. Dist.	Analysis Type
		Case A	Case B	Case C	Case A	Case B	Case C		
Optical Resolution	[μm]	0.50	0.50	0.50	0.50	0.50	0.50	Norm.	B
Variability Along Track	[μm]	2.96	2.46	2.12	3.42	2.66	2.00	Norm.	B
User Selection	[μm]	0.37	0.37	0.37	0.37	0.37	0.37	Norm.	A
Standard Uncertainty of the Mean	[μm]	1.07	1.87	0.37	0.82	0.50	0.48	Norm.	A
Combined Uncertainties									
Combined Standard Uncertainty, u_c	[μm]	3.21	3.15	2.24	3.57	2.78	2.15		
Expanded Uncertainty, U (k=2)	[μm]	6.42	6.30	4.48	7.14	5.56	4.30		

Table 7:

Uncertainty budget for the melt pool depth for the AMMT and CBM cases compiled in Table 4.

Components of Standard Uncertainty (Melt Pool Depth)									
	Unit	AMMT			CBM			Prob. Dist.	Analysis Type
		Case A	Case B	Case C	Case A	Case B	Case C		
Optical Resolution	[μm]	0.50	0.50	0.50	0.50	0.50	0.50	Norm.	B
Variability Along Track	[μm]	2.10	1.80	1.50	7.55	4.55	3.00	Norm.	B
User Selection	[μm]	0.37	0.37	0.37	0.37	0.37	0.37	Norm.	A
Standard Uncertainty of the Mean	[μm]	0.49	0.56	0.16	5.75	0.52	0.16	Norm.	A
Combined Uncertainties									
Combined Standard Uncertainty, u_c	[μm]	2.25	1.99	1.63	9.51	4.62	3.07		
Expanded Uncertainty, U (k=2)	[μm]	4.49	3.97	3.26	19.02	9.24	6.14		