NIST Advanced Manufacturing Series
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Thermography of Single Line Scans Performed on the Commercial Powder Bed Fusion Machine for the Additive Manufacturing Benchmark Test Series (AM-Bench 2018)

For the dataset: https://doi.org/10.18434/M31931

Jared C. Heigel

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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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Abstract

This document provides details on the files available in the dataset “In Situ Thermography of Single Scan Tracks Performed on Nickel Super Alloy 625 for the 2018 Additive Manufacturing Benchmark Test Series (AM-Bench 2018): Powder Bed Fusion Commercial Build Machine” available at https://doi.org/10.18434/M31935. These measurements are performed as part of the Additive Manufacturing Benchmark Test Series (AMBench) supporting the melt pool geometry (length) and cooling rate challenges (CHAL-AMB2018-02-MP-Length and CHAL-AMB2018-02-CR). The following sections provide details on the experiments and data files.

Keywords

Additive manufacturing; benchmark tests; powder bed fusion; nickel super alloy 625; IN625; temperature measurement; melt pool length; cooling rate.

Table of Contents

List of Tables

List of Figures

1. Summary

This document provides details on the files available in the dataset "In Situ Thermography of Single Scan Tracks Performed on Nickel Super Alloy 625 for the 2018 Additive Manufacturing Benchmark Test Series (AM-Bench 2018): Powder Bed Fusion Commercial Build Machine" available at https://doi.org/10.18434/M31931. These measurements are performed as part of the Additive Manufacturing Benchmark Test Series (AMBench) supporting the melt pool geometry (length) and cooling rate challenges (CHAL-AMB2018-02-MP-Length and CHAL-AMB2018-02-CR). The following sections provide details on the experiments and data files.

2. Data Specifications

NIST Operating Unit(s)	Engineering Laboratory,
Format	There are several types of data formats in this dataset. Please refer to Sec. 4 for a description of all included data files.
Instruments	An EOSint M270D[1] laser powder bed fusion system was used to create the single track scans. An IRCameras model IRC 912 infrared camera was used to perform the thermographic measurements of the scan tracks. Details are provided in Sec. 3.
Spatial or Temporal Elements	These measurements were performed on February 22, 2018
Data Dictionary	N/A
Accessibility	All data is publicly available at https://doi.org/10.18434/M31931
License	https://www.nist.gov/director/licensing

3. Experiment Method

Individual laser scan tracks are made on a bare nickel-based superalloy 625 (IN625) metal surface. Three different power and speed combinations (Cases A, B, and C) are performed with multiple replications of each. In-situ measurements of the melt pool length and the cooling rate of the solidifying material are performed. There are 10 experiments presented in this data set, as shown in **Table 1** and in **Fig. 1**. These scans are performed in a commercial EOS M270D laser powder bed fusion machine with a custom sample holder mounted on the build platform [1] and a custom door [2] to allow a camera to observe the region of interest in the build area. The camera records data at 1800 frames per second and an integration time of 40 µs. The field of view (FOV) of the camera is approximately 12 mm long and 6 mm wide. The field of view of the camera is centered at the machine coordinates of X = 135.5 mm, Y = 95.0 mm. The IN625 substrate is placed on the sample holder. Then individual laser scans are executed on the surface. Infrared emissions from the surface of the sample are measured using an IRC912 short wave infrared camera. Details regarding the measurements setup and data analysis are provided in [1, 3, 4]. Experiment details can be found at https://www.nist.gov/ambench/amb2018-02-description, with the following exceptions:

[1] Certain commercial equipment, instruments, software, or materials, commercial or non-commercial, are identified in this paper in order to specify the experimental procedure adequately. Such identification does not imply recommendation or endorsement of any product or service by NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

- Laser scans travel left to right, not right to left as originally indicated
- The substrate surface is prepared with 320 grit random orientation polishing. The original experimental plan called for a bead-blasted surface. However, bead blasted media was embedded on the surface and scan track and measurement was adversely affected.

Table 1. - List of the experiments contained in this dataset and their case number according to https://www.nist.gov/ambench/amb2018-02-description. Test names indicate the date, surface preparation, and scan line number.

Test Name	Case	Programmed laser power (W)	Programmed speed (mm/s)
20180222_320grit_Line01	C	195	1200
20180222_320grit_Line02	B	195	800
20180222_320grit_Line03	A	150	400
20180222_320grit_Line04	C	195	1200
20180222_320grit_Line05	B	195	800
20180222_320grit_Line06	A	150	400
20180222_320grit_Line07	C	195	1200
20180222_320grit_Line08	B	195	800
20180222_320grit_Line09	A	150	400
20180222_320grit_Line10	C	195	1200

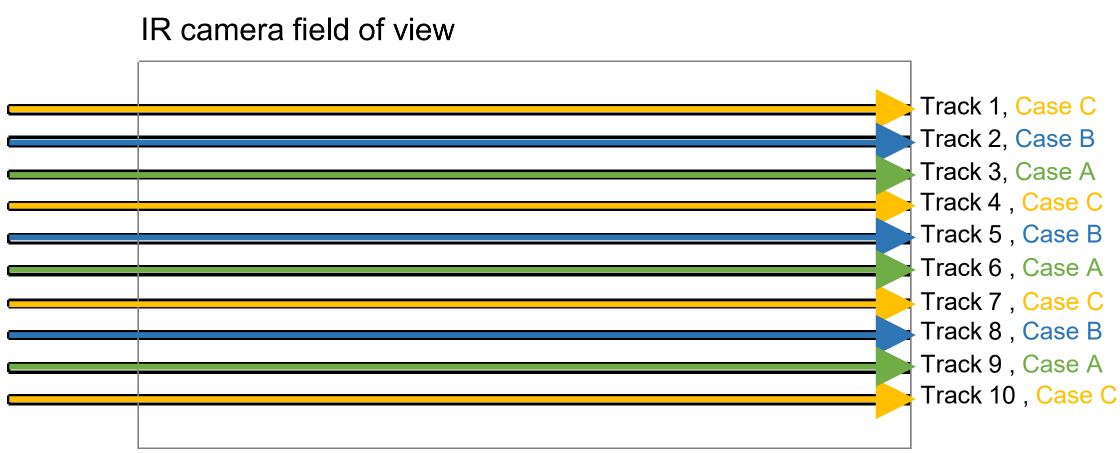

Fig. 1 - Arrangement of the 10 scan tracks within the field of view of the IR camera. Note that this is slightly different than was originally proposed https://www.nist.gov/ambench/amb2018-02-description.

4. Data Files

The dataset contains the following files:

- DataSetOverivew-AMBench2018-Callenge02-CBM.docx
    - This dataset overview document.
- CHAL-AMB2018-02-MP&CR_Summary.xlsx
    - A summary and comparison of the melt pool length and cooling rate measurements.
    - Details provided in Section 4.1
- RadiantTemperatureVideos.zip
    - Videos of the radiant temperature measurements acquired during each test.

    - Details provided in Section 4.2
- TemperatureProfilePlots.zip
    - Plots containing the temperature profiles from each frame of each test.
    - Details provided in Section 4.3
- CHAL-AMB2018-02-DataSet.mat
    - A MATLAB data file containing structure arrays for each test. These structures contain the radiant temperature data, relevant test information, and measurements.
    - Details provided in Section 4.4
- NIST_DataSetPlot.m
    - MATLAB function to recreate the radiant temperature videos and the temperature profile plots. This code allows the audience to better understand the data structures contained in CHAL-AMB2018-02-DataSet.mat.
    - The function is commented to provide detail.
- RawCameraData.zip
    - Contains .img files from the IRC infrared camera.
    - .img files contain the raw measurement as well as metadata
    - Intended only as raw-data back-up

4.1. CHAL-AMB2018-02-MP&CR_Summary.xlsx (Test results summary in an Excel file)

This Excel workbook contains a sheet that summarizes the results from the analysis of each test presented in Figure 1. The spreadsheet contains results for each test, and calculates the average value and variation (±1 σ) for each case based on the results from each replication. **Fig. 2** presents the melt pool length and cooling rate measurements that are summarized in the workbook.

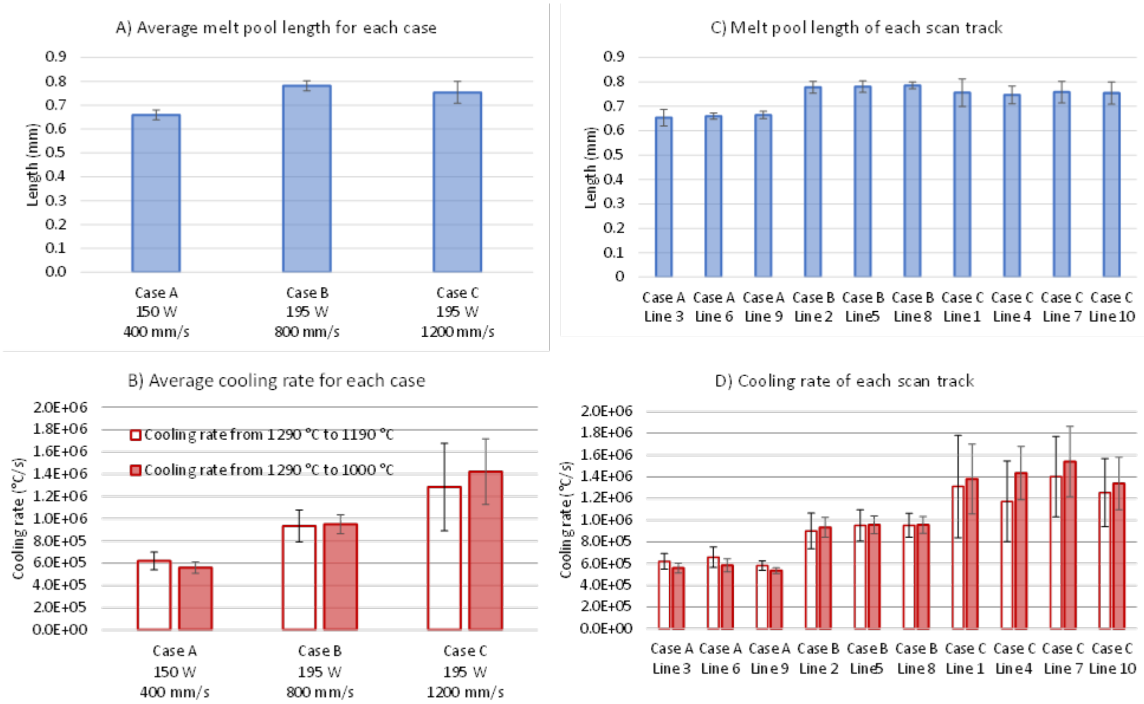

Fig. 2 - The average melt pool length and cooling rate results from each scan line and each case.

There are two tables in the spreadsheet: "Average values for each scan track" and "Average values for each case." Comments within the spreadsheet describe the data contained in each column.

4.2. RadiantTemperatureVideos.zip (Compressed folder with infrared videos)

This is a compressed folder containing videos created from the infrared videos. Each video is named according to the test name. The videos present the full field of view of the camera, but only display radiant temperatures from 550 °C to 1050 °C. The camera is sensitive to slightly lower temperatures, but noise becomes an issue. The camera saturates at temperatures between 1050 °C and 1100 °C, depending on each pixel. For simplicity, the upper temperature bounds are limited to 1050 °C.

Fig. 3 presents an example video frame from one of the tests. The test name, frame number, laser power, and scan speed are provided in the title. The X and Y axes indicate distances (in mm) from the lower left corner of the field of view. These values are based on the camera resolution, which is provided in the MATLAB structure in the CHAL-AMB2018-02-DataSet.mat data file. In each of these videos, the melt pool travels from left to right. A plume can often be seen above the melt pool. In this instance, the plume is rising at an angle and trails the melt pool. As stated earlier, only temperatures between 550 °C and 1050 °C are displayed. Any temperature below 550 °C is not measurable and is indicated by the gray background. These videos can be recreated in MATLAB using the NIST_DataSetPlot.m function.

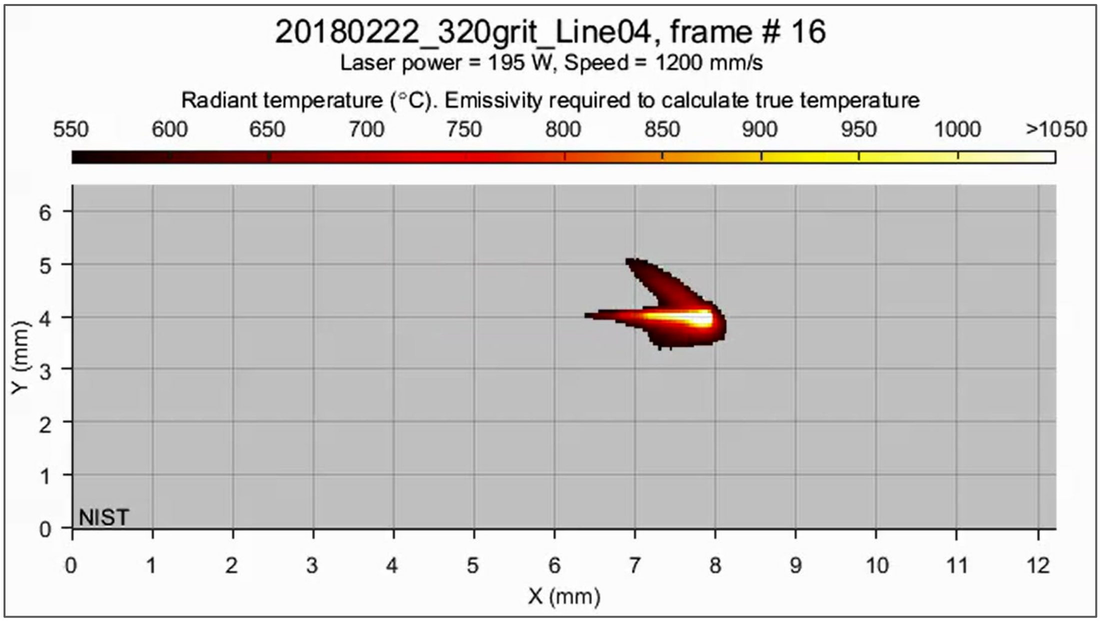

Fig. 3 - Example frame (FOV) from an infrared video provided in RadiantTemperatureVideos.zip.

4.3. TemperatureProfilePlots.zip (temperature profiles from each frame of each test)

This compressed file contains radiant temperature profiles extracted from every frame in each replication. These plots are provided as pictures in .jpg format and as MATLAB .fig files. The .fig files allow each radiant temperature profile to be investigated, since each plot is labeled as shown in **Fig. 4**. Only the radiant temperature is reported on the vertical axis, not the true temperature. The horizontal axis (X) represents the horizontal distance relative to the front of the melt pool. Temperature profiles are displayed as either red or blue curves, depending on the success of the algorithm in detecting the solidus. Frames in which the solidus was positively identified are presented in blue, whereas those frames without a positive solidus detection are in red. This does not mean that the solidus is not evident, since the red and blue curves in **Fig. 4** are consistent with one another. In addition to the temperature profiles, the average melt pool length and radiant temperature of the solidus for the test are indicated on the plot for comparison.

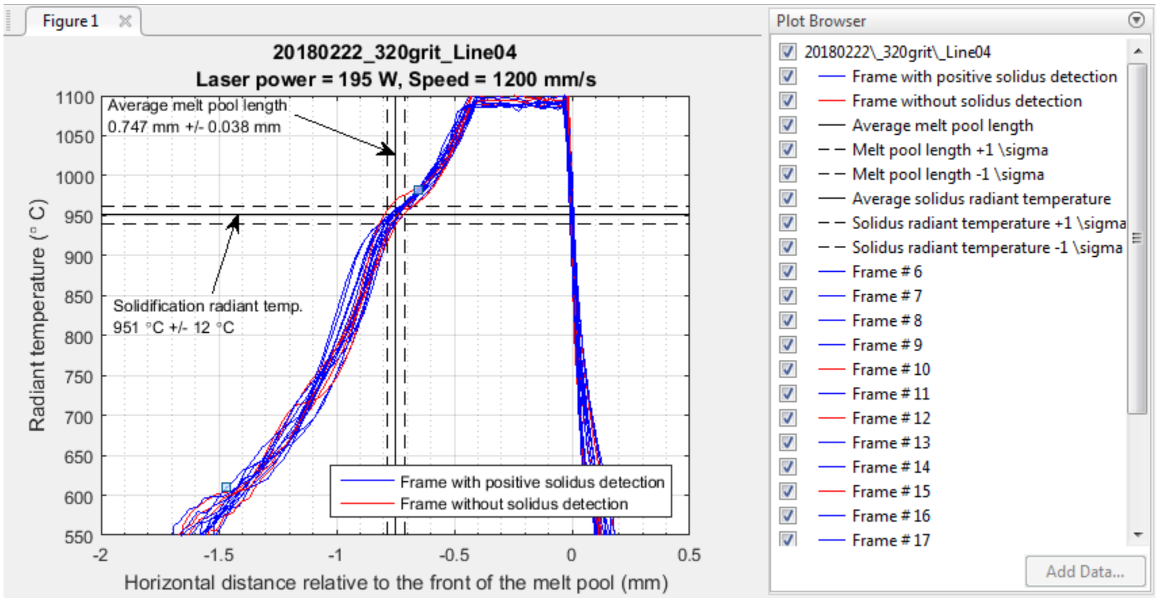

Fig. 4 - Demonstration of the radiant temperature profiles available in TemperatureProfilePlots.zip.

4.4. CHAL-AMB2018-02-DataSet.mat (MATLAB measurement and analysis results)

This MATLAB data file contains structure arrays for each test, named according to the scan line number. **Fig. 5** provides an example of the structures contained in the data file and the variables within each structure.

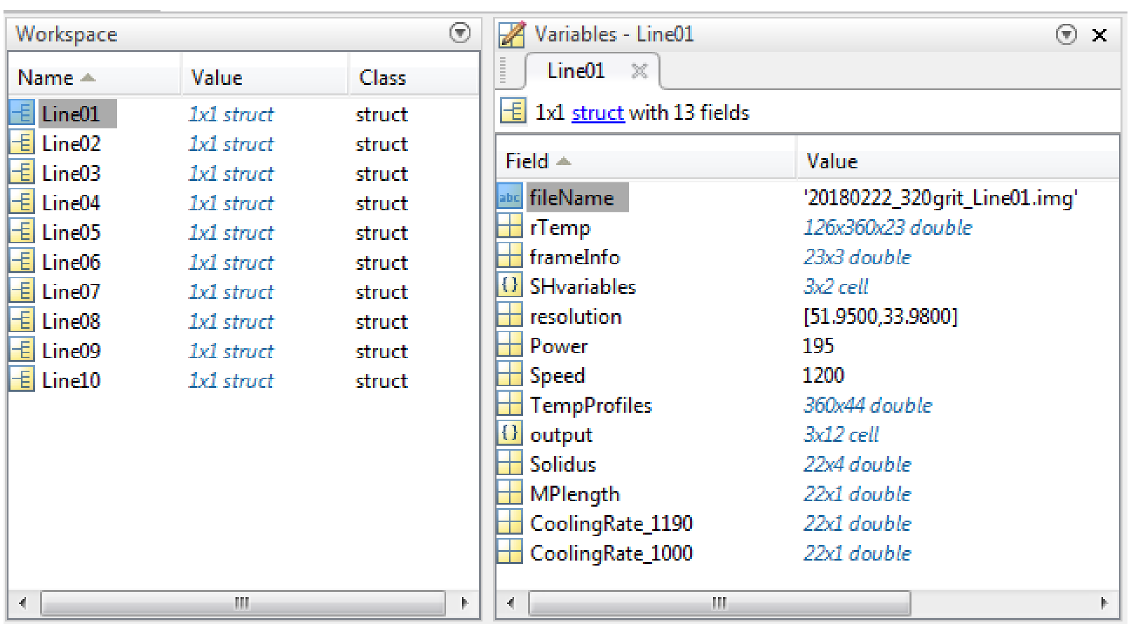

Fig. 5 - Example of the structures in the MATLAB data file and the variables within each structure.

Each structure contains the following:

- LineXX.filename
  - A text string providing the raw camera data file associated with the data.
- LineXX.rTemp
  - A 3-dimensional array containing the radiant temperature measured during the test. The raw camera file (.img) has many more frames than are provided in this array. The array is limited to the frames that acquired data while the substrate surface was at an elevated, measurable temperature.
  - Radiant temperature is calculated from the camera signal provided in the corresponding .img file and a black body calibration.
- LineXX.frameInfo
  - This is a 2-dimensional array containing information on every frame provided in the LineXX.rTemp array.
  - Column 1 provides the frame number out of the total number of frames in the .img file. For instance, if there are 3600 frames, but the laser scan occurred during frame 455 through 478, then the first column will reflect that. This is useful for correlating this data to the original frames in the .img file. These numbers increase from frame to frame, but do not indicate if frames are skipped during the acquisition.
  - Column 2 provides the frame counter according to the camera. This value indicates if frames are skipped. The number is quite large and does not consistently increase from one frame to the next, as the number occasionally resets. Consequently, it is not the best indication of a skipped frame.
  - Column 3 provides the time (in seconds) extracted from the internal camera timing. This value does not start at zero for the first frame. This is useful for determining if frames are skipped and for calculating the frame-to-frame cooling rate.
- LineXX.SHvariables
  - These are the $A_{\text{S-H}}$, $B_{\text{S-H}}$, and $C_{\text{S-H}}$ variables in the Sakuma-Hatori equation [4], which converts the camera signal to radiant temperature based on a black-body calibration:

$$T_{radiant} = \frac{c_2}{A_{S-H}\ln\left({}^{C_{S-H}}/_{S}+1\right)} - \frac{B_{S-H}}{A_{S-H}} \tag{1}$$

    where c_2 is the second radiation constant (14388 µm/K) and S is the camera signal.
- LineXX.resolution
  - This array provides the effective pixel size in µm per pixel.
  - The first value provides the pixel size in the vertical direction (Y), the second value provides it in the horizontal direction (X)
- LineXX.Power
  - The programmed laser power (in W) of the test
- LineXX.Speed

  - The programmed laser speed (in mm/s) of the test
- LineXX.TempProfiles
  - This is a 2-dimensional array that provides the temperature profile extracted from the centerline of the scan track for each frame and the corresponding distance from the front of the melt pool.
  - Since the scan tracks move in the horizontal direction, the centerline for each frame is determined by locating the row in LineXX.rTemp(:,:,frame#) with the maximum temperature profile trailing the melt pool. The row is fairly consistent during the test, but may drift up or down if the camera is slightly rotated relative to the scan direction.
  - Even numbered columns are the temperature profiles.
  - Odd numbered columns provide the relative distance to the front of the melt pool.
    - The relative distance is only provided for temperature profiles of frames in which the solidus was positively identified using an algorithm.
  - Stepping through the NIST_DataSetPlot.m function will provide clarity.
- LineXX.output
  - This contains the results from the analysis to determine the values presented in the “Average values for each scan track” table within the CHAL-AMB2018-02-MP&CR.xlsx Excel workbook. These values were copied directly from this variable and pasted into the Excel worksheet.
- LineXX.Solidus
  - A 2-dimensional array that provides data related to the detection of the solidification plateau
  - The radiant temperature of the detected solidus point, the corresponding camera signal correction factor that relates the assumed true temperature of the solidification of IN 625 (1290 °C) and the radiant temperature of the solidification plateau,
- LineXX.MPlength
  - This 1-dimensional array contains the melt pool length measured in each frame. Each value corresponds to a frame in the video, with the first value corresponding to the first frame.
  - The size of this variable is less than or equal to the number of frames in the movie. The analysis was only performed up to the last frame with a melt pool, therefore any additional frames in the video were not included.
  - If the solidus was undetectable by the algorithm, or the frame did not contain a melt pool, the reported length is zero.
  - The MATLAB function NIST_DataSetPlot.m demonstrates how to calculate the average melt pool length from this data.
- LineXX.CoolingRate_1190 and LineXX.CoolingRate_1000
  - These are 1-dimensional arrays containing the cooling rate (from a solidus temperature of 1290 °C to either 1190 °C or 1000 °C) measured in each frame. Each value corresponds to a frame in the video, with the first value corresponding to the first frame.Cooling rate is calculated using the following equation:

$$\frac{dT}{dt} = \frac{T_{high} - T_{\mathrm{low}}}{(x_{high} - x_{\mathrm{low}})/V} \quad (2)$$

where T_{high} is the higher temperature of interest (1290 °C), T_{low} is the lower temperature of interest (either 1190 °C or 1000 °C), x_{high} and x_{low} are the distances in mm of, T_{high} and T_{low}, respectively, from the front of the melt pool, and V is the laser velocity, in mm/s, of the laser.

- The size of this variable is less than or equal to the number of frames in the movie. The analysis was only performed up to the last frame in which a cooling rate could be measured.
- If the solidus was undetectable by the algorithm, or the frame did not contain a melt pool, the reported cooling rate is zero.
- The MATLAB function NIST_DataSetPlot.m demonstrates how to calculate the average cooling rates from this data.

5. Impact

This dataset is for the validation of process models for laser powder bed fusion. The melt pool length and cooling rates can be compared with predicted values from models. In addition to validating thermal models, the post process characterization of these scan tracks has been performed and is publicly available to validate track topography, melt pool shape, and microstructure.

References

[1] Heigel JC, Lane B (2018) Measurement of the melt pool length during single scan tracks in a commercial laser powder bed fusion process. *Journal of Manufacturing Science and Engineering* 140(5). https://doi.org/10.1115/1.4037571.

[2] Lane B, Moylan S, Whitenton EP, Ma L (2016) Thermographic measurements of the commercial laser powder bed fusion process at NIST. *Rapid Prototyping Journal* 22(5):778:787. https://doi.org/10.1108/RPJ-11-2015-0161.

[3] Heigel J, Lane B (2017) The effect of powder on cooling rate and melt pool length measurements using in situ thermographic techniques. *Proceedings of the 2017 Annual International SFF Symposium*, pp 1340-1348.

[4] Lane B, Whitenton EP (2015) Calibration and measurement procedures for a high magnification thermal camera. *NIST Interagency/Internal Report (NISTIR) – 8098*. http://dx.doi.org/10.6028/NIST.IR.8098.