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Melt-Pool Temperature and Size Measurement During Direct Laser Sintering

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August 7, 2017

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OAK RIDGE NATIONAL LABORATORY
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Materials Science and Technology
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ABSTRACT

ORNL worked with Stratonics to integrate the ThermaViz system into the Renishaw Direct laser Sintering (DLS) system in order to demonstrate its ability to measure melt pool size, shape and temperature.

1. MELT-POOL TEMPERATURE AND SIZE MEASUREMENT DURING DIRECT LASER SINTERING

This phase 1 technical collaboration project (MDF-TC-2016-095) was begun on July 20, 2016 and was completed on July 19, 2017. The collaboration partner Stratonics Inc. is a small business.

1.1 BACKGROUND

Stratonics Inc., is a small business that manufactures the ThermaViz system, which includes a high-speed 2-color camera and the requisite software needed to control, calibrate, and analyze the images. This project demonstrates the ability of this system to be integrated into the Renishaw Direct Laser Sintering system and characterize the melt pool size and temperature. The goal of this project was to use the ThermaViz system to measure melt pool size, shape and temperature.

1.2 TECHNICAL RESULTS

Additive manufacturing has demonstrated the ability to fabricate complex geometries and components not possible with conventional casting and machining. In many cases, industry has demonstrated the ability to fabricate complex geometries with improved efficiency and performance. However, qualification and certification of processes is challenging, leaving companies to focus on certification of material though design allowable based approaches. This significantly reduces the business case for additive manufacturing. Yet, real time monitoring of the melt pool can be used to detect the development of flaws, such as porosity or un-sintered powder and aid in the certification process. Characteristics of the melt pool in the Direct Laser Sintering (DLS) process is also of great interest to modelers who are developing simulation models needed to improve and perfect the DLS process. Such models could provide a means to rapidly develop the optimum processing parameters for new alloy powders and optimize processing parameters for specific part geometries. Stratonics' ThermaViz system was integrated into the Renishaw DLS system in order to demonstrate its ability to measure melt pool size, shape and temperature.

A test small sample was designed by ORNL staff in order to test the ThermaViz's ability to characterize the melt pool. The size of the part was selected to optimize the field-of-view (FOV) of the ThermaViz camera and its frame rate. The smaller the FOV, the faster the frame rate. Since the DLS process is extremely fast, the part size was chosen to have maximum dimensions 15 mm wide by 5 mm high (Figure 1).

1.2.1 Build Geometry

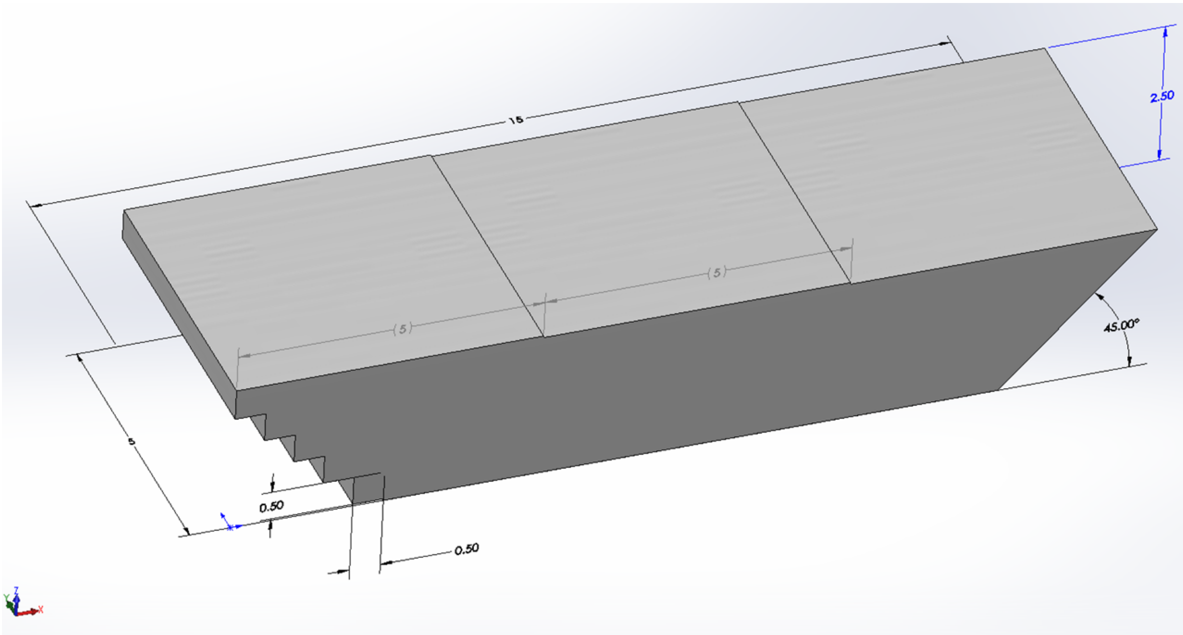

Figure 1: Part geometry

1.2.2 Layers Analyzed

Two layers were selected for this report. The first layer, Layer 50 is a regular layer as shown in Figure 2 and Layer 51 also includes the "downskin" of a stair step as seen in Figure 3.

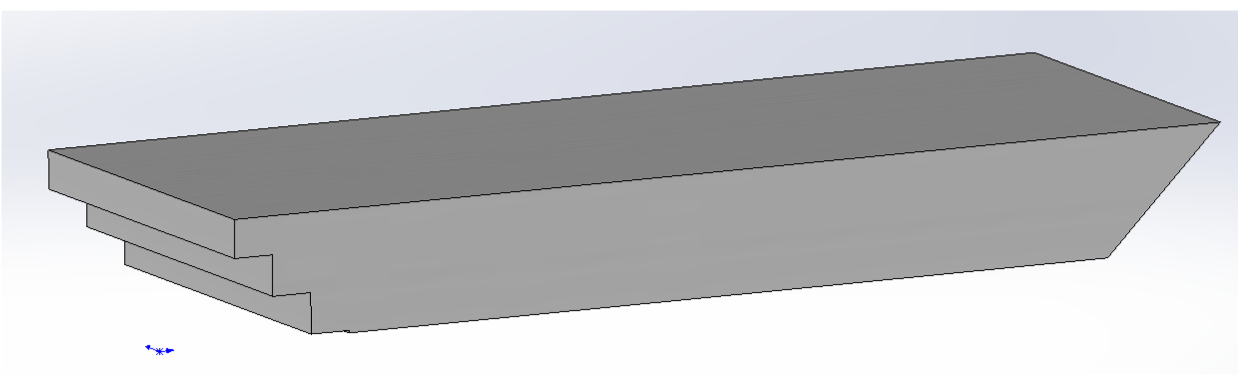

Figure 2: Part Geometry at layer 50

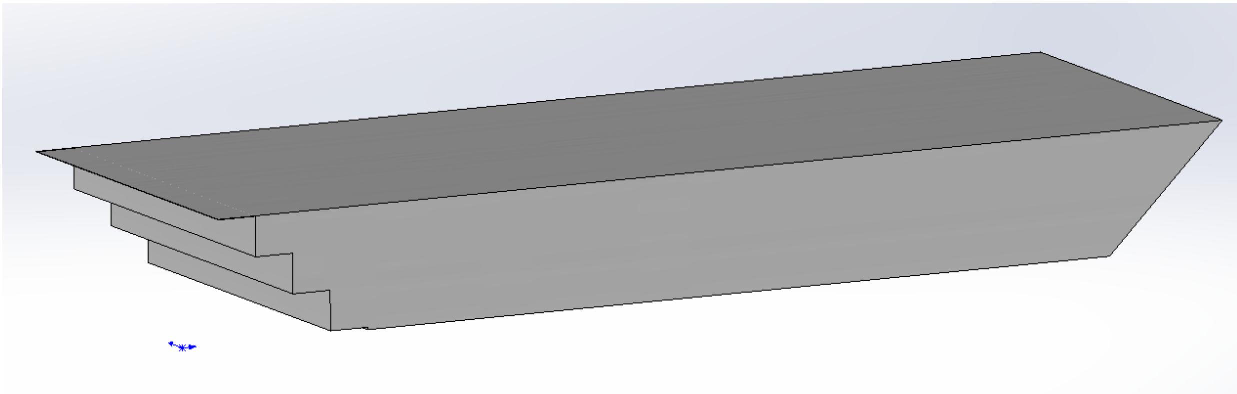

Figure 3: Part geometry at layer 51 showing the added step that is processed with the downskin parameters

1.2.3 Processing Parameters

Each layer of the build can have up to seven different sets of processing parameters (Runs) as shown in Table 1. Each layer was 30µm thick.

Table 1. The Renishaw processing parameters used for test samples.

	Run #	Power (W)	Layer Thickness (µm)	Hatch Space (µm)	Point Spacing (µm)	Exposure Time (µs)	Veff (m/s)	Duty Cycle (%)	Lin. Heat Input (J/m)	Vol. Heat Input (KJ/mm^3)	Build Rate (cc/hr)
Volume Hatch	1	200	30	85	85	100	0.714	84.0	235	92	6.6
Inner Border	2	200	30		40	90	0.400	90.0	450		0.0
Outer Border	3	120	30		20	100	0.189	94.3	600		0.0
Downskin Volume Hatch	4	110	30	60	40	80	0.444	88.9	220	122	2.9
Downskin Inner Border	5	110	30		40	80	0.444	88.9	220		0.0
Downskin Outer Border	6	110	30		40	80	0.444	88.9	220		0.0
Upskin Volume Hatch	7	160	30	100	50	110	0.410	90.2	352	117	4.4

1.2.4 Scan Strategy

For the layer 50 scan strategy shown in Figure 4, the start point is the lower left corner and scans the lower stripe. The laser then jumps to stripe boundary at left end scans the top stripe. The contour is scanned next with the inner border starting at upper right corner and traveling clockwise. The outer border follows with last melt ending in upper right corner.

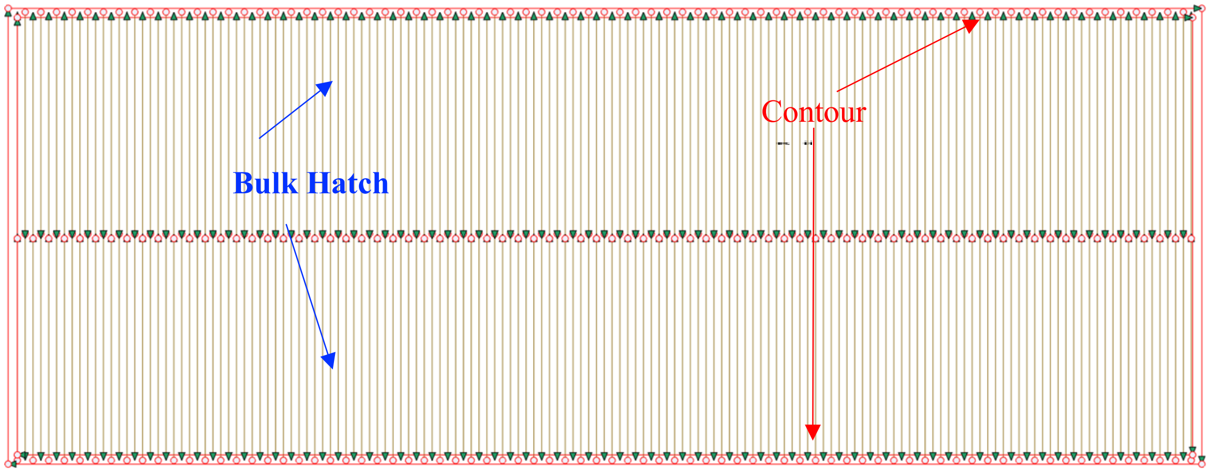

Figure 4: Scan strategy for layer 50

For the Layer 51 scan strategy shown in Figure 5, the start point is the upper left corner of previously melted area (within the bulk hatch) working left to right from top of screen to bottom in a 2mm wide stripe. The laser then comes back to top edge left and scans two 5 mm wide stripes. The bulk hatch region is finished. With a 1mm wide stripe on the right end. The laser then jumps to the upper left corner just off the edge of previous melt and runs from the top edge at a slight downward angle filling in from right to left using the downskin parameters. The inner border then starts the lower right corner and runs clockwise with the inner border first and the outer boarder second.

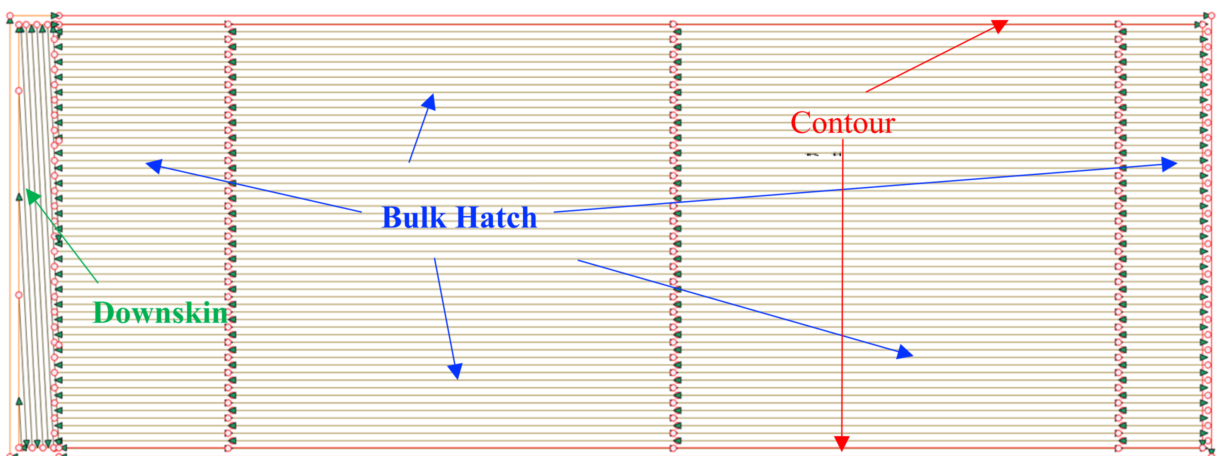

Figure 5: Scan strategy for layer 51

1.2.5 Data Analysis Procedure:

The collected data is loaded into the ThermaViz software where each frame is represented as a separate.viz file. (Currently, an error is present when more than 2000 frames are attempted to be loaded.) Once the data is loaded, the background subtraction must be performed, and the calibrations must be checked. The background is subtracted using an image when the laser is not firing in the system.

1.2.6 Background Image Subtraction

The image for background subtraction was taken from frame before the laser fires after the recoating time between the first two layers. However, after further analysis, there is some variation in the background temperature, and the noise in the background shows temperatures that are above the melting temperature. Further investigation into this issue should be completed. This issue may be causing the large melt pool sizes reported below. For example, see the temperature contours shown in Figure 6. The temperature range is set to begin at 1355 ºC, which is the melting temperature of Hastelloy X. However, much of the background is showing above this temperature.

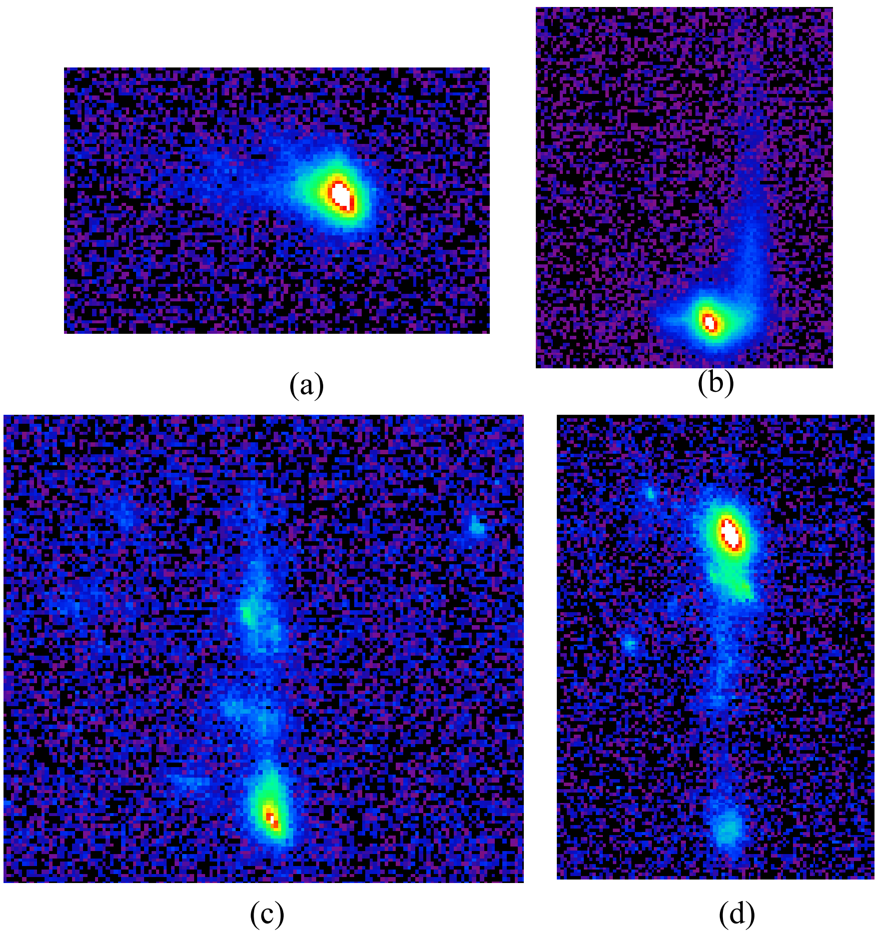

Figure 6: Temperature contours for (a) bulk, (b) contour rounding a corner, (c) downskin hatch and (d) downskin contour

1.2.7 Data Extraction

Once the calibrations are set, the powderbed analysis tool is used for data analysis. This tool allows for the output of an excel file with the temperature data and some calculated results. The inputs are analysis ROI size (default-101), scale factor (32.018 µm/pixel), minimum radiance threshold (10), and maximum radiance threshold (default-4094). The user can also define thresholds of interest at specified temperature contours. For this analysis, the melting temperature is the interest region, so the temperature of interest is chosen at the liquidus temperature (1355 ºC) for Hastelloy X.

The frames are split into three sections showing the bulk hatching (blue), contours (red) and the stair step/downskin (green) portion. A representation of melt pools seen in the various regions are shown in 6.

1.2.8 Results

Once the data is extracted from the ThermaViz software into a csv file, the rest of the analysis must be coded by the user in a software of choice for further analysis and plotting. Matlab was used in this analysis. The csv output contains many other values, but those discussed in this document are related to the temperature contour of interest: melt pool area, melt pool length, and melt pool width and the average and peak temperatures within the melt pool.

1.2.9 Melt Pool Dimensions

The melt pool area, width and length are calculated by the ThermaViz software and output in a csv file. These results for Layers 50 and 51 are plotted using Matlab in Figure 7. Results show that the melt pool area is largest for the bulk hatching and smallest for the contours. The downskin parameter gives the largest lengths.

An interesting oscillation is seen in the bulk scanning for the melt pool area for layer 51. The hatching is orientated in a way that there is a short stripe, followed by two long stripes, and another short stripe. It appears that the oscillation follows this pattern.

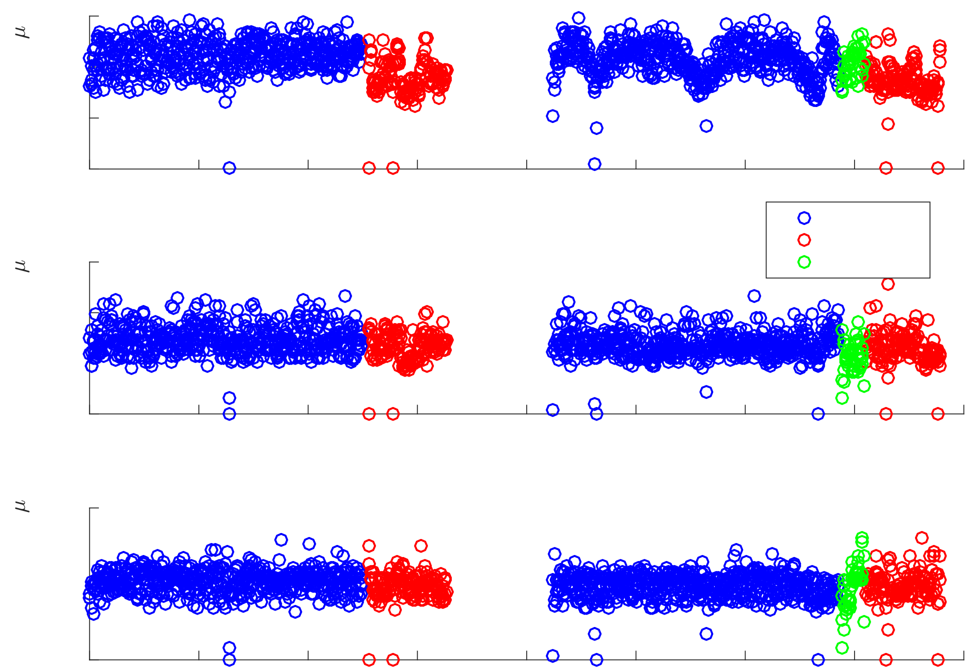

Figure 7: Melt pool dimensions

Melt Pool Aspect Ratio

The melt pool Length/Width ratio is plotted in Figure . The melt pool has a relatively small aspect ratio, generally below 2. The downskin parameter region has the highest number of frames with a larger aspect ratio.

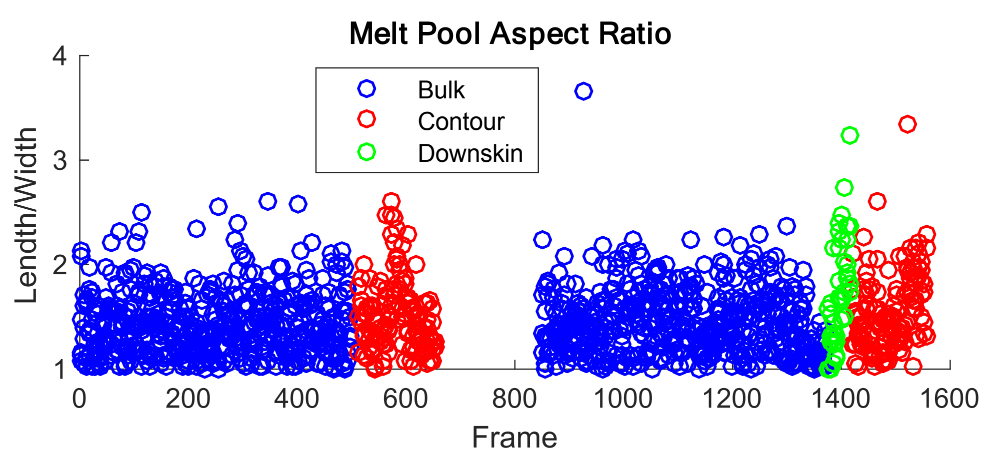

Figure 8: Melt pool aspect ratio

1.2.10 Melt Pool Temperatures

The average and peak temperatures of the melt pool are plotted in Figure 9. The highest average temperature reported are well over the boiling point-vaporization of nickel, which is 2730 ºC. Therefore, it is expected that these are non-physical results. The average temperatures are around the 2000 ºC range, which is more reasonable. Several outliers exist with very high average temperatures. When the peak temperature is plotted vs the average temperature (Figure 10), the outliers with a high average temperature have a low peak temperature, which is not physically possible. It is expected that there is a calculation error, and these points can be neglected. Two points for the contour data set have an average melt pool temperature of 0, so these points are at the very beginning of the contour when a melt pool has not formed yet. All other points follow a linear relationship where an increase in peak temperature also increases the average melt pool temperature.

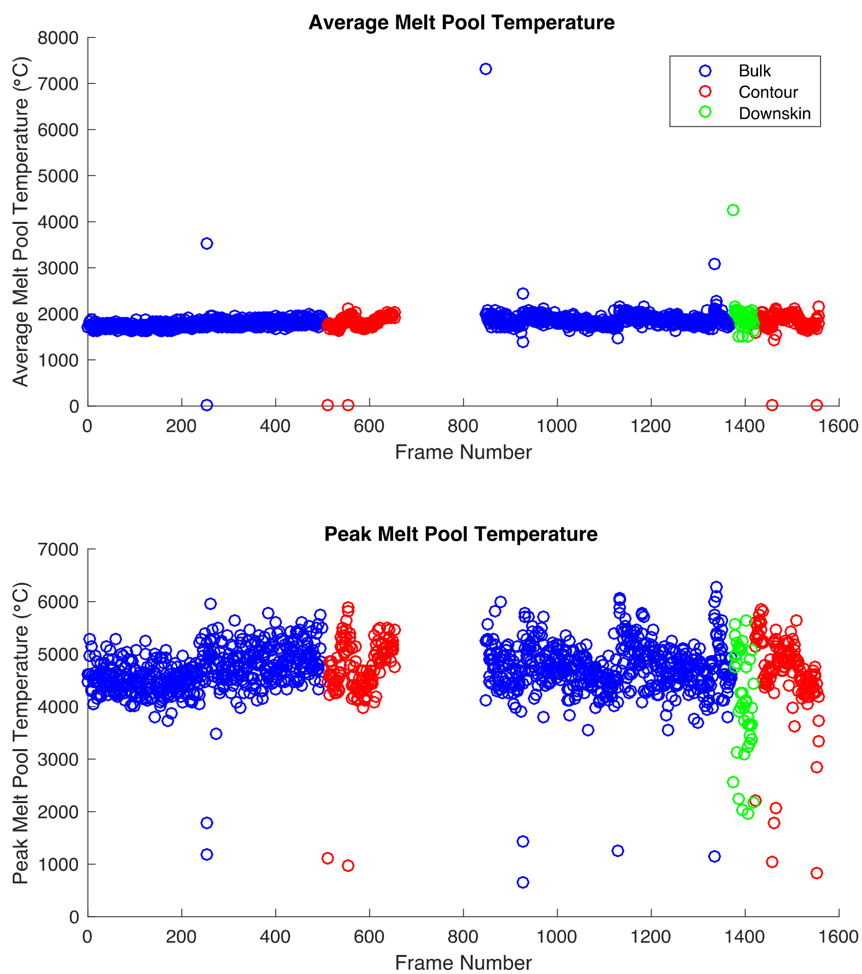

Figure 9: Melt pool temperatures of interest

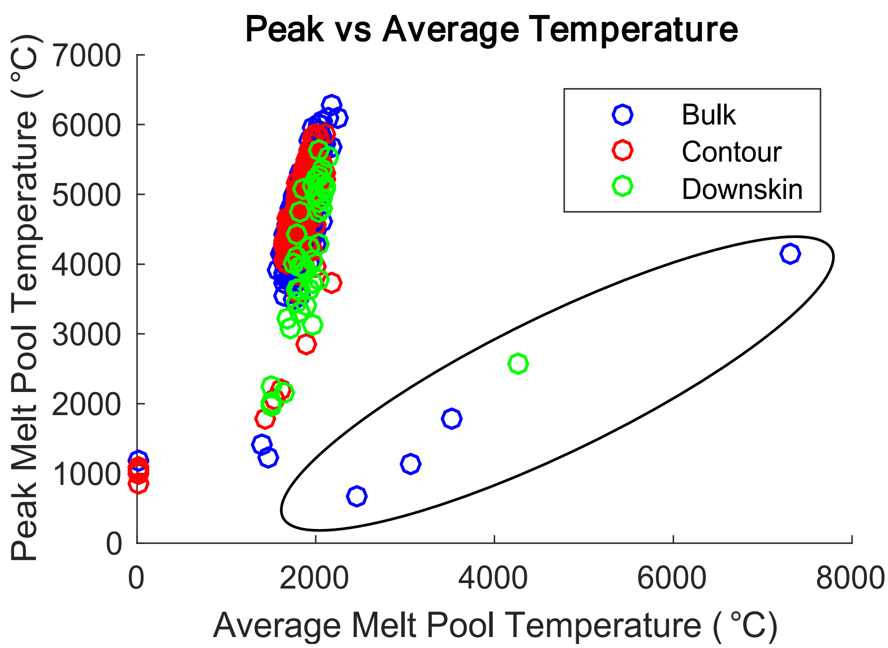

Figure 10: Peak vs average temperatures showing the anomalous temperatures that can be neglected

The cooling rate cannot be reliably calculated because the temperature gradient is too large between successive frames.

1.3 IMPACTS

Successful real-time melt pool monitoring can alert the user when processing conditions are not optimum and when flaws, or other unwanted conditions, are occurring. A feedback system could provide information to the laser control system, to change processing conditions as needed or go back and re-melt a layer or region. Quantitative measurements of melt pool size and temperatures can help develop models to effectively optimize the process for powder characteristic and part geometry. All together, these advancements would lead to increased performance, reduced waste, and lower cost.

1.4 CONCLUSIONS

The ThermaViz system could capture images of the melt pool at a rate of 700 Hz while imaging the Direct Laser Sintering build of a Hastelloy X part 15 mm wide and 5 mm high. The melt pool area is largest for the bulk hatching and smallest for the contours. The downskin parameter gives the largest lengths. The imaging rate was not sufficient to capture the ultra-fast cooldown rate.

APPENDIX A : STRATONICS SUMMARY

Summary:

The ThermaViz® sensor is mounted above the build chamber, looking through a sapphire viewport in the ceiling and located within the Renishaw enclosure, as shown in Figure A-1. The ThermaViz line of sight is through the viewport. The side and front views of the integration are shown in Figure A-2. In the side view, the optical line of sight from the sensor to the print surface is shown including the reflection off the mirror. In the front view, the backside of the mirror is seen, as installed inside the build chamber.

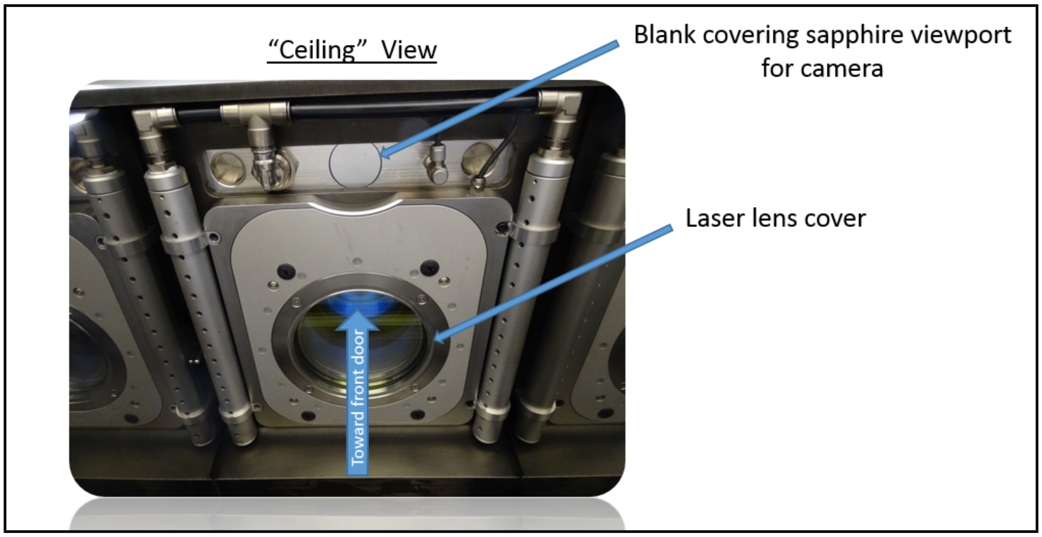

Figure A-1 Viewing the ceiling of the build chamber, note laser lens cover and blank covering the sapphire viewport.

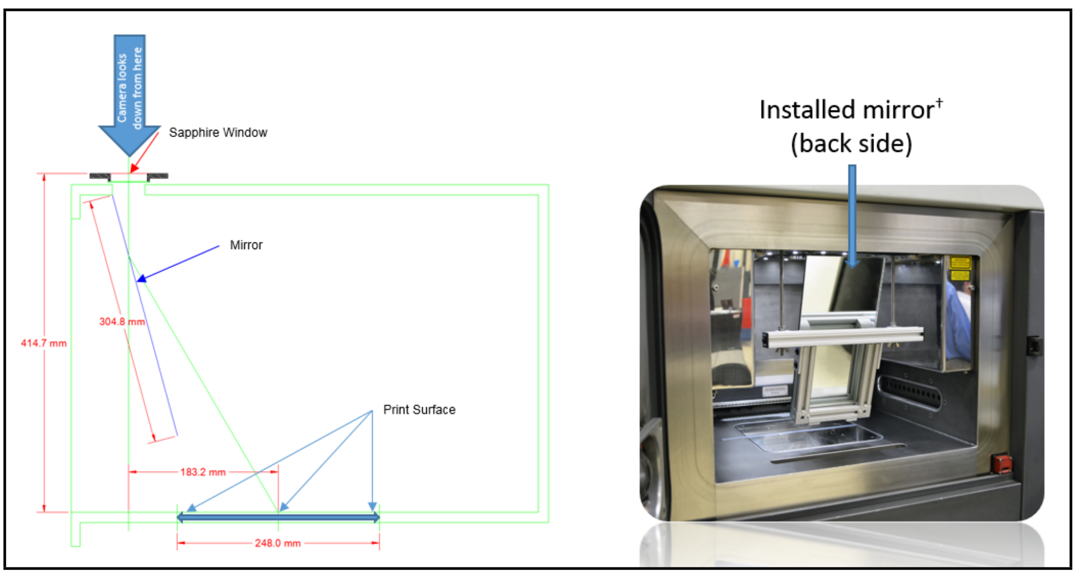

Figure A-2 Printer/Mirror/ThermaViz sensor integration. Mirrors are ¼" thick silvered glass with 1 λ/inch flatness.

The ThermaViz sensor calibration uses a tungsten filament lamp that is positioned on the print surface. The sensor is focused on the lamp and its temperature is varied from 2500°C to 1100°C in 100 degree increments. The intensity ratio is measured at each temperature, as plotted in Figure A-3. The calibration data is fit to a theoretical function, which results in the linear and offset terms.

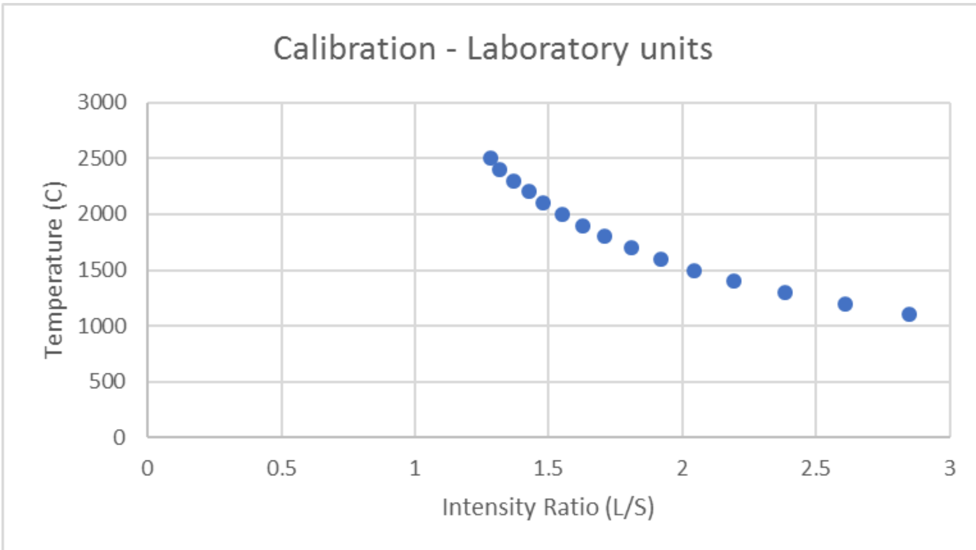

Figure A-3 Calibration data, intensity ratio (long /short wavelength) measured over temperature range, 2500℃ to 1100℃. Data fit parameters, (Linear = 0.000453484 and Offset = 0.000243031).

A typical dual wavelength image is shown in Figure A-4, with the long wavelength image at the top and the short wavelength image at the bottom. The color scale indicates the peak exposure is blue or an intensity of about 1000 counts. The sensor saturation is at 4096 counts, 12 bits, indicating that the exposure has been set low. For example, if the exposure had been increased by about 4X, the peak intensity would have been about 4000 counts, possibly saturated. The accuracy of the temperature conversion is enhanced with higher image exposures. ThermaViz has been used to convert the intensities into a temperature image, Figure A-5, note the peak temperatures reach over 3500°C. The temperature image shows 3 small spots where the temperature spikes strongly from the otherwise smooth distribution in the melt pool. Most of the melt pool shows temperatures in the range of 2500°C to 3000°C.

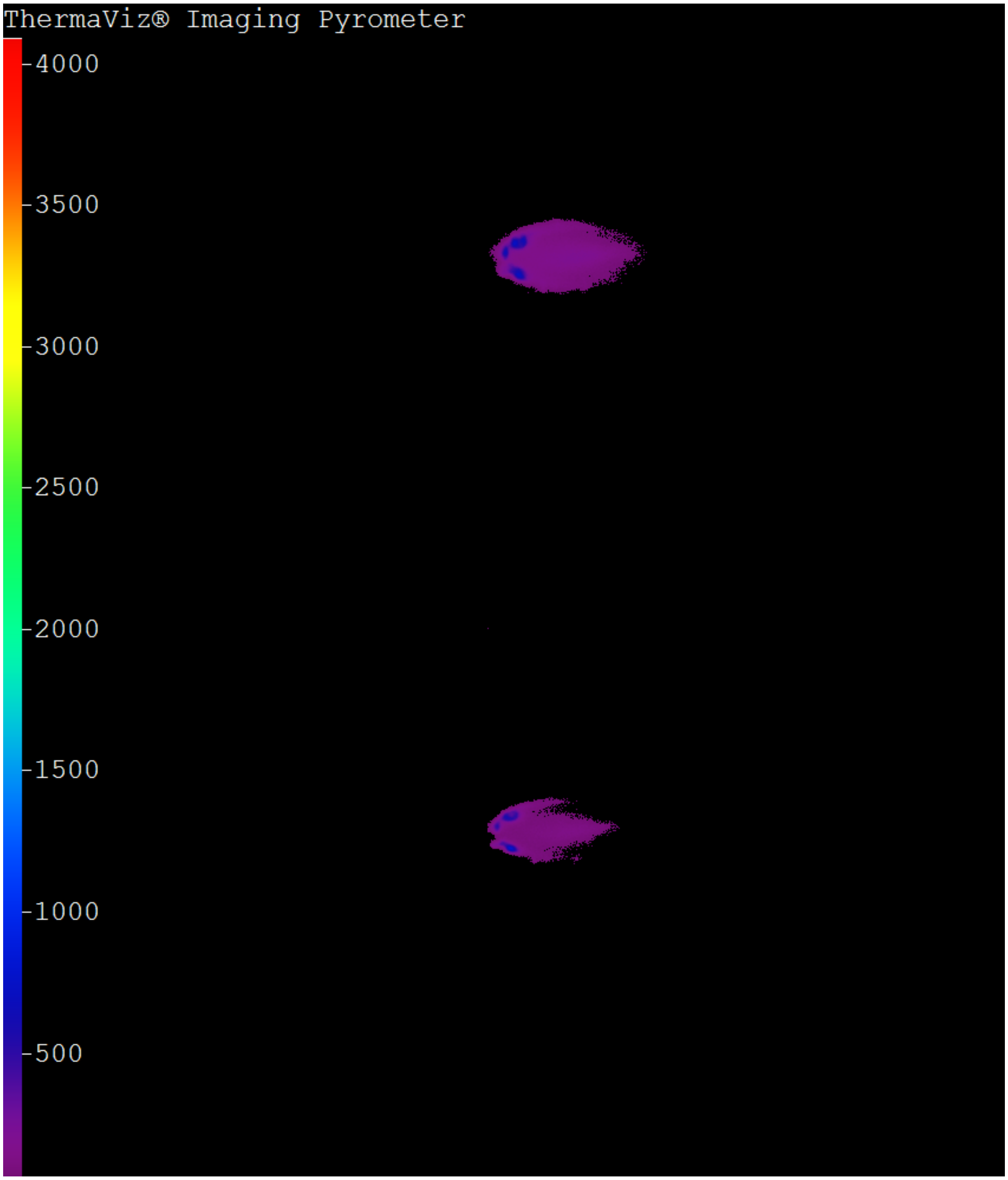

Figure A-4 Dual wavelength image, 80251, long wavelength image on the top, short wavelength image on the bottom. Note color intensity scale on the left-hand side.

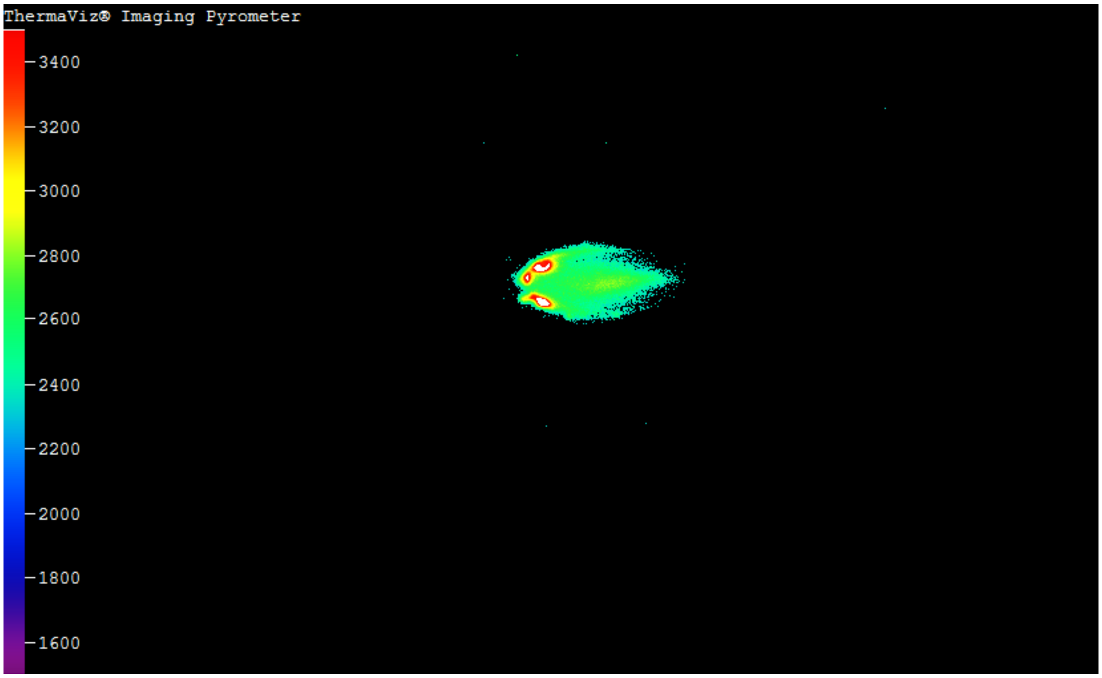

Figure A-5 Thermal Image of the melt pool, 80251. Note that most of the melt pool has a smooth temperature distribution, ranging from 2500℃ to 3000℃, except for the 3 small spikes where temperature reaches over 3500℃.

A short sequence of images was analyzed, i.e. intensities were converted into temperature. The results are shown in Figure A-6. The intensities range from 500 to 1000 counts. The peak temperatures range from 2800°C to 4500°C. These peak temperatures are indicative of the small spike temperatures seen at the front of the melt pools and not of the more nominal temperature seen across most of the melt pool. The average temperature ranges from 2000°C to 2500°C, and is more representative of the melt pool temperature.

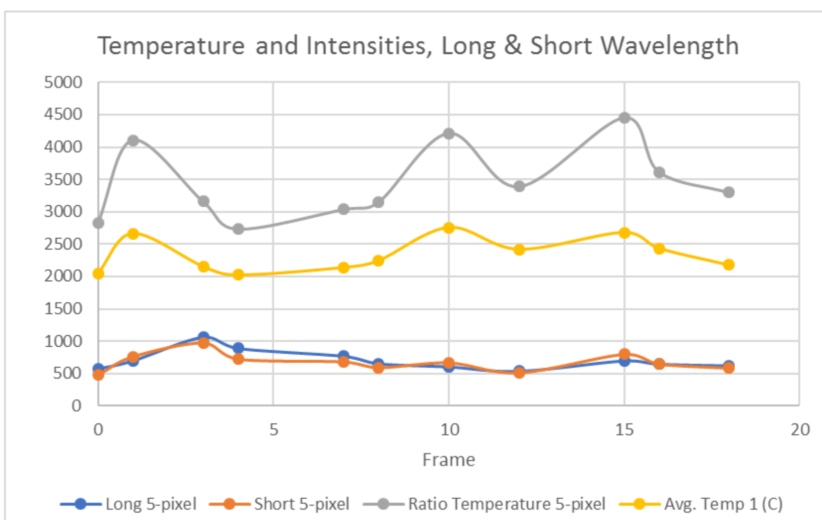

Figure A-6 Temperature and Intensity for a sequence of images.

The temperature images, Figures A7 through A14 (frames 80252/80259), all appear to have the small, hot regions leading the melt pool.

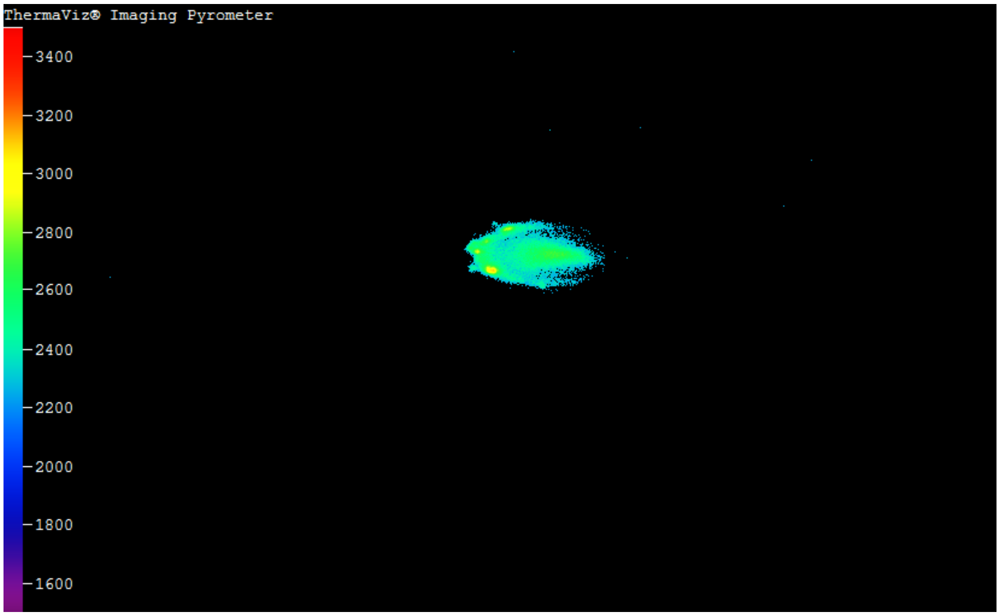

Figure A-7 Frame 80252.

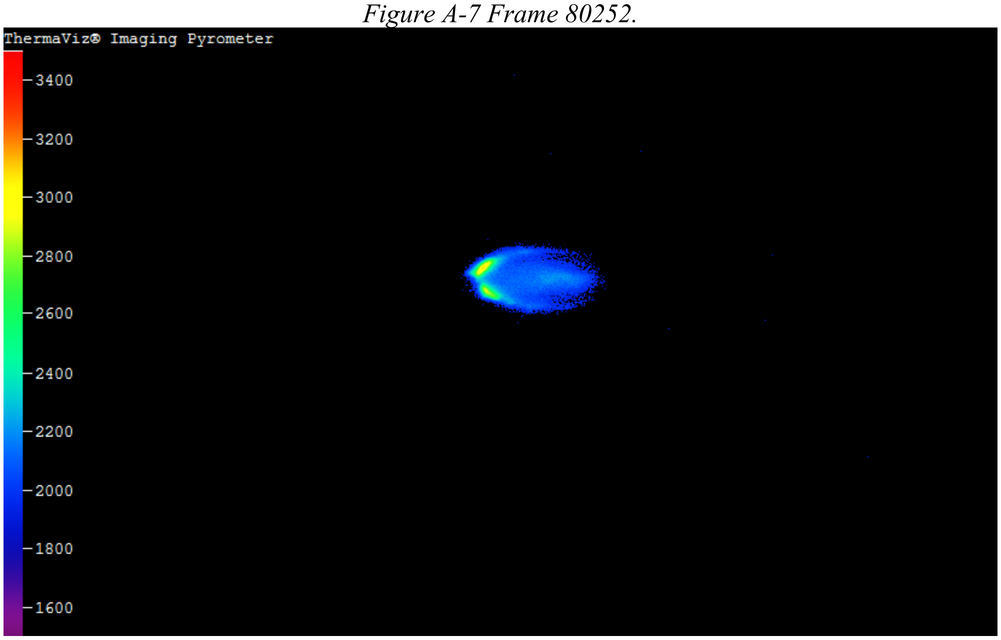

Figure A-8 Frame 80253.

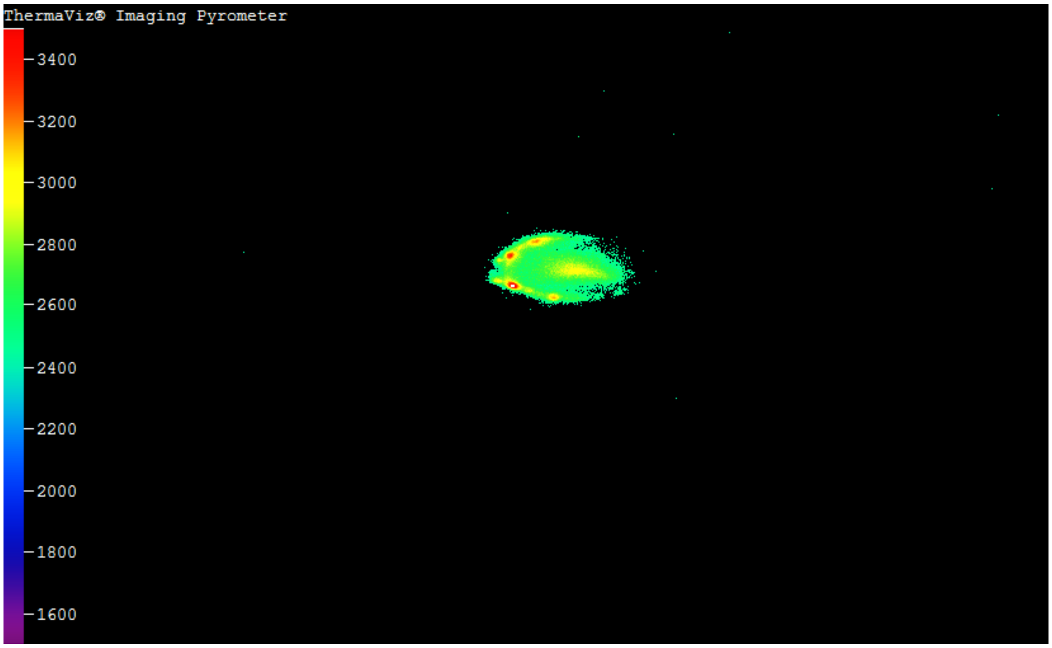

Figure A-9 Frame 80254.

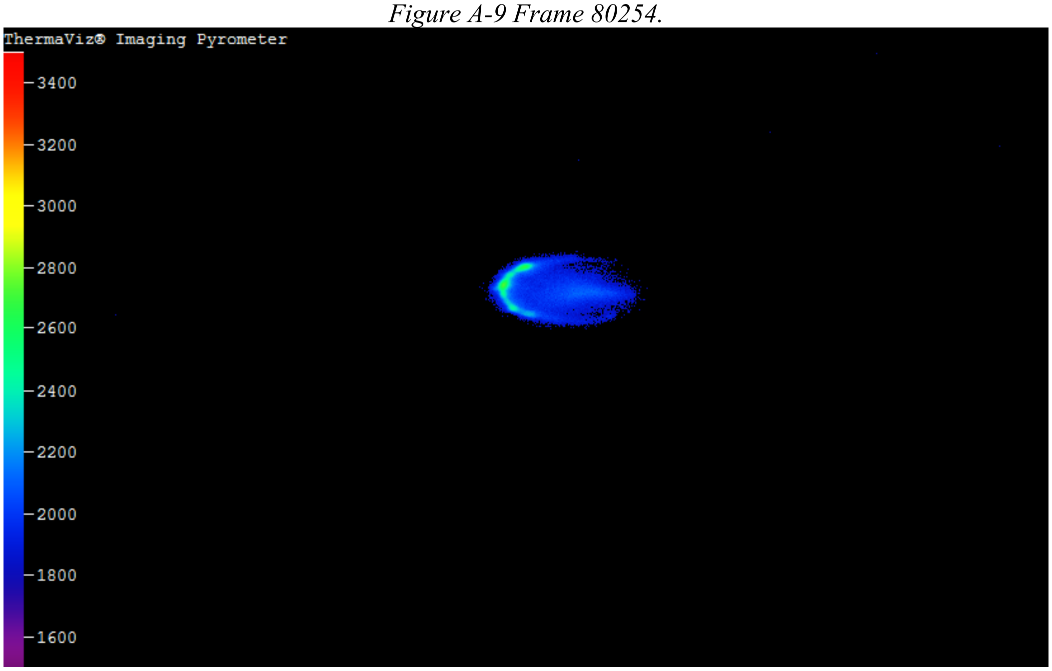

Figure A-10 Frame 80255.

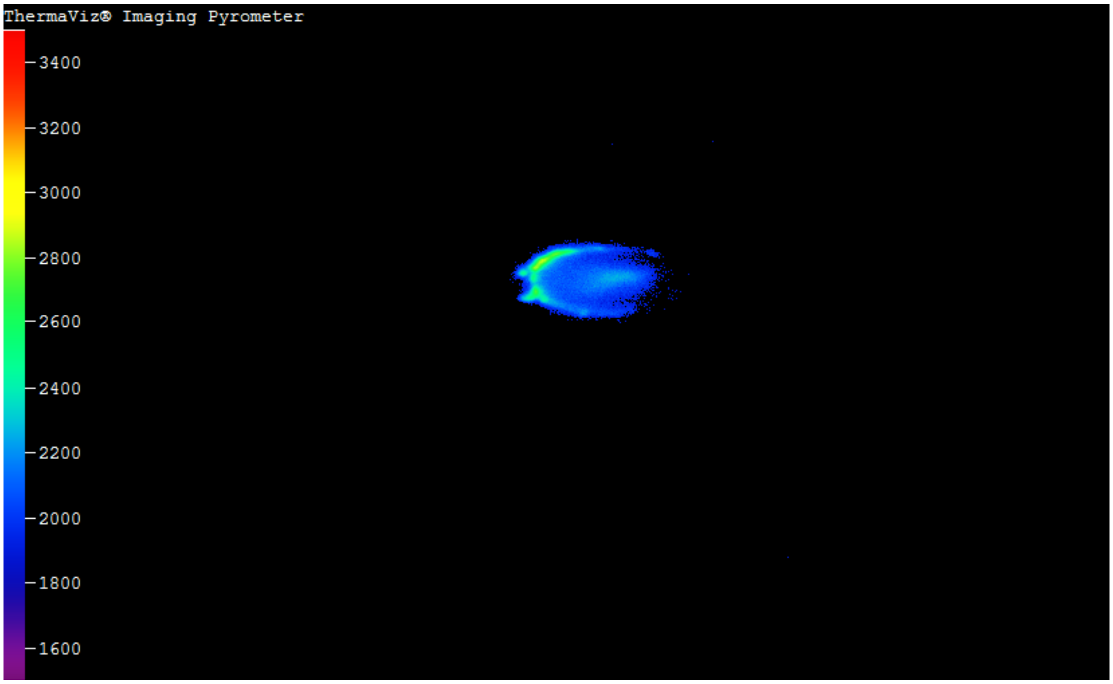

Figure A-11 Frame 80256.

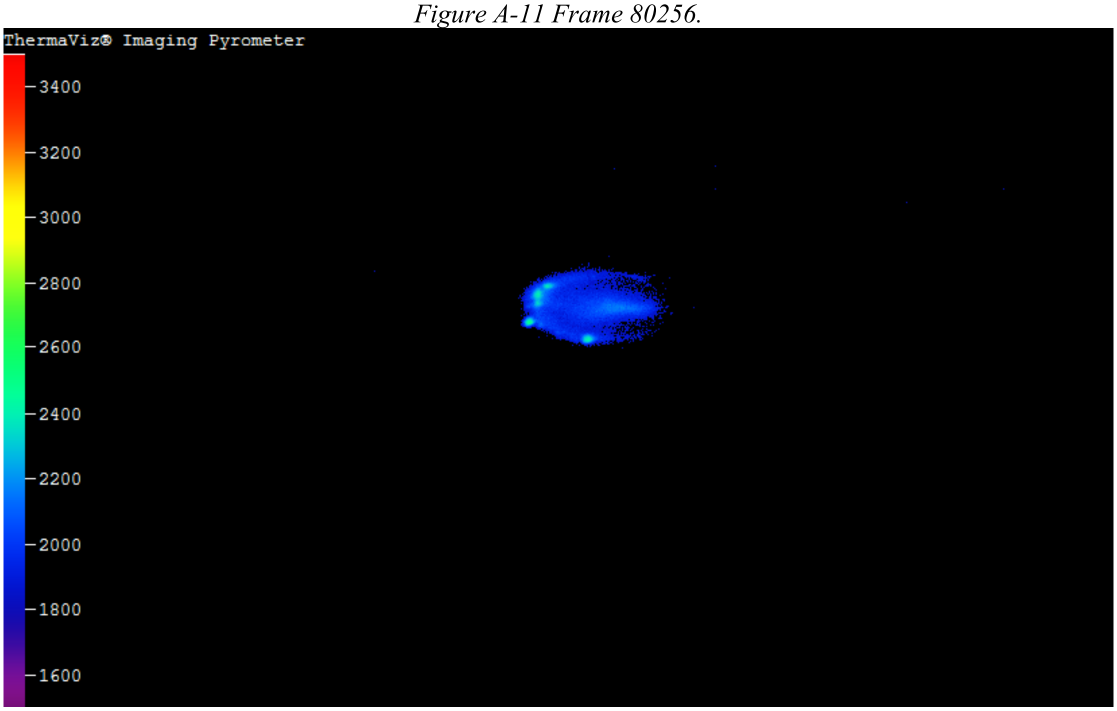

Figure A-12 Frame 80257.

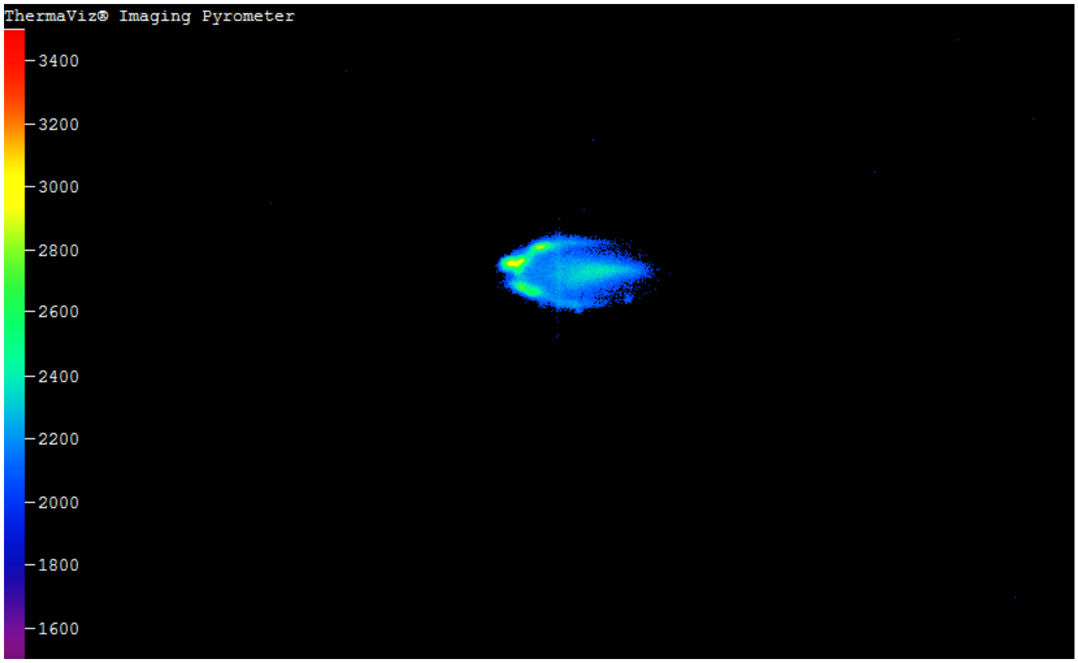

Figure A-13 Frame 80258.

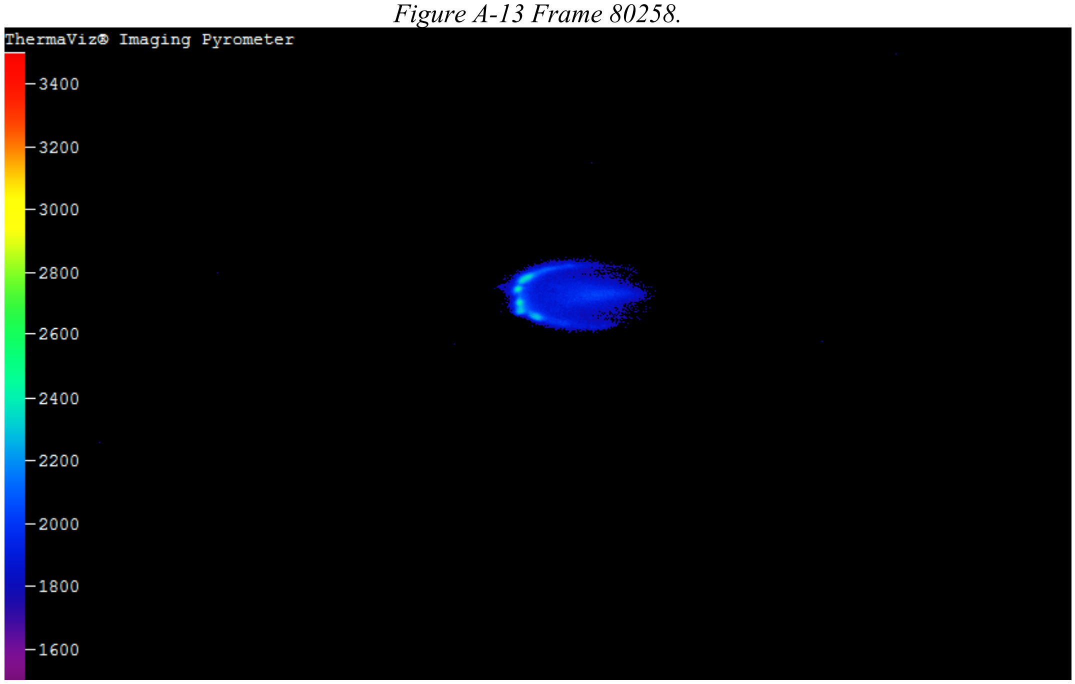

Figure A-14 Frame 80259.

<u>Conclusions and Recommendations:</u>

1-The ThermaViz sensor was successfully integrated into the Renishaw printer.

2-A high level of focus was achieved with the sensor, thus providing excellent information about the melt pool temperature distributions.

3-The imagery exposure was not optimized, as the exposure was too short and the image intensity was about ¼ of the desired level, i.e. slightly under 12 bits. This conclusion only applies to the one movie discussed in this summary.

4-The thermal data provided representative imagery of the temperature distributions in the melt pools. The melt pools were found to contain unique spatial features not seen in many other powder bed type printers, namely, EOS, ProX, and Concept Laser, Figure A-15. These other printers all produce smooth temperature distributions, that do not contain the spiked features seen in the Renishaw printer. While the actual temperature levels were comparable with other printers, the spikey distributions have not been observed before.

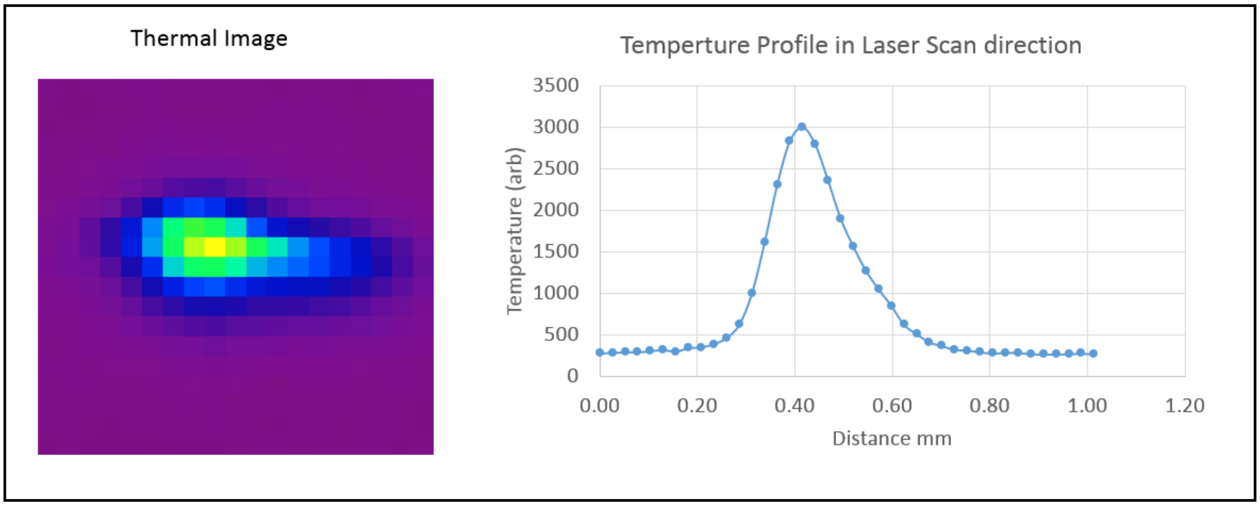

Figure A-15 In contrast to the spiked images observed in the Renishaw printer, this thermal image is typical of those observed in the ProX printer, and shows a smooth temperature distribution in both 2D image and profile. This behavior is also observed in EOS and Concept Laser printers.

5-A deeper research program should be pursued including:

- a-Determine the physics behind the spiked temperature distributions and their influence on the material characteristics of the deposit
- b-Importance of the modulation in laser power
- c-Improved methods for sensor integration
- d-Improved image analysis methods and correlation to deposit material characteristics
- d-Spectrally resolved sensor added to the experiments

2. STRATONICS BACKGROUND

Stratonics Inc., was founded by Dr. James Craig as an extension of his work in the development and implementation of aero-optic evaluation instrumentation. Stratonics was incorporated in California in 1992 with an emphasis on physics-based diagnostics in defense science R&D. The application of Stratonics instruments and experimental techniques was transitioned to materials processing. The Stratonics team has a substantial history of successfully managing research and development programs and transitioning innovation to viable, state-of-the-art products. Stratonics key capabilities lead to the development of a patented two-wavelength imaging pyrometer. This initial sensor platform was applied to the monitoring of surface temperatures in materials processes and particle conditions in thermal sprays and launched the development of a suite of sensors now integrated to monitor and control additive manufacturing.

Stratonics develops and engineers solutions based on the physics and mechanics of complex processes. Stratonics has extensive experience and understanding in laser materials processing through the use of experimental diagnostics and sensors. Stratonics currently supports industry with Stratonics's innovative sensor suite, ThermaViz®, developed to provide methods and tools to advance additive manufacturing. Collaborative R&D programs with leading-edge scientific organizations and industry provides significant advancement and new systems. Access to state-of-the-art equipment and direct interaction with customers throughout development validates Stratonics's technology and commercial products.

Stratonics provides custom engineering sensor integration, on-site installation, calibration, training, and technical consultation. Stratonics' agility and experience results in a cost competitive solution for Stratonics's customers who include national labs, universities, research organizations, additive manufacturing (AM) equipment manufacturers, and industrial users of additive manufacturing.