

Combination of Modeling and Thermal Sensing to Understand Additive Manufacturing Processes

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Metal laser powder bed fusion (LPBF) is a rapid prototyping or additive manufacturing (AM) technique that makes use of a high-power laser to fuse metallic powders into a desired geometry. The inconsistencies in the AM process lead to a need for a large amount of experimental trial and error to qualify a part. This makes an already expensive process even more costly and can be prohibitive to the widespread adoption of additive manufacturing. To expedite the design, development and qualification process of an AM part, manufacturers can turn to simulation and process monitoring. In this application brief, we compare thermal history capabilities from Ansys additive manufacturing simulation solutions with thermal imaging results from Sigma Labs using the NIST Additive Manufacturing Test Artifact as a basis.

/ Introduction

Laser Powder Bed Fusion

Metal laser powder bed fusion (LPBF) is a rapid prototyping or additive manufacturing (AM) technique that makes use of a highpower laser to fuse metallic powders into a desired geometry. Many adjustable input parameters directly influence the quality and successful fabrication of the part. Complex geometries are processed using software that slices, develops scan patterns and sets parameters for the build. Metal LPBF is desirable because it enables use of high-performance, low machinability materials and offers extreme design flexibility that is unmatched by conventional fabrication processes. These desirable characteristics are offset by a lack of process consistency and a wide array of possible defect and failure modes ^[1, 2].

The inconsistencies in the AM process lead to a need for a large amount of experimental trial and error to qualify a part. Even after a part is qualified for production, frequent testing is required to ensure that changes in the machine over time have not significantly altered the final part. This makes an already expensive process even more costly and can be prohibitive to the widespread adoption of additive manufacturing. To expedite the design, development and qualification process of an AM part, manufacturers can turn to simulation and process monitoring. Simulation enables manufacturers to predict issues or flaws that may occur in a part and can allow users to experiment in the digital world without spending time and resources on repeated experiments. Process monitoring allows manufacturers to observe the build process and identify locations where flaws may have occurred.

The powerful combination of simulation and process monitoring can be used to interpret what a “good” or expected process signature should look like. When process monitoring data deviates from what is expected through simulation, manufacturers know that there may be an issue with a certain part. Additionally, if anomalies are found via process monitoring, simulation can be used to identify the implications of the issue and whether the final part would be acceptable for use. This all makes a compelling case for the use of simulation in conjunction with process monitoring to expedite the part qualification process in additive manufacturing.

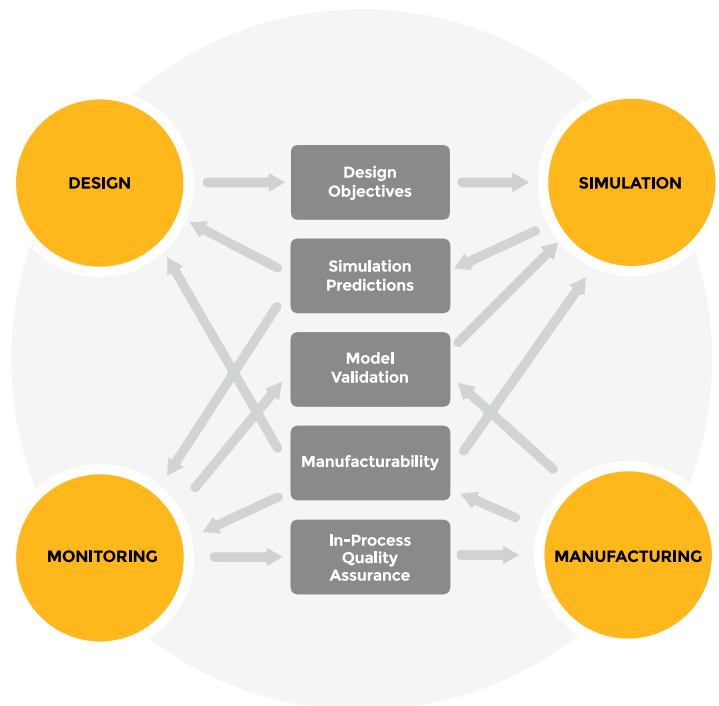


Figure 1. Flowchart showing relationships between different aspects of the additive manufacturing process for successful part qualification.

Four main components of additive manufacturing development are all linked through various channels and are important to the qualification of AM parts. Figure 1 outlines these interactions. Simulation, monitoring and manufacturing are linked by model validation. Manufacturing produces the data for in-process quality assurance to capture and analyze, and quality assurance produces the physical measurements to validate the simulation model. Simulation, design and monitoring are linked via predictions. Simulation takes design and makes predictions which are compared against physical measurements. Manufacturability links manufacturing, monitoring, simulation and design. Manufacturing gives insights into the ease of manufacture of a product and its quality. These insights provide guidance for what conditions are nominal or defective when monitored. They also give feedback for changes to design and further validation for model predictions.

NIST Test Artifact

To compare In-Process Quality Metrics (IPQMs™) data to multiphysics simulations, the NIST Additive Manufacturing Test Artifact was chosen. This geometry contains a variety of different geometries, leading to varying thermal conditions in the build that can be captured by process monitoring and simulation alike. The NIST Additive Manufacturing Test Artifact is a freely available, public domain geometry engineered to characterize capabilities of an AM system [5]. This part was built out of Ti64 using EOS Ti64 Performance parameters on an EOS M290 with PrintRite3D installed.

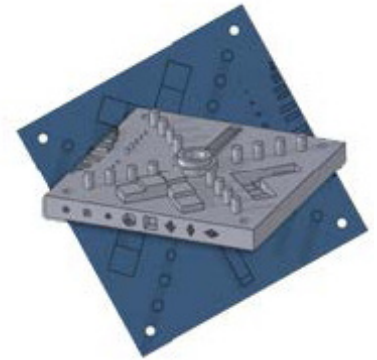


Figure 2. NIST Test Artifact Rendering

Product Offerings and Capabilities

Ansys has additive manufacturing products that aid in the additive manufacturing development process from research to design to part and machine build setup. Simulation capabilities cover both the structural and thermal aspects of the process and enable users to identify and solve potential problems while also optimizing for the AM process. Design capabilities help in the optimization and validation of parts for additive manufacturing as well as the part orientation and support design. Structural simulations allow users to identify issues with part distortion, cracking, tendency for recoater interference and other problems that may result in a failed build. Thermal simulations range from micro scale, where melt pool dimensions can be analyzed, to full part scale to identify trends in thermal conditions. These thermal simulations are also capable of outputting simulated sensor results that can be used to compare against experimental results.

Sigma Labs develops and engineers advanced, in-process quality control systems for commercial firms worldwide seeking productive solutions for metal-based additive manufacturing or 3D printing, and other advanced manufacturing technologies. PrintRite3D® is a proprietary hardware and software technology that uses thermal readings to detect and predict anomalies during the 3D printing process. It features real-time monitoring, analysis, feedback and control. Figure 3 outlines some of the specifications for the PrintRite3D sensor.

PrintRite3D Specifications			
Resolution	100 micron	Data processing Rate	Interlayer
Speed	200 kilohertz	Server Performance	10 terabyte multi-core 2u w/ co-processor
Wavelength	300 - 1000 nanometer	Host Machine Connections	Laser power, laser drive, XY protocol
Data File Size	Average 10 megabytes per layer	Sensor Array Dimensions	200 x 200 x 150 mm
Data Processing Time	Average 20 seconds per layer	HMI Server Cabinet Dimensions	580 x 580 x 810 mm

Figure 3. PrintRite3D Specifications.

In this work, thermal history capabilities from Ansys are compared with thermal imaging results from Sigma Labs. Temperatures from the simulation are processed to produce a coaxial average output across a given layer. While the layout of this result is similar to results that can be produced with Sigma Labs capabilities, the difference between simulation temperatures and intensities processed by the sensor means that the focus will remain on trends.

/ Methods

In-Process Quality Monitoring Using On-Axis Pyrometry

In-Process Quality Metrics are quantitative features computed by direct on-axis observation of the LPBF process aggregated over a pixel grid. The pixel grids typically have a spatial resolution of [100 μm x 100 μm] for high resolution analysis. TED™ is one such metric and uses a wide band of observed wavelengths to aggregate intensity of light emitted during the build process.

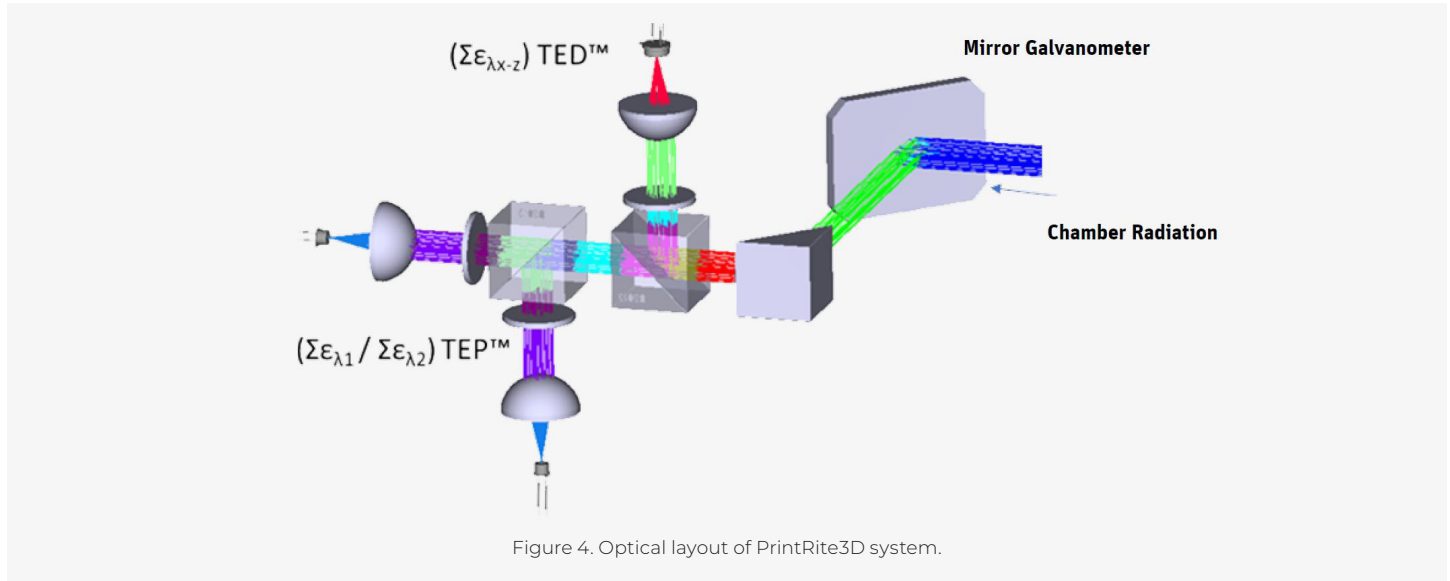


Figure 4. Optical layout of PrintRite3D system.

TEP™ is another such metric which uses two narrow bands of observed wavelengths to calculate a relative temperature. Using narrow bands allows for on-axis pyrometry; “on-axis” means the field of view of the photodetector follows the laser path. Pyrometry means using the relationship between the output signal of the photodetector and irradiance of the observed melt pool (j^*) through the Stefan Boltzmann law to calculate a temperature using emissivity (ϵ) and the Stefan-Boltzmann constant (σ).

Emissivity represents a challenge in that it has been found to change significantly with phase changes, surface roughness and even temperature [3]. This is corrected for by using two photodetectors at different wavelengths. This correction is possible because Planck’s law (Equation No. 2), which relates temperature to irradiance at individual wavelengths, can be solved for temperature with emissivity canceled out. This operation uses the assumption that emissivity is the same at the different wavelengths. This is also known as the gray body assumption [4].

$$j^* = \epsilon \sigma T^4$$

Equation 1

$$B_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{\frac{hc}{e\lambda k_B T} - 1}$$

Equation 2

/ Data Collection

Sigma Labs collected IPQM data for 424 layers of the NIST Artifact and compared this data with Ansys simulation for the same layer slices. These images represent standard PrintRite3D analysis outputs automatically generated by the monitoring system available for analysis after the completion of a layer of the LPBF process.

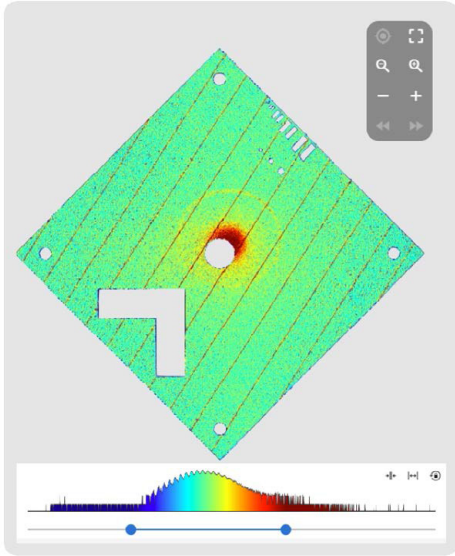


Figure 5. PrintRite3D TED IPQM for layer number 200 of NIST Test Artifact.

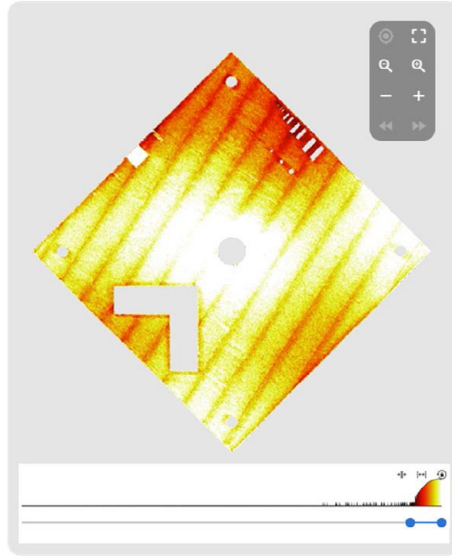


Figure 6. PrintRite3D TEP IPQM for layer number 200 of NIST Test Artifact.

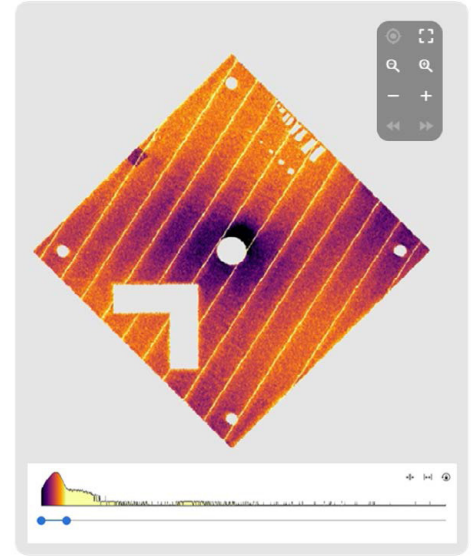


Figure 7. PrintRite3D TEP-Sigma IPQM for layer number 200 of NIST Test Artifact.

/ Thermal History Simulation Formulation

Ansys Additive uses a conventional approach to capture thermal history in a LPBF process. The thermal equilibrium equation can be represented using the transient equation of a moving heat source [6]:

$$\rho C_v \frac{\partial T}{\partial t} = k \nabla^2 T + Q$$

Equation 3

where ρ is the density, C_v is the specific heat capacity, T is the temperature, k is the heat conductivity, Q is the volumetric heat generation and ∇ is the gradient operator. The heat flow through the volume can be captured by its component q_x , q_y , and q_z defined as:

$$q_x = -k \frac{\partial T}{\partial x} \quad q_x = -k \frac{\partial T}{\partial x} \quad q_x = -k \frac{\partial T}{\partial x}$$

Equation 4

So, Equation 3 can be rewritten using the definition of heat flow:

$$\rho C_v \frac{\partial T}{\partial t} = - \left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right) + Q$$

Equation 5

The inner volumetric heat generation rate Q can be calculated by:

$$Q = \int_v^{v+dv} q dz$$

Equation 6

where in an LPBF process, the laser flux q can be calculated using the most common Gaussian distribution beam profile:

$$q = \frac{2AP}{\pi\omega^2} e^{-\frac{2r^2}{\omega^2}}$$

Equation 7

where P is the laser power, A is the absorptivity, w is the radius of the laser beam, r is the radius distance between a point on the current solving domain and the current laser beam center location.

These equations form the basis from which we can build up a thermal simulation of entire layers to identify trends in thermal conditions and characteristics important to additive manufacturing. Once temperatures throughout the layer have been obtained, the challenge then becomes the processing of the thermal results into a form that is meaningful to the user. For this work, a coaxial average sensor output was used. The coaxial average sensor output sensor averages all the temperatures on the surface of the part within a user-defined radius. This output gives us results that are similar to what is observed by the PrintRite3D sensor and allows us to compare trends between the two result sets.

/ Model Setup

The NIST Artifact geometry was simulated using the Ansys Additive Thermal History solution. For these simulations we did not have build files to read in to set up the model, so the geometry was imported and a generic scan pattern was generated by the software. Inputs to generate the scan pattern include layer thickness, hatch spacing, stripe width, starting layer angle and layer rotation angle. In addition to the inputs for the scan pattern, other key parameters must be provided as well. These include the preheat temperature, scan speed, laser power and laser beam diameter. To define the output for the coaxial average sensor, the sensor radius and locations of the desired output layers are specified. Figure 8 shows the coaxial average sensor output for layer 200 with a 1mm sensor radius.

/ Results

In analyzing results from the PrintRite3D sensor, we can identify trends in the data to compare with simulation results. Each result set is built up from a series of sampled points along the scan line where results for the real or simulated signal was obtained. We can observe trends at both size scales to get a better understanding of what is going on in the process. In this work a 10 mm coaxial viewing radius was used for the simulation results to match the Sigma Labs sensor.

/ Narrow Stripe Regions

Regions with a narrow scan stripe compared to the surrounding regions are unavoidable in additively manufacturing parts. These are also some of the more distinctive parts of the results for the NIST artifact geometry. We see good agreement between experimental results and the simulations. In these regions there is a decrease in intensity and temperature as the stripe gets thinner. Figure 9 highlights one of these regions and we can compare the result with what we see in Figure 10 from the simulation. The decrease in averaged temperatures and thermal intensity in these regions can be explained by the coaxial viewing area seeing a larger portion of cooled material compared to the hot, recently deposited material.

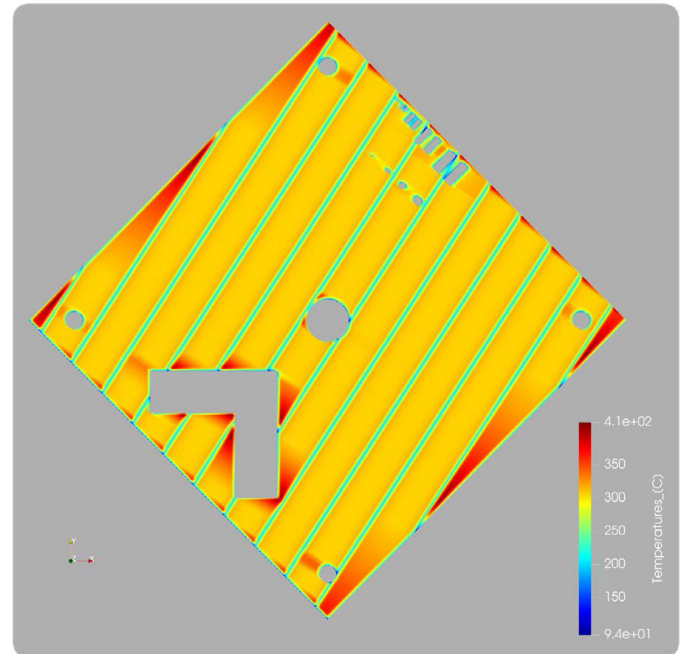


Figure 8. Ansys coaxial average sensor results with a sensor radius of 1mm.

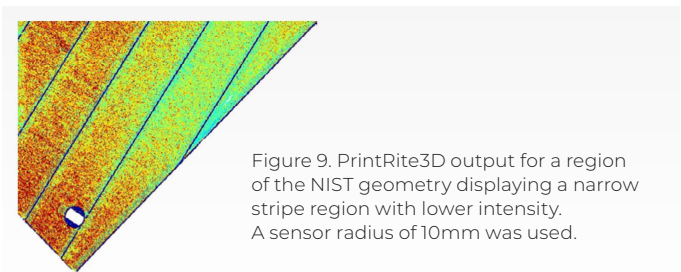


Figure 9. PrintRite3D output for a region of the NIST geometry displaying a narrow stripe region with lower intensity. A sensor radius of 10mm was used.

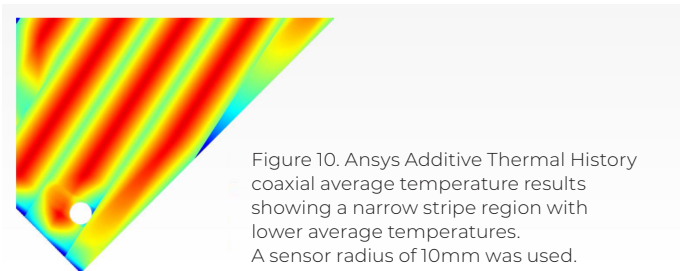


Figure 10. Ansys Additive Thermal History coaxial average temperature results showing a narrow stripe region with lower average temperatures. A sensor radius of 10mm was used.

/ Turn-Around Regions

If we zoom in to view results on a line by line scale, we can also see similarities in the signal behavior near turn-arounds at the end of a scan (Figures 11 and 12). Experimentally, we can see alternating high and low signals coming into and out of turnarounds. This is again reflected in the simulation results. What we're observing here is a steady-state melt pool entering a turnaround exhibiting a lower thermal signal compared with a larger melt pool exiting the turn around due to the local preheat from the previous pass.

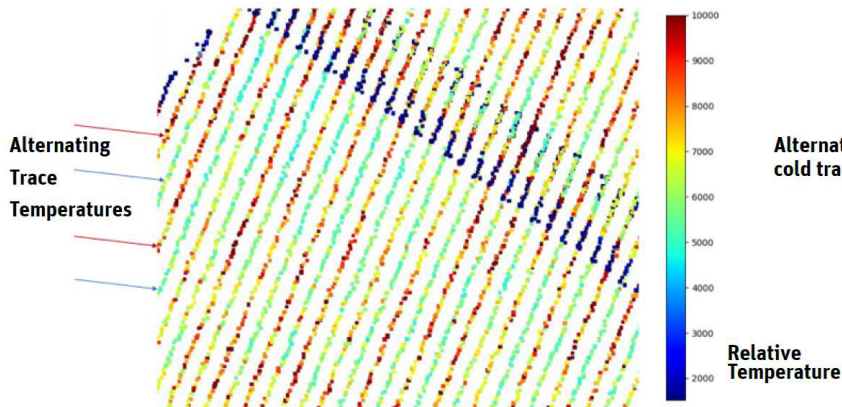


Figure 11. PrintRite3D output near a turn-around region showing the alternating high and low intensity scan tracks.

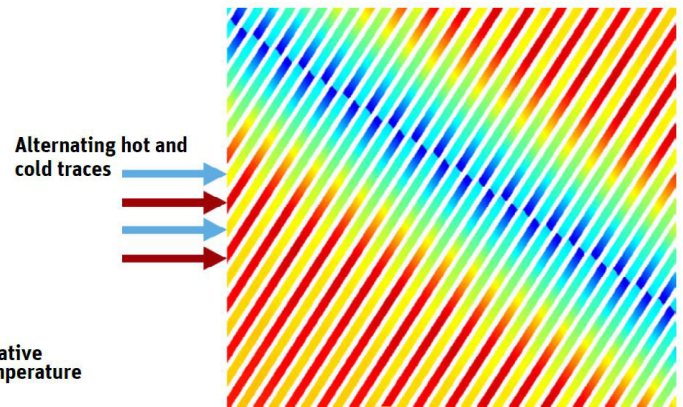


Figure 12. Ansys Additive Thermal History coaxial average sensor output near a turn-around region showing the alternating temperature values in scan traces.

/ Conclusions

A simulation model of the additive manufacturing process was used to compare with Sigma Labs' coaxial thermal sensor response. Thermal effects of scan strategy in critical locations such as hatch turn-around regions and small stripe areas were predicted by Ansys modeling; these thermal effects were experimentally validated using PrintRite3D in-situ thermal process monitoring data. Validated thermal models in combination with thermal measurement can offer valuable insight to part design and manufacturing. Disagreement between modeling and monitoring can highlight important changes in the process that affect part quality.

Further research should be done into the effect of scan strategy parameters, such as contours and up/down skins, on simulation temperatures, as standard LPBF uses these by default. Detailed quantification of the comparison between measured temperatures and simulated temperatures should be performed and discrepancies between the two should be investigated. This work should guide the development and improvement of the simulation and help to close the gap between measurements and predictions.

Additionally, the identification of flaws (e.g., lack of fusion, keyholing) using process monitoring and simulation would bring great value to the additive manufacturing community. Phenomena observed in the process can be investigated with simulation to identify the source of potential flaws and to determine potential solutions. New solutions to problem regions in a part can be identified with simulation without costly experimental trial and error. Promising solutions can then be validated experimentally via process monitoring. This type of workflow where process monitoring and simulation complement each other can also aid in parameter optimization and rapid qualification of new materials.

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