Infrared Thermography for Laser-Based Powder Bed Fusion Additive Manufacturing Processes

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Abstract. Additive manufacturing (AM) has the potential to revolutionize discrete part manufacturing, but improvements in processing of metallic materials are necessary before AM will see widespread adoption. A better understanding of AM processes, resulting from physics-based modeling as well as direct process metrology, will form the basis for these improvements. Infrared (IR) thermography of AM processes can provide direct process metrology, as well as data necessary for the verification of physics-based models. We review selected works examining how IR thermography was implemented and used in various powder-bed AM processes. This previous work, as well as significant experience at the National Institute of Standards and Technology in temperature measurement and IR thermography for machining processes, shapes our own research in AM process metrology with IR thermography. We discuss our experimental design, as well as plans for future IR measurements of a laser-based powder bed fusion AM process.

Keywords: Additive Manufacturing, Powder Bed Fusion, Infrared Thermography, Thermal Imaging, Hyperspectral Camera

INTRODUCTION

ASTM F2792 recognizes seven categories of additive manufacturing (AM) processes [1]. Powder bed fusion (PBF) processes are among the most common approaches for the direct production of metal AM parts. As is common to most AM processes, the design file describing the part (either a .stl file or .amf file) is first digitally sliced into individual layers. In PBF processes, an energy beam traces the geometry of an individual layer onto the top surface of a bed of powder. After an individual layer is completed, the powder bed is lowered by the prescribed layer thickness, and a new layer of powder is swept over the powder bed, filling the resulting gap and allowing a new layer to be built (see Fig. 1). During the direct production of metal parts, the energy beam (either a laser or an electron beam) melts the powder particles, which become fused together and to the previous layer(s) when the beam leaves the area and the metal cools. Repeating this process, layer-upon-layer, results in a part with near-100 % density.

At their most basic level, PBF processes are about melting and cooling. Knowing which areas of the powder bed were exposed to localized heating and melting will allow one to know the shape of the part. Knowing the temperature history of an individual point within the part will allow one to know the microstructure, residual stress, and other properties in and around that point. These characteristics will govern the performance of the part in its intended application. As such, measuring temperatures during a PBF process is vital.

Infrared (IR) thermography is well suited to measure the temperatures during PBF processes. The build chambers of commercial PBF machines are closed boxes. The building takes place either in an inert environment (for laser-based processes) or in a vacuum (for electron beam-based processes). The energy beam must have free access to the entire build platform, and a recoating mechanism traverses the build area between each layer. These aspects of the process make remote sensing with IR thermography very desirable. Additionally, because each layer is built in the same plane (atop the powder bed), the current build layer is continually in focus to a stationary camera. Finally, while remote point pyrometers can provide valuable information about a single point on the build plane, IR

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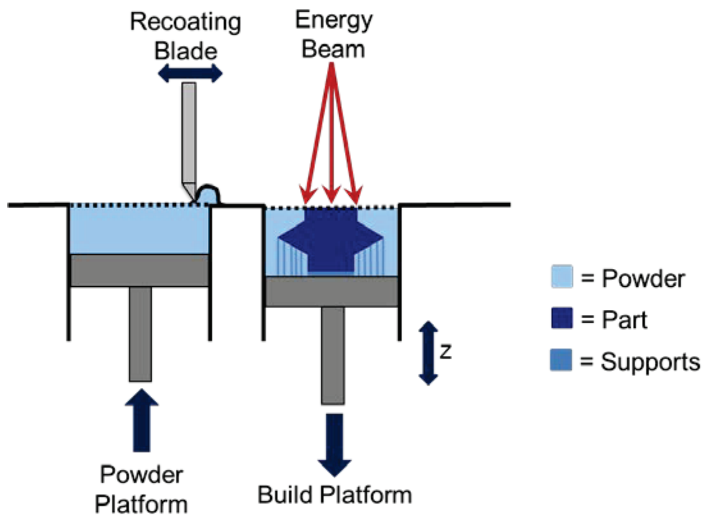

FIGURE 1. Schematic of a powder bed fusion process.

thermography's 2D area of measurement allows one to learn about the spatial temperature gradients in addition to the temporal changes.

Of course, challenges persist with IR thermography of PBF processes. This paper discusses the approaches to be undertaken by researchers at the National Institute of Standards and Technology (NIST) to address the challenges and accurately measure the true temperatures during a laser based powder bed fusion (PBF-L) process. The focus of this paper will be on the work intended to measure true temperatures for the purpose of validating high-fidelity multi-physics models of the PBF-L process.

BASIC PRINCIPLES OF IR THERMOGRAPHY

An object, when heated, radiates electromagnetic energy over a range of wavelengths. The amount of energy radiated at each wavelength is a function of the object's temperature. Temperature sensors collect this electromagnetic energy and relate the intensity of the collected radiation to the temperature of the object. The "pixels" in a thermal camera are actually separate sensors, arranged in a focal plane array (FPA), each collecting electromagnetic radiation. This allows collection of the radiation emitted from a two-dimensional space. A thermogram results when the intensity of the radiation is converted into a two-dimensional map of temperature. IR thermography is the use of thermograms, resulting from the collection of radiation in the IR part of the spectrum, to study the temperature distribution in an object.

Converting the intensity of collected radiation to temperature is complicated by emissivity of the observed object. A "blackbody" is an object that radiates the maximum possible energy for its temperature. The intensity of radiation resulting from a blackbody at a certain temperature is well known, described by Planck's Law:

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

where B is the spectral radiance, T is the absolute temperature, λ is the wavelength, k_B is the Boltzmann constant, h is Planck's constant, and c is the speed of light through the medium. However, no object radiates its maximum possible energy. An object's emissivity is the fraction of energy emitted compared to the maximum possible. For example, if an object at a certain temperature radiates 65 % of the maximum possible energy, the object is said to have an emissivity of 0.65. Therefore, when determining the object's temperature, the object's emissivity must be considered along with the intensity of captured radiation.

The emissivity of an object is not simply a physical constant. An object's emissivity varies with temperature, surface roughness or texture, the state of the material (e.g., solid, liquid, powder, etc.), the angle of observation, and more. As such, when measuring over a two-dimensional space, especially with a temperature gradient, emissivity is rarely uniform.

The true temperature of an object is difficult to measure with low uncertainty. Capturing electromagnetic radiation and converting that to temperature assuming the imaged object is a blackbody is the "imaged temperature," and is rather straight forward. Often, a thermal camera will be calibrated against a blackbody calibration object with emissivity very close to 1 to relate camera signal to the blackbody temperature. After the calibration, the camera can report an image as "apparent temperature," which assumes the emitting object has an emissivity of 1. This is not necessarily equal to the true temperature. Converting imaged temperature to true temperature requires a qualitative and quantitative understanding of the physical properties of the object, the characteristics of the camera, and the conditions encountered while acquiring the image. Understanding the characteristics of the camera optics are especially important when imaging very small heat sources such as a metal melt pool.

IR THERMOGRAPHY APPLICATIONS IN PBF

Reviewing the literature makes it clear that IR thermography will play a major role in metals-based AM. Confining the scope of the review to IR thermography for PBF processes still yields dozens of papers discussing a variety of issues, many of which came within the last two years. For example, Dinwiddie et al. at Oak Ridge National Laboratory are studying an electron beam based powder bed fusion (PBF-E) process, examining the focus size of the electron beam during preheating and melting, detecting melted and un-melted regions of the build, and searching for areas of unwanted porosity (defects) [2]. Rodriguez et al. at the University of Texas El Paso have a similar study of PBF-E examining the temperature uniformity across the entire powder bed searching for possible defects and implementing feedback control [3]. Craeghs et al. at the University of Leuven, Belgium are using a beam splitter in a PBF-L process to look along the beam path at the melt pool, implementing real time process control [4]. Krauss et al. at the Technische Universitaet in Munich, Germany are also studying a PBF-L process using IR thermography to characterize the geometry of the heat affected zone, as well as to detect pores and flaws [5].

All of these previous applications succeed using only relative temperatures, meaning the imaged temperature does not need to be converted to true temperature to provide valuable results. These researchers understand the importance of emissivity, its non-uniformity, and the opportunities and challenges it presents. It is noteworthy that none of these recent papers use the temperature measurements to validate computer models of PBF process, since this application would require true temperatures. Review of the literature revealed only two papers discussing thermal imaging for model validation [6,7]. Unfortunately these papers do not discuss emissivity and how imaged temperatures were converted to true temperatures.

NIST APPROACH TO IR THERMOGRAPHY FOR PBF

The IR thermography for AM to be conducted at NIST will build upon previous success using IR thermography to study the machining process. Researchers in NIST's Engineering Laboratory have significant experience measuring the temperatures of the 2D orthogonal metal cutting process, especially in characterizing the various sources of measurement uncertainty [8-10]. Many of the challenges involved in measuring the processes and many of the sources of uncertainty (e.g., variations in emissivity, motion blur, reflections) are similar between machining and AM.

The novel approach will be the use of hyperspectral imaging as a complement to the more traditional IR camera imaging. Where a traditional IR camera integrates over a range of wavelengths, the hyperspectral camera simultaneously captures individual images at multiple discreet wavelengths. This allows each individual pixel to be analyzed, plotting intensity versus wavelength. A curve can be fit to this data and a peak can be found (see Fig. 2). Wein's displacement law allows one to solve for temperature given the peak wavelength:

$$T = \frac{b}{\lambda_{max}} \quad (2)$$

where b is Wien's displacement constant equal to 2.897 x 10^{-3} m·K. This allows for determination of temperature at every pixel independent of emissivity. Further, the plot of intensity versus wavelength can be compared to a plot of

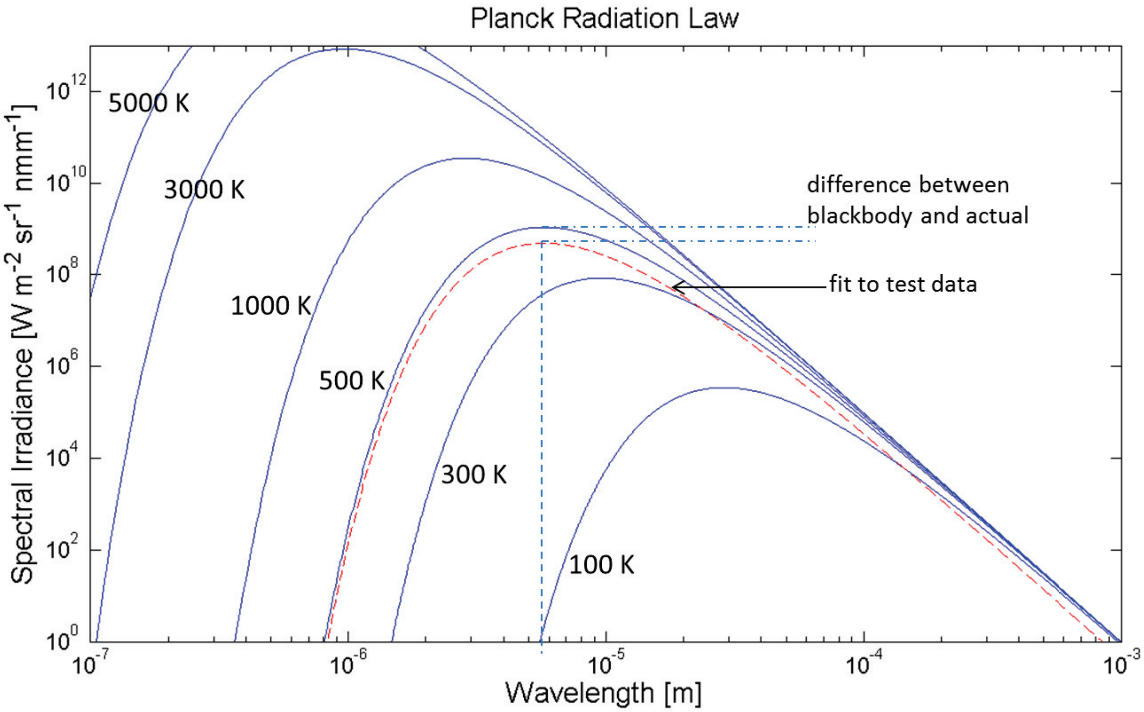

FIGURE 2. Plot of Planck's Law at several temperatures (solid lines) along with an example of a line fit to possible test data. The peak of the fit line will help determine temperature while the difference between the radiance of the fit line and the radiance determined by Planck's Law will help determine emissivity.

Planck's Law for the determined temperature. The plot of the measured data will be slightly lower than the plot of Planck's Law because the emissivity of the imaged object will be lower than that of the pure blackbody represented by Planck's Law. This difference in height gives a measure of the object's emissivity. Therefore, the hyperspectral camera allows the simultaneous determination of both temperature and emissivity at every individual pixel.

The drawback of the hyperspectral camera relates to the data collection. Our camera (custom manufactured by a commercial vendor) captures an 80 pixel by 80 pixel by 11 wavelength data cube at a rate of up to 50 cubes per second. This small size and speed make it difficult to capture a clear representation of the temperature profile of the highly dynamic PBF processes. However, the captured data can be used to get a better understanding of the temperature and emissivity values of the captured scene. This better understanding allows for a better conversion from imaged temperature to true temperature using a more traditional thermal camera.

Following measurement using the hyperspectral camera, the same scene can be captured using the more traditional thermal camera. The traditional thermal camera can capture 640 pixels by 512 pixels at speeds up to 100 Hz (or up to 3.4 kHz with windowing) with integration times ranging from 3 µs to 20 ms. This provides a more detailed imaged temperature. The data analysis from the hyperspectral camera data analysis provides the emissivity values for the various objects within the scene (powder, solid metal, melt pool, etc.). These emissivity values can be used to convert the imaged temperature to true temperature. This conversion will likely need to be done post-process because the non-uniform emissivity will require a pixel-by-pixel conversion using the appropriate emissivity value for that region of the scene.

EXPERIMENTAL SETUP

An additional challenge to thermal imaging of commercial PBF processes (like the direct metal laser sintering machine at NIST) is that most commercial systems are closed boxes with small working volumes, making it difficult to locate the camera in a position to image the working plane. Fitting a camera (especially the 185 mm x 160 mm x 540 mm hyperspectral camera) inside the small build chamber while avoiding all the working components (i.e., recoating arm and energy beam) is impractical. Therefore, a portal must be made to allow the camera to be mounted outside the build chamber, but view into the working plane. The easiest path to accomplish this on the system at NIST is through the front door of the machine. The existing viewport of the machine (a simple window with IR-blocking glass) will be replaced with a metal structure that protrudes into the build chamber a bit, allowing the camera to be positioned closer to the working plane.

Figure 3 shows a solid model of the modified viewport, and its assembly with the machine's door. The viewport was designed to maintain safe machine operation and allow the camera to get as close to the build platform as possible. The viewport will be made of metal to ensure any stray or reflected light from the laser will be blocked, but will have a 75 mm diameter sapphire window to allow viewing by the camera. The sapphire window will be at the end of a metal tube or sleeve, and the camera optics will fit within that tube. The tube will be allowed to slide in and out (along the optical axis) to accommodate different focal lengths. A nut over a tapered o-ring that fits around the tube will be tightened to hold the tube in place and ensure an air-tight seal. These considerations will allow the chamber to maintain proper pressure and atmosphere and will allow the machine's safety systems to operate as they are intended. The camera will be supported by a tripod at a 45° angle. Ordinarily this would be noteworthy because that angle would affect the emissivity of the object being viewed. However, the hyperspectral camera will image the same object at the same 45° angle, providing an in situ characterization of the emissivity. The primary concern with getting the camera close to the build platform is the clearance of the recoating arm. Figure 3c shows that the tube can protrude into the chamber by several centimeters while still allowing the recoating arm to safely pass by.

The primary benefit to imaging through the existing viewport is that it will not require any permanent modification to the machine. However, using the viewport requires a rather shallow imaging angle that because of the depth of focus will limit the field of view.

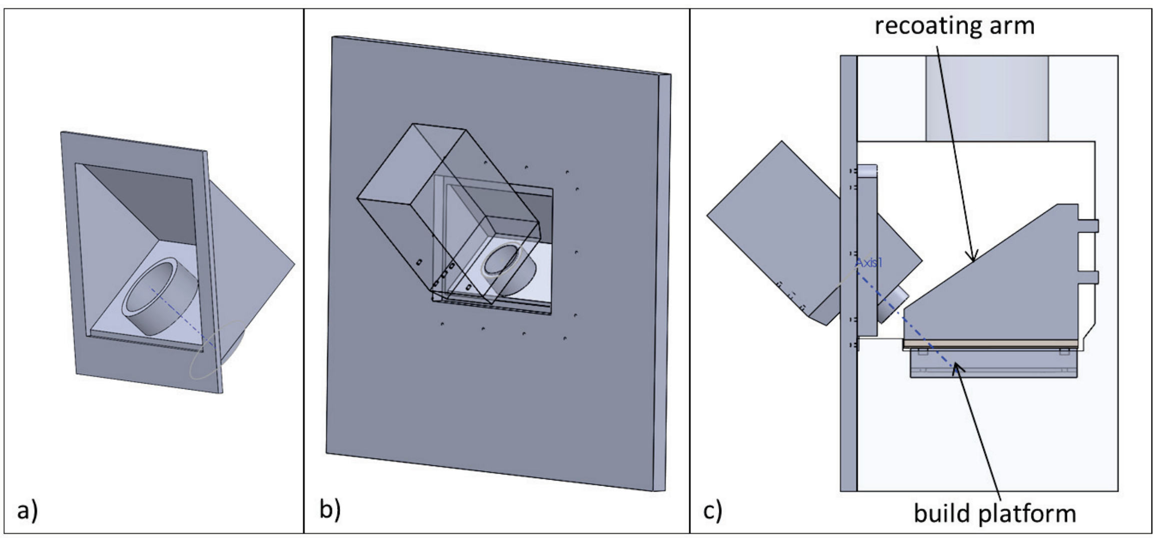

FIGURE 3. Solid model of the viewport used to accommodate imaging by thermal cameras (a); an assembly of the viewport, the machine's door and a thermal camera (b); and a side cross-section of the build chamber (c). In (c) the recoating arm would travel in and out of the plane of the page.

NEXT STEPS

Once all of the components are manufactured and in place, process parameters and camera settings must be determined before experiments are conducted. We aim to use industrially relevant process parameters and choose camera settings that allow measurement at those speeds and temperatures. However, the actual magnification achievable will be observed when the camera is in place, and this value may affect the necessary camera settings. For example, at very high magnification, a beam traveling near 1 m/s will pass through the field of view very quickly, requiring precise timing to trigger the camera as well as a very fast integration time to reduce motion blur. Fast integration times make the camera less sensitive to measuring lower temperatures, possibly limiting the spatial gradient that can be measured. As such, multiple measurements using a variety of camera settings may be required to fully measure the scene.

We will work closely with industrial stakeholders and academic collaborators to ensure the temperature data we provide will allow validation of multi-physics models of the process. Validated process models will allow more rapid understanding of the PBF-L processes and, with model-based qualification, can reduce the time from design to final product.

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