# Overview of In-Situ Temperature Measurement for Metallic Additive Manufacturing: How and then What

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## Abstract

Additive manufacturing (AM) is important in industrial and economical domains but still lacking process accuracy. In-situ measurement and process control can offer an effective solution. In AM based on metals, the temperature field of melting pool has critical impacts on phase transformation and mechanical properties. Researchers have developed various approaches to track real-time temperature during ultrahigh temperature in AM. Nevertheless, large temperature gradient around the energy source demands a capable measurement system and method due to the limitations of the conventional infrared cameras and pyrometers. This study will explore the deficiency and improvement of the existing approaches with a focus on the cutting-edge methods of AM process temperature measurement, along with a critical thinking about the follow-up usage of the collected data. Specifically, it will report the status and trends in employing various machine learning and advanced control techniques with the in-situ sensor data for process qualification purposes.

## Introduction

Metallic additive manufacturing (MAM) is a branch application of additive manufacturing (AM) that applies to metallic materials. However, metallic materials have melting points as high as thousands of Celsius. This means that the working temperature of MAM is usually much higher than conventional AM which copes with polymers and composites. A pioneering work, whereas, has extended the realm of AM into metals since higher temperature is required to melt metal and reform solid shapes and complex [1, 2]. MAM has great potential and prosperity as it facilitates development of industry grade metallic materials which are tailored for various properties and applications. However, the complexity of MAM overwhelms traditional AM as the thermal process of MAM involves phase changes, crystallization and residual stresses. The temperature of MAM where metals are firstly heated to melt and solidify in layer stacks, demands strict control. Because temperature changes induce metal phase variations that can affect mechanical properties such as tensile strengths [3, 4]. Thus, in-situ temperature measurement is critical in determining the quality of MAM.

Temperature measurement based on the radiation emission spectrum of material has been widely adopted and continuously improved. At higher temperatures (above 1000 °C), a thermocouple is not able to give reliable temperature values. What is more, in-contact technique where there is direct contact between thermocouple and targeted material brings about significant interference and inconvenience to the measurement. The physical limitation of thermocouple prevents it from probing temperature measurement of a small heated region by laser. Thus, for higher temperature measurement, non-contact temperature measurement is a more preferred way to fulfill this purpose. There have been great progresses ever since infrared pyrometer has been invented to detect infrared radiation emission from an object to indicate temperature corresponding to the emission intensity.

This article reviews various existing methods for in-situ temperature monitoring during MAM with a focus on the relatively sophisticated methods using two-wavelength and hyperspectral imaging techniques. We critically review the issues in the two emerging methods and point out possible approaches in evolving them and aim to realize more comprehensive and accurate in-situ temperature measurement for MAM. Challenged by the potential large-scale measurement data, this study highlights the perspective on applying machine learning to enhance these in-situ measure-

ment methods. Besides, given the availability of in-situ temperature data, we look forward to boosting the utilization of in-situ measurement data to serve the ultimate process control goal for the AM qualification purposes. We describe the evolving and development of two-wavelength temperature measurement technique for MAM process and the application of hyperspectral imaging as the detecting method for the temperature. We firstly explain the physical principle of the two-wavelength measurement. Then we introduce when two-wavelength technique is applied into MAM, it is faced with several problems. As a result, the signal captured by photo diodes may be replaced by high speed camera through hyperspectral imaging in the improvement cases. Finally, based on the development of two-wavelength technique and the application of hyperspectral imaging advancement within this technique, we speculate the application of hyperspectral cameras in two-wavelength system that allows for accurate measurement of multiple materials. Such suggestions to the current systems aim to address the listed problems.

## Conventional In-situ Temperature Methods

Originally, based on the principle that any material emits the electromagnetic wave, a great part of which is infrared light, and that the intensity of the emitted infrared wave is dependent on temperature, it is feasible to relate the temperature of an object to its infrared emission. Because semiconductors absorb light and transfer it to current through photoelectric effect, the produced voltage of a semiconductor detector may reflect the temperature of what the detector is absorbing infrared light from. This is a classic method of temperature measurement and it is called infrared irradiation temperature measurement. Its industrial process application is firstly designed for measuring grinding metal grain temperature by Ueda et al [5].

The infrared pyrometer (single-wavelength temperature measurement technique) is based on the determination of an object's radiation at different temperatures. By Planck's Law, for absolute temperature T, the spectral radiance of $L$ an ideal black body ($\varepsilon = 1$) can be demonstrated as:

$$L_d(\lambda, T) = \frac{c_1}{\lambda^5[exp(\frac{c_2}{\lambda T}) - 1]} \tag{1}$$

where $c_1 = 2hc^2, c_2 = hc/k_B$ ($h$ stands for Plank constant while $c$ means the light speed in the medium and $k_B$ Boltzmann constant).

Due to the complexity of the temperature in real cases and different material properties, there have been several assumptions which are able to make the problem easier. However, for the real case, since no material thermally behave similar to black body, the emissivity $\varepsilon$ for any material is always between 0 and 1. What is more, considering another fact that the radiation detection of emitted light from an object is accompanied with the loss of radiation during propagation, the transmission efficiency of the emission is specified as $\sigma$. Eq. 1 closer to the real situation is demonstrated as

$$L_d(\lambda, T) = \frac{c_1 \varepsilon \sigma}{\lambda^5[exp(\frac{c_2}{\lambda T}) - 1]} \tag{2}$$

If the exact spectral emissivity $\varepsilon$ and transmission efficiency of the optical path, $\sigma$, are obtained, the actual temperature can be solved by the detected signal $L_d$:

$$T_{actual} = \frac{c_2}{\lambda ln(\frac{c_1 \varepsilon \sigma}{\lambda^5 L_d} + 1)} \tag{3}$$

Eq. 2 can be further simplified by applying Wien's Approximation to Planck's law, which assumes that $hc \gg k_B T$ and thus $\frac{c_2}{\lambda T} \gg 1$. This leads to the simplified form of Eq. 2 for real cases

$$L(\lambda, T) = \frac{c_1 \varepsilon \sigma}{\lambda^5 exp(\frac{c_2}{\lambda T})} \tag{4}$$

There have been few experimental setups that apply single infrared measurement technique to probe the temperature of MAM process. Dinwiddie et al use infrared technique as the method for thermograhic in-situ monitoring on electron beam metlting MAM [6]. As an advancement, thermographic imaging is applied by Krauss et al to check MAM defects and discontinuous failure
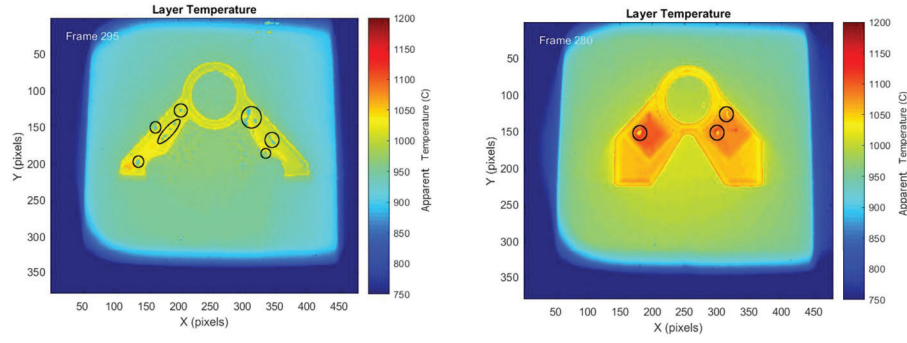
Figure 1: Wrong temperature displays in thermal imaging of MAM melted metal (reprofuced from [9])

spots in MAM melting pools [7, 8].

Conventional thermal imaging based on single-wavelength measurement technique, however, is proved to come along with significant problems. In a comprehensive study of thermographic in electron beam MAM, Raplee et al discover mispresentations of temperature measurement using infrared single-wavelength as the method [9]. It is obvious that this causes wrong temperature display on thermal imaging graphs (Figure 1). This is because that the sensing model of single-wavelength temperature technique is lacking adequate parameters. It is also worth mentioning that single-wavelength measurement can be easily interfered and disrupted by the variance of an object's ability to emit infrared radiation (which is named emissivity) under different wavelengths. Overall, the drawbacks of single-wavelength technique can be further replaced by more advanced and complicated temperature measurement method to eliminate such interference and disruptions.

### Advancing In-situ Temperature Measurement Based on Two-wavelength Pyrometer

Interestingly, a more reliable methodology is further developed by Zhu et al [10] where two photo detectors are applied to selectively absorb emitted infrared light in different ranges of wavelengths. The ratio between two voltage reads of detectors reflects the temperature as a linear dependence. This two-wavelength temperature measurement technique brings about significant advantages over the previously developed single infrared measurement technique and is widely adopted.

Most temperature measurements utilize a system composed of two infrared pyrometers for a favor of higher accuracy and less noises. This is called two-wavelength technique. Two-wavelength pyrometers use two separate and distinct wavelength sets on a filter wheel. Because the design allows for separate wavelengths, these wavelength sets can be independently selected and combined to allow for some unique capabilities.

For two-wavelength technique, it employs two discrete measurements of the object emission based on Eq. 4 but at two different wavelengths. The ratio is made between the radiated light intensities at two different wavelengths, $\lambda_1$ and $\lambda_2$. which yields to

$$R_{12} = \frac{L_{\lambda_1}}{L_{\lambda_2}} = \frac{\sigma_{\lambda 1}}{\sigma_{\lambda 2}} (\frac{\lambda_2}{\lambda_1})^5 \frac{\varepsilon_{\lambda 1}}{\varepsilon_{\lambda 2}} exp[\frac{c_2}{T}(\frac{1}{\lambda_2} - \frac{1}{\lambda_1})] \tag{5}$$

The optical transmission efficiency (from the target object to the detector) does not change with different wavelengths. Then, temperature is measured through the ratio

$$T_{Measure} = \frac{c_2(\frac{1}{\lambda 2} - \frac{1}{\lambda 1})}{ln R_{12} - ln(\frac{\varepsilon_1}{\varepsilon_2}) - 5ln(\frac{\lambda_2}{\lambda_1})} \tag{6}$$
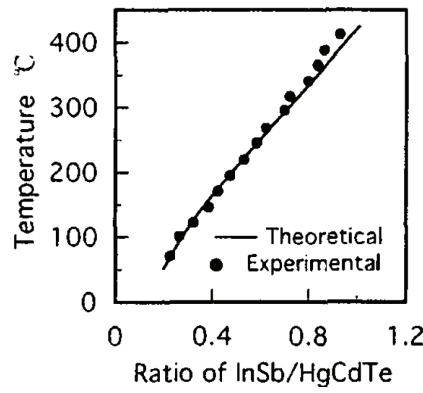
Figure 2: Two-wavelength measurement of single crystal diamond tool in turning(reproduced from [11])

As an example of two-wavelength measurement made by Ueda el al, the result should occur in the form of a ratio-temperature curve [11].It is worth mentioning that the second term in the denominator of Eq. 6, $ln(\frac{\varepsilon_1}{\varepsilon_2})$, is often neglected. This is because that the Wien's Approximation simplifies the term so that the emissivity value, for a short range of wavelength, of the object may be treated as a fixed value ($\varepsilon_1 \approx \varepsilon_2$). In this way, the two-wavelength technique bases the measurement of temperature on two different measurement wavelengths and their corresponding irradiation intensities.

### The Emissivity in Two-wavelength Pyrometer

To fulfill the Wien's Approximation that the emissivity values at different wavelengths are offset by each other, it is required that the difference between the emissivity values at two different measurement wavelengths is small enough to be ignored. However, this raises a challenging issue where two-wavelength measurement based on Wien's Approximation is not always accurate. It is expected that the wavelength range where two-wavelength technique choose is certain region where the emissivity relatively keeps flat. If the emissivity does not vary with wavelength, by no means temperature measurement in this way will cause error because of wavelength. For example, in Figure 3, two-wavelength technique gives very accurate temperature measurement values in the range of $8 - 10\mu m$ as it is anticipated that emissivity value keeps flat within this wavelength range.
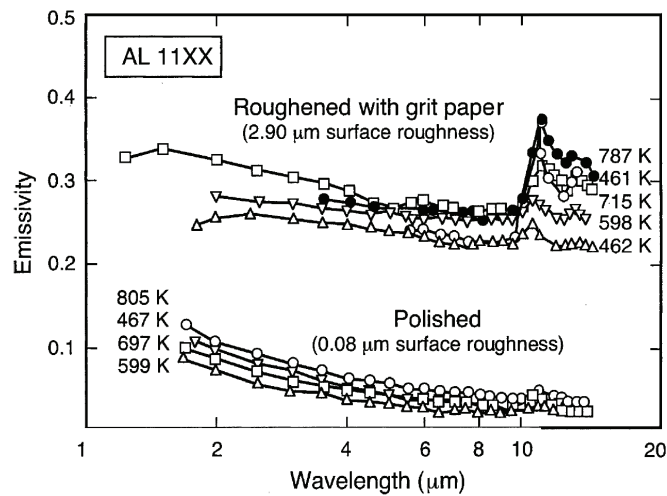


Figure 3: Emissivity of Al in different mechanized level at different temperatures from the wavelength $1\mu$m to $20\mu$m (reproduced from [12])
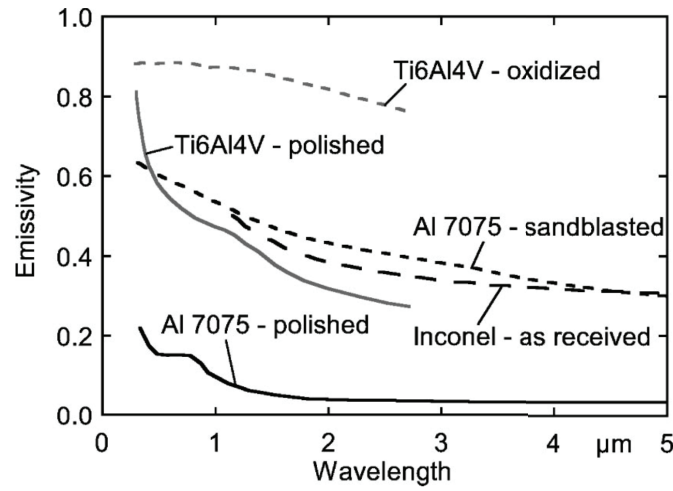
Figure 4: Analyzed spectral emissivity of metallic surfaces (Temperatures: Al 7075 - 306K, Inconel - 1023K, Ti6A14V - 298K)(reproduced from [13])

Figure 4 demonstrates the relationship between spectral emissivity and wavelength of several typical material surfaces [13]. From the graph, the emissivity of oxidized Ti-6Al-4V tends to be stable when the wavelength is smaller than $1\mu m$. The polished Al's emissivity value over wavelength is further confirmed by Figure 3. There is consistent demonstration of the emissivity of polished Al from $1\mu m$ to 5 between Figure 4 and Figure 3. It can be concluded that Al emissivity remains relatively flat without fluctuation from 2 to 5 $\mu m$. where we see the feasibility of designing two-wavelength measurements to minimize the interference brought by emissivity changes. What is more, Figure 5 shows that the emissivity of nonoxidized Ti–6Al–4V alloy has nearly no fluctuation in the wavelength of 2000nm-2200nm . Thus, similarly, the detection wavelength can be set into this region to reduce the error, too. Two-wavelength technique effectively works under high temperature higher than metal melting points, making this technique feasible for the tool to probe MAM temperatures.
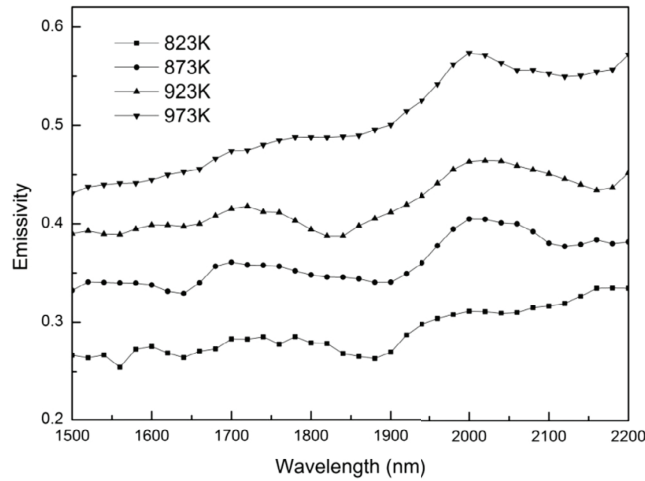


Figure 5: Normal spectral emissivity of the Ti–6Al–4V alloy (reproduced from [14])

However, during MAM process, despite that using two-wavelength technique for the measurement of the melted metal is suitable, it is also faced with emerging challenges, especially the variance of emissivity value. Although two-wavelength technique works for higher temperature measurement, due to the heat source from a focused laser beam in MAM, the measuring area of the melted metal is very small. This requires more sensitive detectors. Moreover, the requirement to plot spatial temperature profile within the irradiation of the laser spot cannot be fulfilled by photo diode detectors. This is because that detectors only measure total voltage of an area.

It is extremely difficult for detectors to provide temperature distribution in physical radius basis. There are advancements of two-wavelength technique that allows for spatial measurement of temperature. Hooper has designed a two-wavelength system where two high-frame rate (200,000 fps) cameras were employed to create melted metal thermal profile over time for the cooling of the heated metal and the effect of a laser displacement scan [15](Figure 6). Because two photo diodes are also installed in this layout, the system is also able to traditionally measure the voltage ratio to determine average surface temperature of the irradiated melted area. A series of bandpass filters are applied to either prevent the reflected laser from burning measurement components or provide beams in two discrete wavelengths. Because of the dichronic beam splitter, it is an advantage that the two camera layout is able to image thermal profiles from different wavelength to make comparisons.
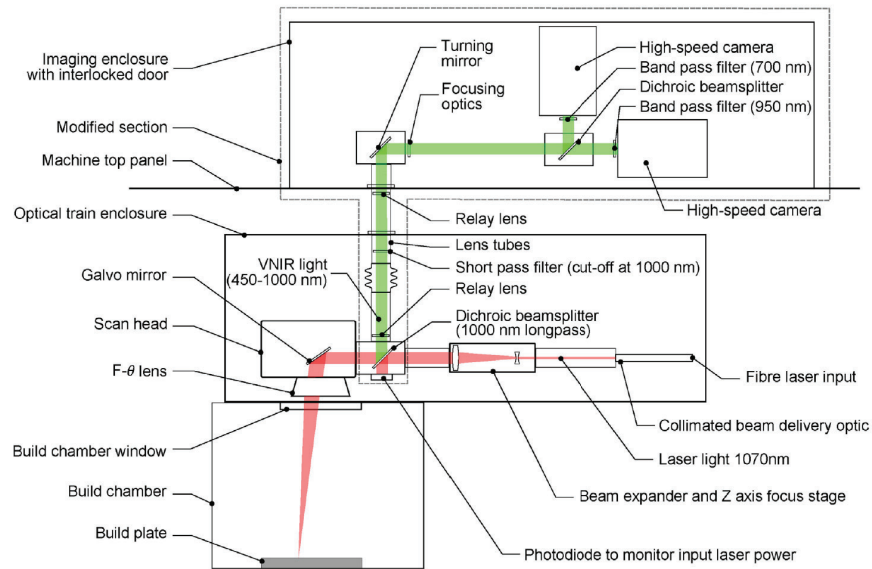


Figure 6: High speed camera aided two-wavelength thermal imaging system (reproduced from [15])

For another major issue of the varying emissivity values, current two-wavelength technique does not helpfully reduce measurement errors. It is clear that the "flat emissivity" wavelength range can possibly found on several materials (shown in Figure 3,4 and 5). The obstacle lies in the difference of these "flat ranges". Almost every material holds different "flat region" and the $\varepsilon - \lambda$ curve is greatly affected by mechanical and physical condition for the same kind of material (Figure 3 and Figure 4). Figure 9 demonstrates the spectral emissivity of several common metal surfaces in Near-IR range [14]. These curves show that different metals have different "flat emissivity areas", making the assumptions behind two-wavelength pyrometer invalid. Therefore, it is challenging to measure temperatures during MAM process, especially while fabricating multi-material components as existing two-wavelength pyrometers are unable to adjust the measuring wavelengths for various materials. This explains that a two-wavelength pyrometer with certain wavelength working range is always not able to accurately measure temperature of different objects in MAM.

As for the system in Figure 6, it has a few limitations. Firstly, this improvement only has allowed for the thermal imaging of two-wavelength techniques. The particular problem with the huge difference of the emissivity-wavelength relationship between various materials is still not addressed. It is reasonable to assume that this technique facilitates the need to expand measurement areas but does not effectively eliminate the issue of measurement accuracy in terms of multiple materials. Secondly, owing to a large flow of data captured by the high speed cameras, the system is too stressful to process the mass volume of signal. Lacking proper control and analytic techniques, this system has limited ability to accommodate the transformation from simple photo diode voltage signals to more sophisticated and enormous imaging signals. Further improvements are expected to address these issues based on the current design of Hooper's system. In short, regarding further advancement, this system has paved a way for providing the valuable basis of

hyperspectral imaging and ideas to thoroughly investigate and eliminate the emissivity issues in two-wavelength measurement.

### In-situ Emissivity Measurement for Temperature Measurement

For the accuracy of two-wavelength measurement, knowing the emissivity spectrum of the target is crucial. There have been developments to measure the emissivity spectrum of a wide range of opaque materials. For example, National Institute of Standards and Technology (NIST) has carried on research in determining emissivity spectrum over wavelengths by optically detecting the emission of the target object's radiation under certain temperatures and evaluating the emissivity values in reference to a pre-set black body [16, 17]. The measurement facilities built in NIST along with their Fourier-transform Infrared Spectroscopy (FTIR) tools help measure emissivity of an object optically (Figure 7). There is the reference black bodies on the left side of Figure 7, in comparison with the emitted radiation of the sample placed in a spherical reflectometer, idealized as an optically isolated shell. The laser source mirror is tilted to tune the light source for different wavelengths. The radiated emission is further proceeded by another similar layout (right and bottom side of Figure 7) where the FTIR spectrometer helps measure the radiation. A With this method
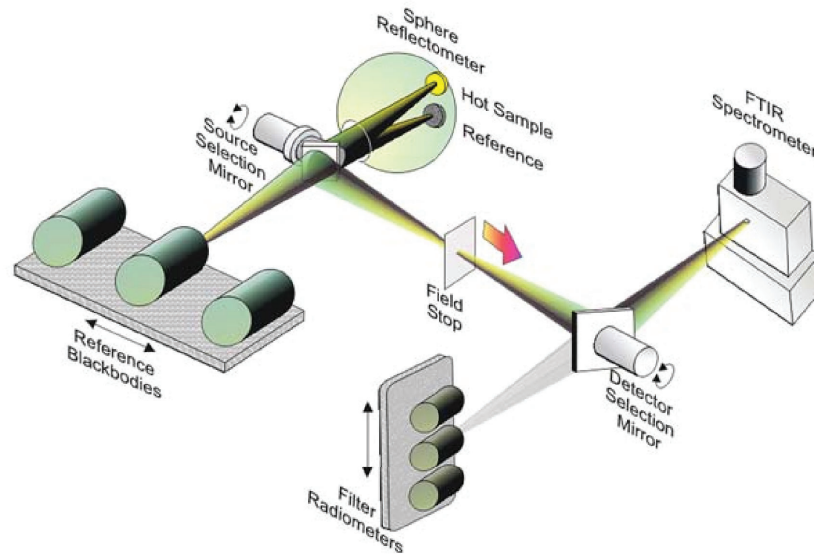


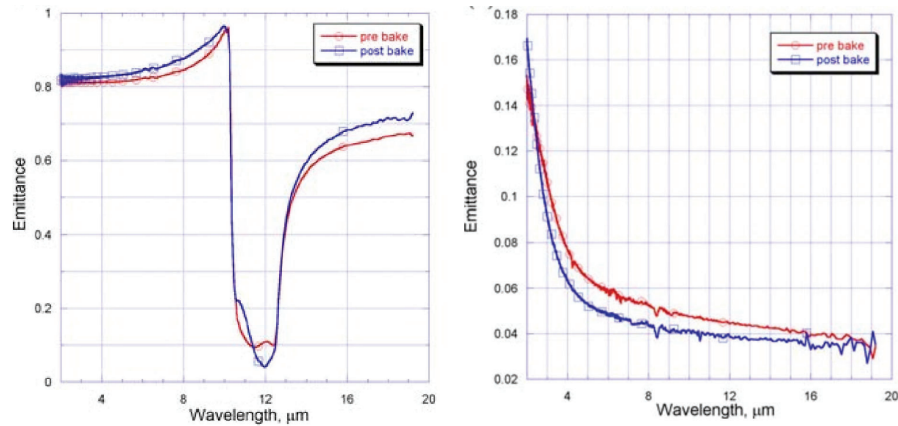Figure 7: The schematic layout of NIST emisivvity measurement facilities (reproduced from [17])



Figure 8: Emissivity Measurement by NIST facilities on various samples. LHS: $\beta$-SiC before and after baking at 600 °C, RHS: Pt–10Rh before and after baking at 1100 °C for 4 (reproduced from [17])

However, It is found that a few disadvantages of this system can impede its application into

two-wavelength measurement technique, especially in MAM. Although this system possesses effective measurement and accurate results in determining the emissivity spectrum of an object, it is not capable of measuring multiple objects from different materials efficiently. Because this system is built based on the function to precisely plot the emissivity spectrum of certain materials that may be used as the component for industrial grade infrared pyrometer, it does not prioritize the direction to improve current two-wavelength technique, which requires that the "flat emissivity region" of materials be known as many as possible. Notably, The limitation of the wavelength range (2-20$\mu m$) of the measurement does not help provide help to the lower working wavelength two-wavelength techniques, which can be as low as 600 $\mu m$. What is more, The physical size and the complexity of the facilities do not allow the system easily being incorporated into current two-wavelength system. In spite of the effectiveness of this system in measuring emissivity, it is still apparent that this system has limited capability to address the problems two-wavelength technique of MAM process.

### Hyperspectral Imaging for Temperature Measurement

As an alternative to in-situ emissivity measurement for tackling the problems with two-wavelength technique, hyperspectral imaging (HSI) is introduced, as a more advanced and convenient technique, into two-wavelength measurement technique where the detectors are replaced by two cameras to detect the flat range of different materials. To address the limitations that stem from the over-simplified assumption of fixed emissivity in current two-wavelength pyrometers, hyperspectral imaging techniques can be employed to obtain the flat-emissivity or near-flat-emissivity wavelength band for AM materials. An offline characterization with HSI will generate emissivity-wavelength 2D plots. Analyzing the HSI data can aid a rapid detection of the desired "flat emissivity area" and identify the two closer but disparate wavelengths which satisfy the measurement principle and can be used in the two-camera pyrometer system to measure temperatures more accurately.
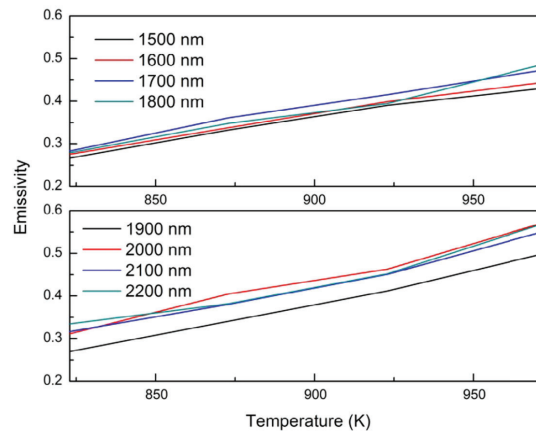


Figure 9: Spectral emissivity of the non-oxidized Ti–6Al–4V alloy as a function of temperature (reproduced from [14])
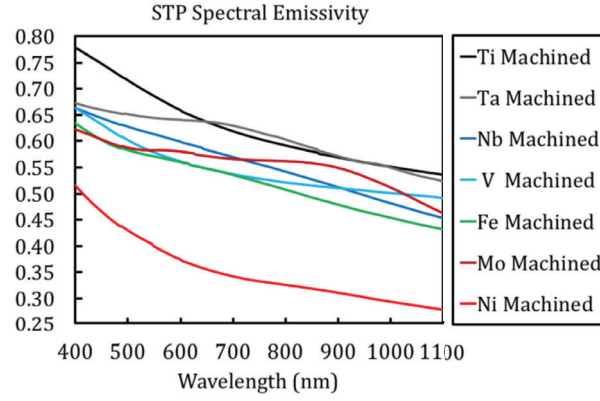
Figure 10: Spectral emissivity of the non-oxidized Ti–6Al–4V alloy as a function of temperature (reproduced from [18])

For more advanced needs in two-wavelength measurement, hyperspectral imaging (HSI) expands the applicability and functionality of two-wavelength techniques and its application proved valid in MAM. HSI technique, which collects electromagnetic waves from material and image each pixel of the temperature profile by color-gradient photo of a certain area to convey the temperature profile and distributions within that area [19, 20]. For melted metal temperature distribution, HSI has been applied to determine temperature profile pf a laser heated melted stainless steel pool (1.35 mm diameter) [21]. HSI is, therefore, a great measurement tool for the temperature plot of melted metal. Another need which is important to the study of MAM is the capability of recording temperature profile of dynamical process, such as heating and cooling process, laser scanning movement. and temperature response of metal to laser heating power variation. Besides, it is possible that data mining may be employed to analyze the great volume of data formed for temperature profile of every pixel in HSI. It is worth applying computational tools, such as machine learning, to study the high amount of temperature profile and distribution data from HSI scanning.

In spite of the benefits of two-wavelength pyrometer, the grey body approximation does not always fit the actual situation. For more accurate measurement, it is necessary to establish a sophisticated model between emissivity and wavelength. For most of the multi-spectral pyrometer, the emissivity is modeled as a smooth function of wavelength, which contains m unknown parameters (emissivity parameters and surface temperature) [22]. The whole system has n equations with $m \leq n-1$.

Most metal materials have an emissivity that linearly decreases as the wavelength increases. Devesse et al. [21] has developed a non-contact method to measure temperature of liquid stainless steel using hyperspectral camera. This method is mathematically based on
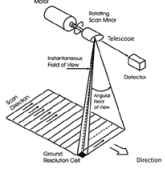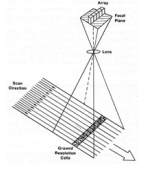
$$\varepsilon_\lambda(\lambda_i) = B_\varepsilon - A\varepsilon \frac{\lambda_i - \lambda_1}{\lambda_N - \lambda_1} \qquad (7)$$

Eq. 7 illustrates the real case emissivity within a range of wavelengths [21]. It is found that emssivity of metals is actually dependent on the wavelength. In Eq. 7, the way to determine the decreasing trended emissivity is by choosing a wavelength range with a number of segments ($1,2,3 \cdots N-1, N$) and plugging the minimum and maximum wavelength $\lambda_1$ and $\lambda_N$, to determine the emissivity of the metal at a certain wavelength within in this range. $B_\varepsilon$ (emissivity at $\lambda_1$) and $A_\varepsilon$ ($\Delta\varepsilon$ between $\lambda_1$ and $\lambda_N$) are constants affiliated to the experimentally tested values. By this method based on Eq. 7, the true temperature can be bounded by a lower value and an upper value. However, although the solid part and the liquid core can be described as the linearly decreasing function, the mushy region in the middle has a chaotic relationship between emissivity and wavelength. Blackbody calibration method might be used for this area.

Fiber is also an excellent method to measure the temperature of the mushy area. Fu et al. [23] developed a fast fiber-optic multi-wavelength pyrometer, which is able to provide sufficient choices of multiple measurement wavelengths using optical diffraction, and avoid the use of narrow-band filters. The optimal bandwidths have been found, which are trade off between the simple emissivity model assumption and the multiple signal discrimination to give the best system.

The spectra emission of target object is captured by the camera and projected onto spectroscope through a slit. The imaging sensor then collected data from the dispersion spectrum. Since this 2-D information $(x - \lambda)$ only belongs to one single line of the object, the whole 3-D data cube can be obtained by scanning the camera through y axis.

Table 1: Two major methods of HSI scanning and their distinct features

| | Cross-track Scanning HSI [24] | Along-track Scanning HSI |
|---|---|---|
| |  |  |
| Advantages | Large FOV (Field of View); Large wavelength range | Long dwell time, for the pixel dwelling time only depends on platform speed; High Spatial and Spectral Resolution; Small instrument volume |
| Disadvantages | Short dwell time for each pixel, hard to improve Spectral Resolution and SNR (Signal Noise Ratio); single-point measurement, cannot provide full-field measurement simultaneously | Small FOV (About 30°); Calibration requirement for thousands of sensors, making data unstable |

The slit cannot be too wide or too narrow. If the slit is too wide, the spectral resolution will be reduced; if the slit is too narrow, there will not be enough energy for the system to capture.

HSI gives the high-resolution and continuous spectral characteristic image of the target. It is easy to choose and extract a specific wavelength band to analyze. HSI can also cover much wider spectrum range than conventional multi-wavelength method while in the same spatial resolution, providing more radiant, spatial and spectral information.

However, due to the tremendous amount of data produced by HSI, precision of classification will be limited if using improper methods. The number of training samples needs to be extremely large, and training parameters might be unreliable if this condition is not met.

Since the spectrometer band channel of HSI is dense, the energy of imaging is insufficient, causing the signal-to-noise ratio (SNR) of HSI hard to improve. In the process of acquiring imaging data, spectral characteristic is prone to distortion under the effect of noise. In addition, due to the large amount of hyperspectral data, it is necessary to reduce the dimension in the fine classification process, during which compressing noise is required [25]. Therefore, noise has a direct impact on the results of fine classification, and it is indispensable to de-noise in the hyperspectral data.

## Machine Learning MAM Temperature Measurement

Machine learning is a popular technique to handle and harness large amount of data. Herein, we will concentrate on mining HSI data for MAM temperature measurement. Overall, machine learning can be employed to analyze HSI data for (1) dimensionality and noise reduction, and (2) accurate temperature calculation, as discussed in the next section.

Firstly, when HSI is applied to replace traditional infrared detectors, it generates much more data owing to a temperature profile in more dimensions, such as physical place, emissivity and time at the same point or different locations. This explosive amount of data cannot be quickly analyzed manually. For dimensionality reduction, the target is to delete most of the redundant part in the data cube, while keeping the valuable information as much as possible. Principal Component Analysis (PCA) is one of the most common method. Each wavelength band is treated as a vector. If the data cube contains p wavelength bands, with each image slice has a dimension of mn, then the procedure can be briefly listed as follows [26].

1. The image cube can be expressed as $X = [x_1, x_2, \ldots, x_p]^T$, where $x_i$ is a $N1$ vector. N equals to $m \times n$, which means cutting the image slice into strips and then paste them in sequence;

2. Subtract the mean vector from X, Y=X-E(X);

3. Calculate the covariance matrix Σ of Y;

4. Calculate the eigenvalue matrix Λ and eigenvector matrix A of Σ;

5. Do PCA Transformation: $Z = A^T Y$.

Besides PCA, researchers have developed more advanced methods, such as Segmented Principal Component Analysis (SPCA), Residual-scaled Principal Component Analysis (RPCA), and Maximum Noise Fraction (MNF) Transform.

Secondly, machine learning provides more a tool to more accurately measure temperature of MAM. This is fulfilled by taking more factors that will affect temperature of melted metal in MAM into consideration. Formal two-wavelength detector values cannot give data of other parameters in MAM, such as optical changes of lenses, to compensate their effects on the temperature measurements. However, by taking data of more parameters, machine learning processes such data in comparison with varying conditions so as to determine the influence of certain condition changes. Such feedback, once processed through data mining, is easy to be recognized and corrected. As shown in Figure 11, a simple utilization of the MAM measurement data, feedback control loop, outperforms traditional data-limited temperature technique in its information-rich data and more comprehensive analysis. The in-situ measurement data from MAM provide the source for data mining and machine learning employs different algorithms to model or analyze the influence of varying parameters. This process finally gives a comparison as well as the accuracy of the data that can be used to improve the temperature measurement technique. Notably, because of the application of camera techniques which allows for pixel to pixel data of temperature profile, the large amount of experimental data can be produced.
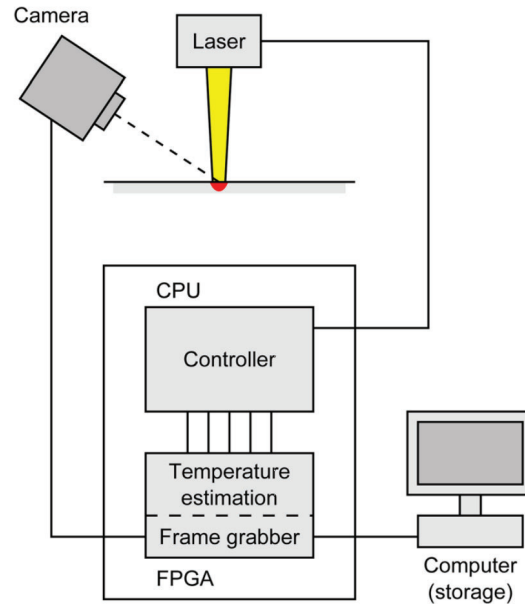


Figure 11: The feed back control loop of computer monitoring MAM temperature measurement (reproduced from [27])

The link between in-situ temperature measurement of MAM and machine learning lies in the fact that a great amount of data from temperature measurement is worth the analysis for modeling. Despite that there has not been work specifically done for data machine learning, MAM temperature measurement has been modeled based on the methodology and various generated data. There has been progress in the data analysis of in-situ MAM temperature measurement outcomes. In correcting the inaccuracy of infrared measurement, Rodriguez et al applied experimental values of emissivity profile of Ti-6Al-4V in temperature scale referred from Yang's work [28] to approximate the surface temperature of powder bed fusion MAM [29]. They make use of the emissivity data at different temperatures to model the surface temperature of powder bed fusion MAM (Figure 12) while compare the corrected temperature measurement result based on emissivity changes over temperature and confirm the validity of the correction by measuring the temperature with a

direct contact thermocouple. The approximation utilizes the factors from optic transmissions and reflected temperature, which have negative influence on the infrared thermographics technique. The feedback turns to be fairly effective in reducing the errors of surface infrared temperature measurement of melted metal. Similar practice that makes use of measurement data has been employed in determining absorptivity of laser powder bed fusion MAM targets [30]. A large group of data produced by a high speed scanner has given a coherent absorptivity of MAM target and provide the fundamental basis for further simulation and modeling (Figure 13) [31].
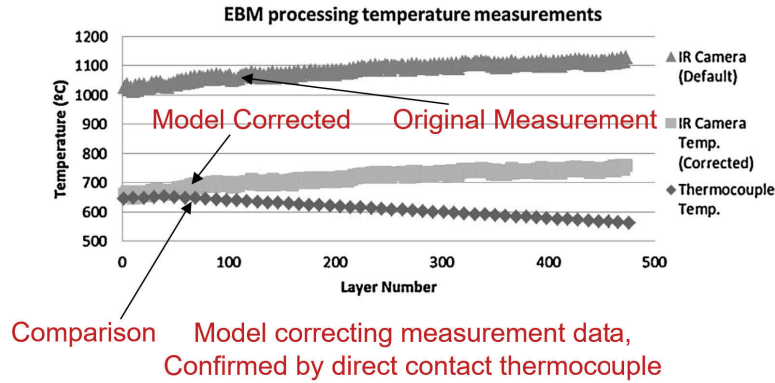


Figure 12: Model Approximation of MAM temperature with the confirmation of direct thermocouple measurement (reproduced from [29])
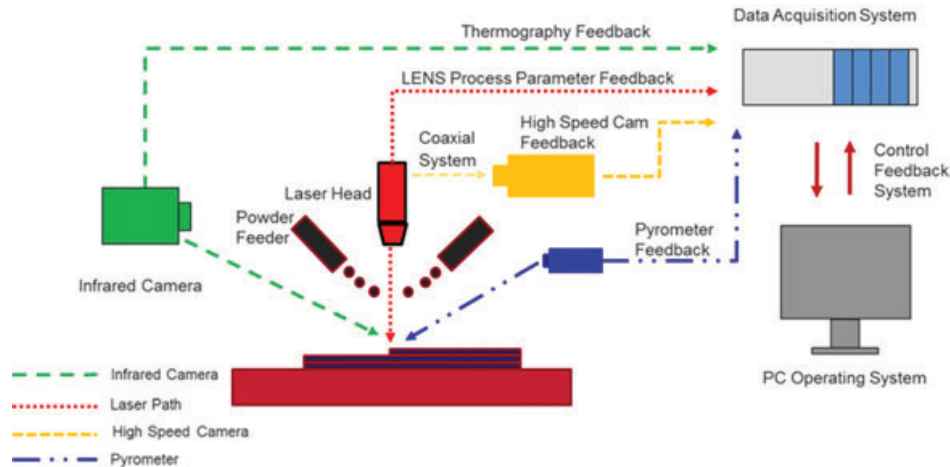


Figure 13: Multi-sensor based comprehensive MAM temperature measurement system(reproduced from [31])

It is quite clear that the mentioned works are following the track to improve the in-situ technique of MAM for higher accuracy and more diverse functionality. However, in terms of the previous work, the complexity of modeling and data amount are lacking. It is recommended that the temperature value of be measured in response to as many aspects as possible. The utilization of data mining lies in exploiting various aspects of temperature data at the same time for analysis.

## MAM Process Control with In-situ Temperature Measurement Results: Status and Outlook

Given in-situ temperature measurement results being available, real-time and closed-loop control technologies are still in infancy stage. Existing literature on MAM process control shows preliminary results based on simple models or limited sensor data [32–34]. Research on real-time and closed-loop control for DED based MAM is relatively ahead of that for PBF MAM, but all of these MAM processes still confront challenges by super-fast process dynamics and by lack of fast and accurate enough in-situ real-time temperature monitoring systems. With the advancement of

high-performance computational and data science enabled in-situ monitoring, MAM process control will gain more substantial development to realize the ultimate goal of on-the-fly input (e.g., energy power and material feed) manipulation to enhance the output quality.

## Conclusions

We introduce the application of two-wavelength technique as a reinvented method to measure high temperature MAM. It is notable that the replacement of infrared detectors with high speed VI-NIR cameras can bring greater spectrum for the temperature measurement of MAM in an extended way to generate temperature fields. Importantly, we see the paramount role of HSI that can provide rich encoded temperate data. Combined with machine learning, the emerging HSI method can offer more robust and accurate estimations for key parameters in temperature calculation and thereby enhance the accuracy of the two-wavelength temperature measurement methods. A more capable in-situ temperature measurement system can be designed to benefit from two-wavelength and HSI methods.

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