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A Review of In-situ Temperature Measurements for Additive Manufacturing Technologies

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Learning Objectives:
The attendee will learn the basics of various additive manufacturing technologies, the methods used for in-situ temperature measurements of these processes, and current and future efforts in improving these measurements.

Abstract
Additive manufacturing (AM) encompasses a rapidly advancing host of technologies used for building parts with complex geometrical shapes layer-by-layer from a wide range of materials such as polymers, glasses, ceramics, metals, and metal-alloys. A wide variety of AM processes are used to build parts on test beds using processes such as material extrusion and laser or e-beam irradiation of powders and liquids, depending on the industrial or commercial application. Unfortunately, the dimensional and compositional quality of AM built parts highly depends on the technology, and can even significantly vary between different AM machines of the same technology, due to a lack of process feedback and control. Improvements have been made by performing computational modeling and ex-situ characterization such as x-ray diffraction, focused ion beam cross-sectioning, x-ray computed tomography, and electron microscopy. These techniques, however, are time consuming, expensive, and do not allow in-situ monitoring of parts as they are built. In-situ temperature measurements are promising as they monitor the build temperature and can provide feedback for better process control. Thermal imaging is widely-used for in-situ temperature measurements, but is limited to qualitative data due to the unpredictability of emissivity as temperature and composition dynamically change. Two-color pyrometry and mm-wave radiometry measurements promise to circumvent these problems but have their own dimensional limitations. These methods and others will be compared and contrasted, and future improvements of in-situ temperature measurements will also be discussed.

Introduction
Additive manufacturing (AM) is a rapidly developing field encompassing a wide range of technologies used for building parts with complex geometrical shapes layer-by-layer [1]. Many different materials have been demonstrated such as polymers, ceramics, metals, and metal-alloys, with metals and metal-alloys being of major interest to industry [2, 3]. AM provides many benefits to industry, where parts are rapidly printed without the need for casting or expensive and

energy intensive processes. A major concern, however, is the quality of build parts, as compared to more traditional manufacturing methods [1]. In most processes, parts contain many defects, with voids (ranging from a few nanometers to several microns) being a common problem, which can cause major problems such as surface roughness on the order of part feature sizes ranging from microns to millimeters, variations in stoichiometry across a part, and unexpected fracturing during tensile testing [4]. The main cause of these problems is variations in process conditions such as powder purity and particle size, the AM energy source (commonly laser light or electron beams), chamber conditions, and unknown process temperatures. Repeatability between each run is also a concern, and the quality even varies for similar AM processes across different manufacturers, which can make it difficult for the operator to choose which machine is best for their application [5]. Since in-situ monitoring is often too complex, ex-situ techniques such as x-ray diffraction [6], x-ray computed tomography [7], and focused ion beam cross-sectioning and electron microscopy [8] are utilized to investigate the build quality after a run is completed. These methods provide insight into the final part quality but do not provide details of how the material and part evolve during the build process. If such problems are not addressed, AM cannot be expected to address the challenges posed by ever increasing demands for part uniformity.

Due to the importance of complex metal parts for industry, this review will focus on in-situ measurements for metal-based AM techniques. Some common AM techniques include laser engineered net shaping (LENS) [9], powder bed fusion (PBF) [10], and material jetting [11]. PBF is one of the most common AM techniques for building parts from metal powders. This technique usually utilizes either electron beam energy or laser energy in direct metal laser sintering (DLMS), shown in Figure 1.

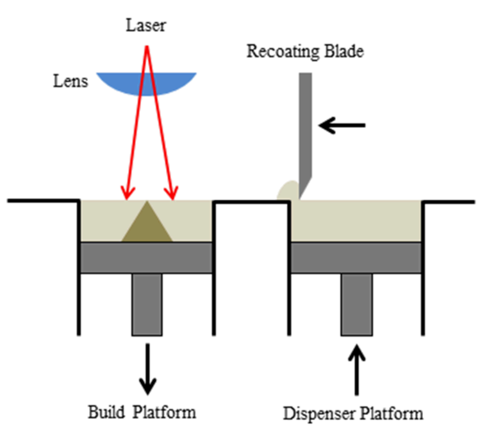

Figure 1. Illustration of a DMLS process build is shown. Laser light melts the powder and the dispenser provides new powder to the build platform. Adapted from Ref. [1].

Metal powder is fed to the build platform from the dispenser platform via a recoating blade for each build layer. Once the powder is dispersed, a focused laser beam rapidly scans across the powder, the powder melts, the melt solidifies, and the build platform lowers to ready for the next powder layer to be dispersed. The extreme thermal gradients during a build means that the stoichiometry and quality of a part can be highly variable throughout a build if process conditions are not tightly monitored and controlled. The lack of feedback control is a major problem for DMLS, since process conditions such as laser scan speed, laser power, and beam overlap are typically set at the beginning of a run and are not changed during the build. This often leads to sections of un-melted powder buried in sections of melted powder and are a source of significant defects [12].

There have been several studies on electron beam and DMLS where in-process monitoring has been performed [10, 13, 14]. These studies, typically, use optical sensors such as photodiodes or IR cameras to monitor the brightness of the melt pool as the laser or electron beam are scanned across the powder and use quantitative data (such as melt pool size) as feedback control to change the electron beam or laser parameters. These efforts lead to increased part uniformity by decreasing warping and increasing part density. Since the emissivity of the material is unknown during these processes, only the intensity of the melt pool can be used as a measured property (not the temperature), and the size of the melt pool is a quantitative parameter that can be used by the feedback control loop to maintain a desired melt pool size.

Temperature is arguably one of the more important properties to measure during a build [1]. Not only is it important for possible application to feedback control during the build, but any modeling effort must utilize realistic or known temperature values for the boundary conditions of the model. Modeling efforts show promise to bring insight to AM experimental builds in terms of predicting the density and microstructure of a build given the input parameters [15]. However, the input parameters are often unknown and if the exact build conditions are not measured, the models can easily be incorrect. Unfortunately, it is difficult to measure absolute and even relative temperatures due to unknown properties such as emissivity of the material as it is heated and rapidly cooled under varying chamber and surface conditions during the build.

Background of Non-contact Temperature Measurements

All objects at a temperature above 0 K constantly emit energy in the form of electromagnetic waves. The intensity of the emitted radiation is related to the temperature of the object, among other factors. In theory, measurement of the intensity of this emitted radiation can therefore be used to calculate object temperature.

Even prior to the introduction of the classical theory of electromagnetic radiation by Maxwell in 1862, it was recognized that the light emitted from hot objects in foundries and kilns was somehow related to the temperature. Josiah Wedgewood, an English potter, is often credited with invention of the first practical pyrometer in the late 18th century [16]. Initially, Wedgewood relied on pieces of clay fired at known temperatures to establish a color scale to which the temperature of the kiln could be compared. However, it was recognized that the technique was often unreliable. This was due to the wide variation in emissivity of the clay materials, which was unknown at the time. Later Wedgwood developed a technique to measure temperature based on shrinkage of fired porcelain.

The publication of Maxwell's equations marked a turning point in the understanding of electromagnetic radiation. Concurrently, Josef Stefan empirically derived the T^4 relationship for radiation emitted from a black body based on extensive analysis of earlier experimental data collected by Dulong and Petit. This was published in Stefan's now famous 1879 textbook, *Über die Beziehung der Wärmestrahlung und der Temperatur*. Stefan's student, Ludwig Boltzmann, approached the radiation problem theoretically using the Laws of Thermodynamics and arrived at the same result. Boltzmann also further extended the relationship to gray bodies [17]. In its modern form, this relationship is often expressed as:

$$E(\varepsilon, T) = \varepsilon\sigma T^4 \qquad (1)$$

Here E is the irradiance (W/m^2), or radiant flux received by a surface per unit area, ε is the emissivity of the body (unitless, ranges from 0 to 1), σ is the Stefan-Boltzmann constant (5.670×10^{-8} W/(m^2 K^4), and T is the absolute temperature (K). The radiant flux emitted by a surface is typically distinguished separately and termed the radiant exitance, M (W/m^2) [18]. Note that the relationship in Eq. (1) does not account for net radiation exchange or attenuation, and therefore applies only to an object in an expansive vacuum. For a black body emitter, ε=1. Emissivity may be defined as:

$$\varepsilon(T) = \frac{M(T)}{M_{BB}(T)} \qquad (2)$$

Here the subscript *BB* denotes black body. In addition to object temperature, emissivity depends on material, surface texture, oxidation, direction of emission, wavelength, and other factors. As a result, emissivity is typically determined empirically. From Kirchhoff's Law of Radiation, we know that:

$$1 = \alpha + \rho + \tau \qquad (3)$$

Here α is the absorptance, ρ is the reflectance, and τ is the transmittance of the object. All are unitless, range from 0 to 1, and depend on material properties and wavelength. Since energy must be conserved, when an object is in thermal equilibrium with its surroundings, the emissivity is equal to the absorptivity, such that:

$$\alpha = \varepsilon \tag{4}$$

This result enables practical measurement of object emissivity from determination of object reflectance and transmittance using Fourier transform infrared spectroscopy.

What is now known as the Stefan-Boltzmann Law, shown in Eq. (1), was empirically based and subsequently derived theoretically using thermodynamics. However, at the time significant additional study was being conducted into the nature of light and electromagnetic radiation itself. It was recognized that some functional relationship existed between the spectral emission of a body and its temperature. Using a classical approach, Lord Rayleigh and Sir James Jeans derived what is now referred to as the Rayleigh-Jeans Law [19]:

$$I(\lambda, T) = \frac{2\pi c k_B T}{\lambda^4} \tag{5}$$

Here I is the spectral irradiance (W/(m^2 μm)), k_B is the Boltzmann constant (1.380×10^{-23} J/K), T is the absolute temperature (K), c is the speed of light in vacuum (2.997×10^{8} m/s) and λ is the wavelength (μm). While the Rayleigh-Jeans Law accurately predicted empirical data at low frequencies (long wavelengths, when $h\nu \ll k_B T$), the relationship deviated significantly at shorter wavelengths (the so-called "ultraviolet catastrophe"). The failure of classical theory at shorter wavelengths is due to the quantum nature of light. It was Max Planck who, in 1900, presented results for a black body which are now known as the Planck Distribution:

$$I(\lambda, T) = I(\lambda, T) = \frac{2\pi h c^2}{\lambda^5 [e^{hc/\lambda k_B T} - 1]} \tag{6}$$

His derivation was based on earlier work by Wilhelm Wien, who developed a Displacement Law which indicated that the maximum spectral emissive power is displaced to shorter wavelengths with increasing temperature [20]. Planck's derivation relied on an additional term, now referred to as the Planck constant, h (6.626×10^{-34} J/s). For a non-black body, the Planck Distribution is scaled by the emissivity such that:

$$I(\lambda, T) = I(\lambda, T) = \frac{2\pi \varepsilon h c^2}{\lambda^5 [e^{hc/\lambda k_B T} - 1]} \tag{7}$$

The Planck Distribution tells us that an object at a given temperature, T, will have a characteristic curve indicating the intensity of photons emitted at each wavelength. Figure 2 plots the Planck Distribution for several black body object temperatures, and provides a comparison to a gray body distribution as well as the prediction using the Rayleigh-Jeans Law.

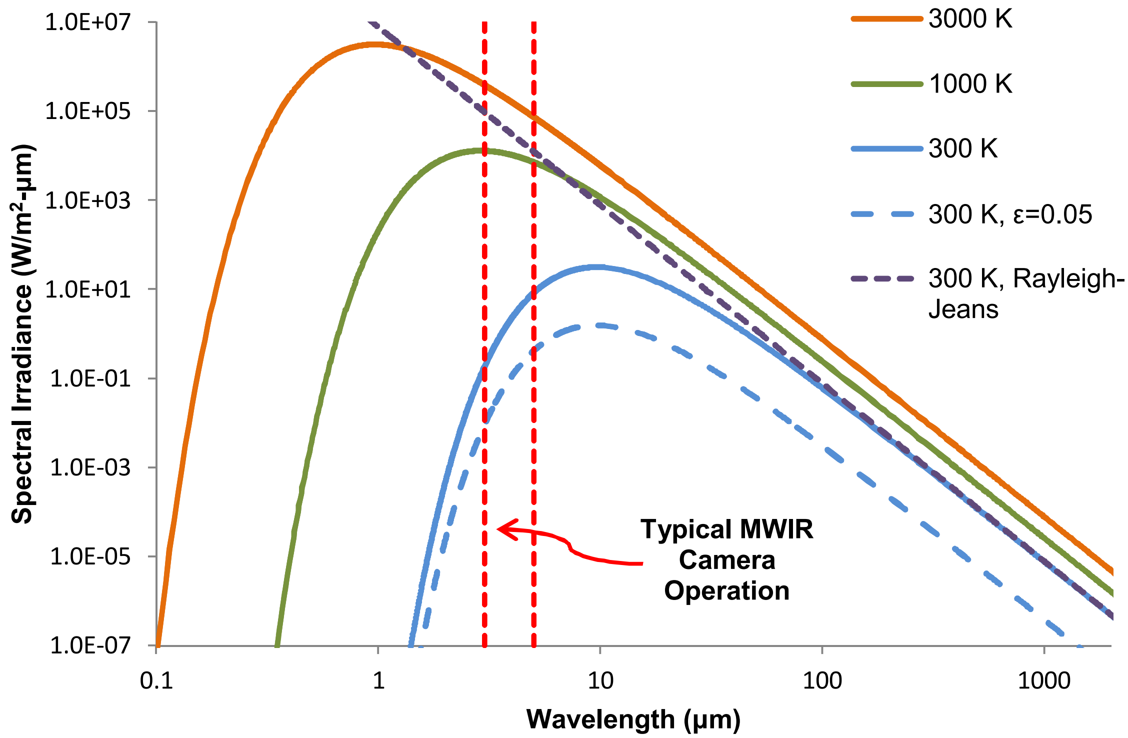

Figure 2. The Planck Distribution for Objects at Various Temperatures as Compared to the Rayleigh-Jeans Approximation. The typical midwave infrared (MWIR) operation range is indicated.

Simultaneous to the development of comprehensive theories describing the nature of light and thermal radiation, progress was made toward practical measurement of temperature using non-contact methods. In 1892, Le Chatelier introduced what is probably the first photometric pyrometer [21]. Not long after, a disappearing filament optical pyrometer was introduced by Holborn and Kurlbaum, with independent development in parallel by Everett Morse [22, 23]. The principle of operation relied upon passing a known current through a filament in a viewing window of the device, whereby the relationship between filament temperature and current was known a priori. When looking into a hot furnace or kiln, the current could be adjusted until the filament 'disappeared' from view, indicating the furnace was at an equivalent temperature. However, as with Wedgwood's technique, measurements were susceptible to very large errors due to emissivity variation.

For modern noncontact temperature measurements, emissivity variation continues to be a primary issue limiting accuracy of techniques relying on emitted radiation. For most practical materials, emissivity is nearly impossible to theoretically predict with reasonable accuracy due to the wide range of factors influencing the value. While data exists in handbooks, these are usually presented for generalized conditions ('polished', 'oxidized', etc.) as representative values. As seen in Figure 3, infrared emissivity varies significantly with temperature, presenting added challenges for laser powder bed fusion and other AM techniques given the wide dynamic temperature range encountered over short temporal and spatial scales.

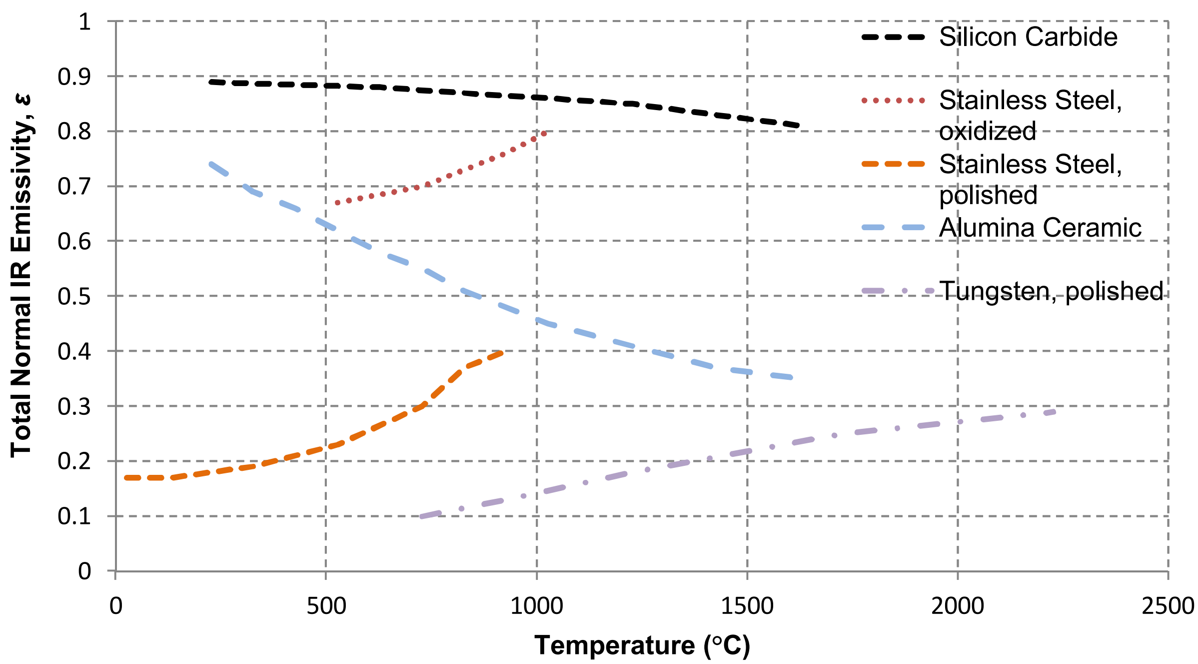

Figure 3. Typical Variation with Temperature of Surface-Normal Infrared Emissivity for Common Engineering Materials. Adapted from Ref. [20].

Emissivity may also vary significantly as a function of wavelength. Figure 4 illustrates the significant, and sometimes non-monotonic, change of infrared emissivity with wavelength of the emitted radiation. This presents challenges for two-color (or ratio) pyrometers, and is discussed further in the next section.

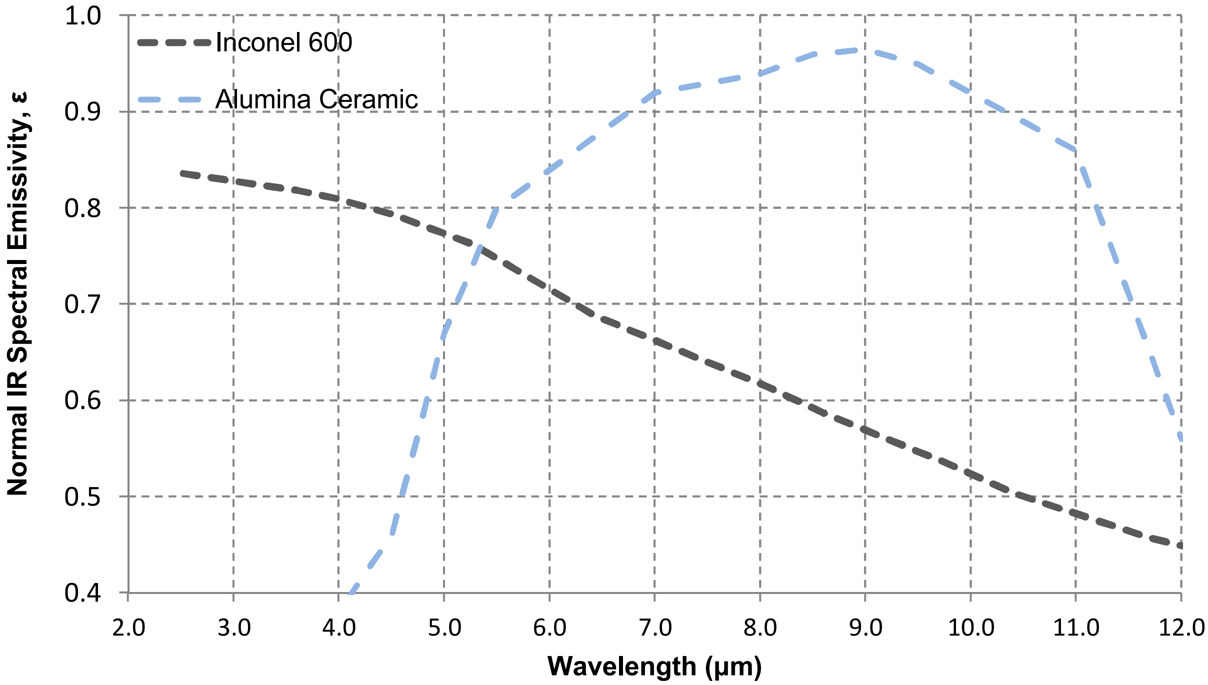

Figure 4. Surface-Normal Infrared Emissivity Variation with Wavelength for Inconel and Alumina. Adapted from Ref. [24].

Current AM In-Situ Temperature Measurements

Several approaches have been proposed or are in use for measuring temperature in-situ during the additive manufacturing process. Two-color pyrometry is not a new concept, but modern imagers are thought to be one of the more accurate off-the-shelf diagnostics for AM applications. Two-color, or ratio, pyrometers rely on measurement of the band-integrated intensity from two wavelength bands, or 'colors'. The wavelengths measured must be far enough apart to reduce amplification of errors when taking the ratio of the intensity values. The temperature may then be solved using the ratio of the Planck distribution for each wavelength or band:

$$\frac{I_1(\lambda,T)}{I_2(\lambda,T)}=\frac{\dfrac{2\pi\varepsilon_1 hc^2}{\lambda_1^5[e^{hc/\lambda_1 k_B T}-1]}}{\dfrac{2\pi\varepsilon_2 hc^2}{\lambda_2^5[e^{hc/\lambda_2 k_B T}-1]}}=\frac{\varepsilon_1\lambda_2^5\left[e^{hc/\lambda_2 k_B T}-1\right]}{\varepsilon_2\lambda_1^5[e^{hc/\lambda_1 k_B T}-1]} \tag{8}$$

Here the subscripts *1* and *2* denote the parameters at wavelength (or band) *1* and *2*, respectively. A critical assumption in solving this equation is that $\varepsilon_1=\varepsilon_2$, which is rarely the case for materials of interest (refer to Figure 4). Even differences in the emissivity of 0.05 between measured bands can introduce temperature errors on the order of 10's of Kelvin.

High speed thermographic cameras, consisting of arrays of sensor elements sensitive to infrared radiation, have advanced significantly over the past two decades. Such cameras are typically single color, and collect counts over a band of wavelengths. For example, cameras relying on InSb arrays typically respond to mid-wavelength infrared radiation in the 3-5 µm band. Camera acquisition rates now exceed kHz acquisition rates, with large fields of view, good spatial resolution (20 µm per pixel or better), and low noise equivalent temperature differences (~ 20 mK) for cameras employing cryogenic cooling. However, such cameras are still susceptible to large errors on the order of 500 °C, due to object emissivity variation, and the extreme dynamic temperature ranges seen in AM processes present difficulties for traditional MWIR cameras.

Infrared hyperspectral imaging is another approach being investigated to obtain more accurate in-situ temperature measurements for AM. Researchers at the National Institute of Standards and Technology (NIST) are building an 11-wavelength camera, in conjunction with a commercial off-the-shelf single color high speed thermographic camera [25]. As opposed to taking the ratio of the intensities, the 11 intensity values would be used to back-fit the Planck distribution for the object temperature and emissivity. Aside from the significant cost of such a camera, acquisition rates and field of view are limited (~ 50 Hz, 80 x 80 pixel sensor array). However, as hyperspectral imaging technologies advance, they may provide a tenable solution to the emissivity problem in non-contact temperature measurement [26].

Another novel approach to temperature correction is to perform an in-situ black body correction inside the build chamber. From Eq. (2), if one can measure the emittance (exitance) of a perfect black body under identical conditions to the object of interest (same temperature, view factor, etc.), it is rather straightforward to calculate the emissivity. Up to 300 °C temperature errors were observed in a recent AM study using a thermographic camera, with considerable correction required to obtain reasonable temperature values [27]. After correction by building a black body in the build chamber, the uncertainty of the temperature was decreased to ~ 3.7% over a limited temperature range. However, in practice, this is difficult. First, it is difficult to create a perfect black body. In addition, as emissivity varies with temperature, surface roughness, and other factors, the black body correction would need to be performed continuously during the build for accurate results. That is to say, a single point black body correction would not be adequate, especially over the extreme dynamic temperature range for powder bed laser fusion and other metal AM processes.

Future of Temperature Measurements for AM

These limitations have significant implications for models and feedback control. Currently, feedback control is largely confined to melt pool size derived from intensity data [10], not absolute temperatures. However, the feedback control techniques that have already been developed for studies such as melt pool size can be adapted to accommodate temperature data.

Ideally, knowledge of the temperature would be used to monitor the surface temperature during the build. This data could be used to identify problems during a build, such as the temperature exceeding a specified range that would cause an irreversible defect such as warping. Additionally, feedback control could maintain the part at a constant set temperature during the build.

In order for non-contact temperature measurements and feedback control to be successful for AM techniques such as DLMS, IR cameras need to be calibrated in the chamber in order to account for changes in emissivity. Calibration could be performed by controlling the surface temperature of a part, measuring the emissivity, and using the emissivity data for in-situ measurements of the part's surface intensity to calculate the surface temperature. The calibration must be performed as close to the build platform as possible since any variation in temperature, pressure, or even powder that is suspended in the build chamber's atmosphere can affect the apparent surface temperature. Once the absolute temperature is measured, the data can be fed back into the process conditions such as laser scan speed and laser power in order to maintain a constant temperature during a build. This temperature control can be used to achieve desired stoichiometry, surface conditions, and density. The defect concentration can be minimized and stress-strain curves can be more tightly controlled and repeatable such that DLMS can be more widely used throughout industry to decrease cost and processing time.

Summary

Current AM techniques were presented and discussed, along with their main disadvantages. The lack of in-process monitoring is a major drawback to current AM technologies, which is the root cause of many defects in build parts, as compared to more traditional build techniques. Temperature is identified as a main parameter that needs to be measured during a build, but new temperature measurement techniques need to be developed in order to accommodate DMLS process conditions. The temperature measurement issues and potential solutions addressed in this review can not only be applied to DMLS, but also LENS and material jetting processes. AM techniques that utilize other materials such as polymer and ceramics can also benefit from in-situ temperature monitoring and feedback control to improve build quality and repeatability.

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Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the authors, Sandia National Laboratories, or NCSL International, nor does it imply that the materials or equipment identified are the only or best available for the purpose.

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