Gustavo Tapia
Department of Industrial and
Systems Engineering,
Texas A&M University,
College Station, TX 77843
e-mail: gustapia06@tamu.edu

Alaa Elwany[1]
Assistant Professor
Department of Industrial and
Systems Engineering,
Texas A&M University,
College Station, TX 77843
e-mail: elwany@tamu.edu

A Review on Process Monitoring and Control in Metal-Based Additive Manufacturing

There is consensus among both the research and industrial communities, and even the general public, that additive manufacturing (AM) processes capable of processing metallic materials are a set of game changing technologies that offer unique capabilities with tremendous application potential that cannot be matched by traditional manufacturing technologies. Unfortunately, with all what AM has to offer, the quality and repeatability of metal parts still hamper significantly their widespread as viable manufacturing processes. This is particularly true in industrial sectors with stringent requirements on part quality such as the aerospace and healthcare sectors. One approach to overcome this challenge that has recently been receiving increasing attention is process monitoring and real-time process control to enhance part quality and repeatability. This has been addressed by numerous research efforts in the past decade and continues to be identified as a high priority research goal. In this review paper, we fill an important gap in the literature represented by the absence of one single source that comprehensively describes what has been achieved and provides insight on what still needs to be achieved in the field of process monitoring and control for metal-based AM processes.
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1 Introduction

The advent of AM technologies capable of processing metallic materials in the late 1990s played a transformational role regarding their application domains. After years of being limited to producing visualization models and prototypes from polymers, metallic AM parts are now used as end parts that cut across many industrial sectors such as toolmaking, dental, medical, and aerospace [1]. With AM, arbitrarily complex geometries, such as intricate internal features, lattice structures, and honeycomb structures, can be produced directly from a 3D CAD model [2]. Some other capabilities include reduced material waste, part consolidation, and the ability to produce parts directly without the need for expensive part-specific tooling. However, many technical challenges continue to hamper the widespread adoption of AM and achieving its full potential. One major barrier is the quality of produced parts, which is still not sufficient to meet the stringent requirements of these industrial sectors. To date, quality and repeatability are still regarded as the Achilles Heel of AM. All the recently published research roadmaps state that the ability to produce parts that are consistent across machines, operators, and manufacturing facilities need to be secured before AM can go into the mainstream [3–6].

Achieving high levels of quality and repeatability of metallic AM parts is an extremely challenging task due to a multitude of factors, such as the high complexity of the underlying physical phenomena and transformations that take place during part production and the lack of formal mathematical and statistical models needed to control the build process and ensure part quality. To overcome some of these challenges, much emphasis has recently been placed on the monitoring of AM processes. In most processes, some key process variables can be taken as proxies for part quality. In other words, the behavior of these variables during the build process are directly correlated with the properties of the manufactured parts such as density, dimensional accuracy, surface finish, and mechanical properties. For example, in a class of AM technologies called powder bed fusion (PBF), thermal energy is used to selectively fuse regions of a powder bed. The temperature field is a process variable that has direct impact on the microstructure of the part. A homogeneous temperature field results in better microstructure and mechanical properties [7]. If relevant process variables are identified, monitored, and properly modeled, they can be used to control process parameters and, in turn, improve part quality.

There are numerous research efforts that address the monitoring and control of AM processes to improve part quality. However, the results and insights of these efforts are sparse and have not been compiled in a single source. There is a plethora of articles that summarize applications, technologies, state of the industry (see for example [1,8–11]), and two excellent review papers that focus on thermal analysis [7] and controllers [12] in AM. None of the published works effectively summarize and categorize the efforts in monitoring AM processes. In this paper, we bridge this gap by providing a review on monitoring metal-based AM. This will serve to accelerate this high priority research area by providing a high-level overview of the work accomplished and the tasks that need further investigation.

The reasoning behind our focus on conducting this review for metal-based AM processes lies in the role that they played in redefining AM as a high-priority growth area for US manufacturers. It is further considered by others to define new manufacturing paradigms such as distributed manufacturing as opposed to centralized manufacturing [13]. AM witnessed its first developments in the mid 1980s [2,14], where it was solely capable of processing polymers using technologies such as stereolithography (SLA) [9,11,15]. Applications were focused on producing visualization prototypes to accelerate the product development cycle and reduce time to market [16]. With further developments, other applications started to emerge such as producing functional prototypes for product testing [1] and biomedical applications [17]. These applications have excellent impacts in many industrial settings and continue to be adopted until today. Nevertheless, it is only with the emergence of technologies that can produce parts

[1]Corresponding author.

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out of steels, titanium alloys, and aluminum alloys, among others, that AM rapidly rose into the eyes of both industries and the public.

It is worth mentioning that until recently, some confusion and ambiguity still exist among the academic community and industrial stakeholders regarding the classification of metal-based AM processes. Some users utilize the commercial names of specific technologies to refer to the entire field (e.g., SLA or laser sintering) while others use the names of particular applications for the same purpose (e.g., rapid prototyping). The ASTM Technical Committee F42 has recently approved a list of AM process terminology [18] to address this issue. Seven broad categories of AM were defined in this approved list. Among these, the following five categories are capable of processing metallic materials: powder bed fusion (PBF), directed energy deposition (DED), binder jetting, material jetting, and sheet lamination processes. For details of these processes, the interested reader can refer to the excellent overviews provided in Refs. [1] and [2]. Some recent works investigate the research and development of hybrid processes that combine both additive and subtractive manufacturing to produce metal parts (see, for example, Refs. [19–21]). These processes are beyond the scope of this review which focuses on additive processes.

The paper is organized as follows. We start by highlighting the key types of sensors that have been most commonly used for monitoring metal-based AM processes in Sec. 2. Next, in Sec. 3, we conduct a comprehensive review of the literature studies that used these sensors in their investigations. We include publications from both academic journals and US patents. In Sec. 4, we present a categorization of these cited studies by the type of material used and then a visual depiction of the increasing trend in works published on AM monitoring and control by year. Finally, we provide our insight on what has been studied and highlight the high priority milestones that need to be addressed by researchers in Sec. 5 and conclude the paper in Sec. 6.

2 Monitoring Techniques and Sensors

In this section, we provide an overview of the key techniques and sensors that have been used to conduct studies on the monitoring and control of metal-based AM processes. In Sec. 3, we will discuss the details and some of the findings of these studies.

2.1 Pyrometers. Powder bed fusion (PBF) and directed energy deposition (DED) are the two most commonly used AM process categories for processing metallic materials. Since both process categories use a focused thermal energy source to fuse metal powder, a vast majority of studies has focused on the thermal monitoring through temperature measurement during the build process. According to Zeng et al. [7], a homogeneous temperature field during fabrication results in better part quality. Monitoring the temperature of the melt pool can provide invaluable information that can be used to control the process parameters to ensure part quality.

Most of the studies within the monitoring of temperatures are centered on pyrometry, which is defined as the noncontact measurement of temperature of a body based upon its emitted thermal radiation. Michalski et al. [22] explains that when a heat flux Φ is incident on the surface of a body, a portion of it is absorbed by the body, Φ_α; some portion is reflected away, Φ_ρ; and a last portion is transmitted, Φ_τ. From this observations, we have three physical properties: absorptivity $\alpha = \Phi_\alpha/\Phi$, reflectivity $\rho = \Phi_\rho/\Phi$, and transmissivity $\tau = \Phi_\tau/\Phi$; which, from the principle of energy conservation, render Eq. (1).

$$\alpha + \rho + \tau = 1 \tag{1}$$

when $\alpha = 1, \rho = 0$, and $\tau = 0$, the body is called a black body and it absorbs all the radiation. On the other hand, if $\alpha = 0$, $\rho = 1$, and $\tau = 0$, the body is called a white body and it reflects all the radiation. Finally, when $\alpha = 0, \rho = 0$, and $\tau = 1$, the body is called a transparent body and all radiation is completely transmitted through it.

These properties depend on the material, surface, and temperature of the body, and the radiation wavelength (λ) [22]. Radiation wavelengths most commonly used in pyrometry applications range between 400 nm and 20 μm, which belong to visible and infrared (IR) light. The basic idea in pyrometry is to relate the intensity of radiation of a gray body (one that is not black, white, or transparent) being measured to that of a black body, which can be quantified based on Plank's law and Stefan–Boltzman law. The interested reader should refer to Ref. [22] for further details.

Pyrometer is a broad term describing sensor devices that use principles of pyrometry to measure temperature. Consequently, there are different types of pyrometers depending on the application. Two types have been primarily cited in thermal monitoring of AM processes

(a) *Photodiodes:* also called photodetectors or photoelectric pyrometers. These are devices used to detect radiation and convert it into an electrical signal. When light reaches the sensitive part of the device, it triggers a signal (electrons) to flow through the circuit. This signal is proportional to the intensity of the light, and in turn is also proportional to the temperature. Almost all research efforts cited in the literature use germanium (Ge) photodiodes with a wavelength range between 400 and 1700 nm [23–25].

(b) *Digital cameras:* these can be regarded as a very large array of photodiodes, called pixels, each of which detects light and converts it into an electric signal. Next, signal processing is used to extract an image, in addition to the electric signal that is proportional to temperature. Depending on the detectable light wavelengths, digital cameras are subdivided into regular (visible light) cameras or thermal (IR light) cameras.

Digital cameras that have been used in AM monitoring studies operate with either one of following technologies: charge-coupled device (CCD), where all of the pixel's signals are processed by a single circuit or chip in the camera, or complementary metal-oxide semiconductor (CMOS), where every pixel has its own processing circuit, which improves speed but increases complexity and reduces capture area [26].

One challenge encountered with using digital cameras to monitor the melt pool is the need of a continuous stream of images in order to be able to capture useful information. High-speed cameras with the average frame rate of 1000 frames per second have been used for this purpose. The use of both CCD and CMOS cameras has been cited in different studies in the body of literature, but none of these studies state preferences for one of them over the other. Another challenge is the need for image processing necessary to extract useful information from the raw data. Most of the commercial cameras readily have their custom software for image processing; however, many works in the literature relied on developing tailored algorithms and software to fulfill their specific needs [27–30].

2.2 Thermocouples. As opposed to pyrometers, a thermocouple is a device that conducts contact measurement of temperature. Thermocouples belong to the class of thermoelectric thermometers [22]. They consist of two dissimilar wires connected together at one end with a voltage measurement device connected across the free ends [31].

The basic physical principle governing these type of sensors is that electric current flows in a closed loop of two dissimilar metals when their junctions are at two different temperatures. Hence, when the connected junction (point of contact for measurement) is at a specific temperature, a voltage difference (or electromotive force) dependent on the temperature at the joint is created between the free ends of the wires [31]. The prominent physicist Thomas Seebeck was the first to establish the mathematical relationships for the thermoelectric effect [22,31]. Although research on thermal monitoring of AM processes primarily focused on using pyrometers, a few research efforts utilized thermocouples as will be discussed in Sec. 3.

2.3 Displacement Sensors. Displacement sensors are devices that detect the presence of objects without physical contact [32]. A displacement sensor is also frequently known as a distance sensor or proximity sensor. It consists of two parts: a transmitter that sends a laser signal and a receiver that collects this signal. Its operating principle is measuring the time it takes the signal to be sent, hit the monitored surface, and return to the receiver. Next, it translates this into a distance between the sensor and the surface it is intended to measure. Many research efforts, particularly in direct energy deposition processes, have used displacement sensors to monitor the layer height during the build process as will be discussed in Sec. 3.

2.4 Discussion and Insight on Temperature Monitoring Sensors. We now provide a comparative discussion for some of the capabilities and limitations of the monitoring techniques discussed in this section, with emphasis on temperature monitoring which will be demonstrated to be the dominant focus in the existing literature on monitoring and control.

One of the key advantages in using pyrometry for temperature monitoring is the capability measuring and collecting temperature data without the need for physical contact with the measured surface. This provides much freedom in monitoring hard-to-access surfaces and features regardless of their location or orientation. The contact-free monitoring also serves to minimize potential damage and degradation of the sensor. A second advantage is the capability of detecting radiation emitted by moving objects within the focus boundaries. This feature makes it particularly attractive for applications involving lasers or moving deposition heads [33] such as PBF and DED processes. The temperatures within which different classes of pyrometers operate and detect can range from below $0\,^{\circ}$C and up to $2000\,^{\circ}$C [34], which is well suited for monitoring metal AM processes. Finally, pyrometry typically eliminates the need for special preparation (e.g., machining) of the surface to be measured.

Although pyrometry has many attractive capabilities to offer, there are some obstacles and limitations that stand in the way of their utilization. First, the investment cost for acquiring basic pyrometers or IR cameras is considerably high when compared, for example, with thermocouples. This cost increases more for units with higher frame rates, temperature ranges, and spatial resolutions as usually required to effectively monitor AM processes. Similarly, pyrometers tend to also be bigger in size than other types of sensors in order to accommodate the electronic and optical components required to accomplish their intended function. This is often challenging for use in commercial PBF and DED systems because space inside the processing chamber is typically limited, and one needs to make sure that the pyrometer does not obstruct the laser or electron beam path, while being mounted to view the working surface at a small angle. Another limitation is the difficulty of calibrating these devices. Since the working principle of pyrometers is based on measuring the emitted radiation of a body compared to a black body, the emissivity of the monitored object need to be known in order to achieve accurate measurements. This is typically very difficult to determine and is further complicated by the physical transformations that the material undergoes during processing (from powder to molten to solid form in the case of PBF and DED). If the device is poorly calibrated, measured data will be wrong and useless [33]. Finally, the high spatial and temporal resolutions required to monitor the melt pool that moves at speeds as high as 2500 mm/s poses challenge in term of the size of the data and need for high computational powers required to process and store these data, especially for real-time control applications.

Thermocouples, on the other hand, represent a considerably less inexpensive alternative to pyrometers for monitoring similar temperature ranges [35]. These devices are self-powered and do not require an external power source. They are typically in the form of small-diameter wires (up to 80 μm-diameter) making them relevant for limited space applications.

One limitation in using thermocouples for AM applications is the fact that they must be in contact with the surface or object being measured. This reduces the freedom offered by contact-less measurement pyrometers and often requires some prior preparation of the object (e.g., machining slots or holes). In addition, calibration of thermocouples can be challenging due to some nonlinearity in the output signals or a slow reaction time of the tip to detect changes in temperature [36].

In general, pyrometry has been the dominant technique for temperature monitoring in metal-based AM, although some studies have also utilized thermocouples as will be demonstrated in Sec. 3.

3 Monitoring and Control of Metal-Based AM Processes

We now discuss in more details how the techniques and sensors outlined in Sec. 2 have been utilized to monitor and control the main categories of metal-based AM illustrated in Sec. 1.

3.1 PBF Processes. PBF processes use a high source of thermal energy (typically a laser beam or an electron beam) to selectively fuse and locally bind regions of a powder bed. Examples of commercially available processes include selective laser melting (SLM), electron beam melting (EBM), and direct metal laser sintering (DMLS) [1]. In PBF, extensive experimentation or round-robin testing are first employed to determine optimal parameter settings that achieve some desired properties upon processing a specific material. These parameters include, for example, scan speed, laser or electron beam power, scan pattern, and layer thickness [37]. For example, the authors in Ref. [38] characterize the effect of different parameters on the fatigue performance of titanium components. Typically, after determining these parameter values, they are kept fixed throughout the build process. With the complexity of PBF processes, this approach is not sufficient to ensure part quality. In practice, process parameters need to be dynamically adjusted in response to the underlying evolution of process variables. Accordingly, research efforts in the literature attempt to monitor process variables in order to subsequently use them to control process parameters.

We first start by research efforts on laser-based PBF processes. Melvin III et al. [39,40] are some of the earliest research efforts that investigate the use of monitoring to gain more insight and improve quality in selective laser sintering (SLS) processes. In Ref. [39], the authors construct a video microscopy system to provide more understanding of powder flow behavior and the sintering process in general. Works by Benda and Parasco [41–43] present early approaches for measuring the melt pool temperature using an IR sensor. A dichroic mirror is used to combine two light beams of different wavelengths (the laser and the camera light) into the same path.

Other works extend this further by using monitoring setups to control the process, as opposed to just demonstrating the ability to monitor process variables. Berumen et al. [44] use a digital camera to monitor the powder coating step for each layer and develop algorithms to detect problems such as low or excessive powder feed and coater problems. Kleszczynski et al. [45] present a system for error detection using a high-resolution CCD camera mounted outside the build chamber. With the aid of subsequent image processing, the system is able to detect errors in process stability (e.g., insufficient powder, poor supports, or coater damage) and part quality. Kruth et al. [46–49] design and patent a feedback control system to stabilize the temperature distribution in the melt pool using both a CMOS camera and a photodiode coaxially to the laser beam. They perform experiments on parts with complex features such as overhangs and test different combinations of scanning patterns. The works in Refs. [50–54] base their studies on this setup. A high-speed CMOS camera captures pictures of the melt pool and a photodiode's signal is used to represent the melt pool area. The authors build a feedback controller to control laser power and use it to test part quality in special geometries: adjacent scan vectors, overhang and down facing structures, and acute corners.

Experimental setups based on a coaxial camera were also reported in several studies. Lott et al. [55] mount a CMOS camera with an additional illumination source to measure temperature coaxially with the laser beam. The main advantage of this setup is that the images captured by the camera followed the path of the laser. The authors then implement image-processing algorithms to test the system and demonstrate its ability to monitor the melt pool. Chivel and Smurov [56–58] use a setup to monitor the maximum surface temperature, spatial temperature distribution in the processing area, and the size of the melt pool, then use this information to control the evolution of these temperatures. The setup consisted of a CCD camera and a two-channel pyrometer, whereby the former measures temperature distribution at the sintering zone, and the latter measures the maximum surface temperature in the irradiation spot. Rombouts et al. [59] use a coaxial CMOS camera system to monitor the build of same parts with seven different materials. In Ref. [60], the authors monitor the build of six different intermetallic powders as well; however, they use thermocouples to measure the temperature on the powder bed. Bayle and Doubenskaia [61] also use a system comprising a high-speed IR camera and a pyrometer to monitor the temperature in a SLM process. However, the system they developed did not capture the pictures coaxially with the laser beam. Consequently, some images from certain locations have better quality than other locations, mainly due to the viewing angle of the camera. In Ref. [62], the authors also use a CCD camera and a two-wavelength pyrometer to measure temperatures from the melt pool. In addition, they add a LED illumination to serve as a filter.

Some of the research efforts rely on process monitoring to validate simulation models built to predict part properties. For example, Kolossov et al. [63] develop a 3D physical model of the AM process then simulate using finite element analysis (FEA). They test the validity of the model using an IR camera to measure the temperature on the top of the powder layer. The experimental results were consistent with the model data, which helps in drawing conclusions regarding the properties of the produced parts. Similar research efforts on using process monitoring to validate simulation models in laser-based PBF can be found in Refs. [64–68].

Next, we examine research efforts on electron beam based PBF processes. Works on monitoring EBM processes strongly resemble laser-based PBF, since the only difference is the type of energy source used to fuse the metal powder. Dinwiddie et al. [69] investigate the best location to setup an IR for monitoring an EBM process. The authors test the system on the production of complex overhang structures and analyze the properties of the parts produced. In Ref. [70], the authors construct a setup to measure the temperature distribution in the build chamber and the melt pool temperature using an IR camera and then compare the behavior of process parameters with two different sets of optical lenses. In Ref. [71], the authors continue to investigate the melt pool, specifically the behavior and repeatability of its temperature and its geometry and emissivity. Schwerdtfeger et al. [72] setup an IR camera system to monitor layer flaws and imperfections. Images were captured right after a layer was processed and before the next powder layer had been deposited. This enables the detection of flaws, such as porosities, during the part build.

Many studies also focus on using EBM monitoring to validate simulation models. In Ref. [73], the authors develop a mathematical model for the process and conduct a numerical simulation using FEA. Experimental data using thermocouple attached underneath the substrate plate were compared with the numerical solution and used to validate the model. Scharowsky et al. [74] develop a simulation model for the EBM process and use a camera to monitor the melt pool size and temperature. The objective was to draw conclusions regarding the dependence of these process variables on beam and powder parameters. Sammons et al. [75] build a FEA model to determine the effect of scan speed and part height at the melt pool solidification boundary and use a 3D scanner for measurement and validation. The scanner maps the surface features to coordinate points in order to compute the width and height of the deposited tracks. In a similar study, Jamshidinia et al. [76] develop a numerical model to investigate the effect of EBM process parameters on the heat distribution and molten pool geometry and validate their model using measurements acquired with a profilometer.

Numerous other studies have been conducted to solely accomplish the monitoring of PBF processes, without further investigating using the monitored variables for process control. In Refs. [77–81], the authors use a system consisting of a camera and a pyrometer to monitor the temperature of the melt pool. In Refs. [82–84], only a high-speed IR camera is used to capture melt pool characteristics, whereas in Refs. [80] and [81] only a pyrometer is used. In Ref. [85], a thermocouple and a strain gauge are attached to the bottom of the base plate to measure residual stresses during the build process. Taylor and Childs [86] also use thermocouples to measure energy absorptance and thermal conductivity within the powder in the build area during laser processing. The authors in Refs. [87] and [88] employ a high-speed IR camera located on top of the chamber to retrieve measurements about temperature in two modes of laser: continuous and pulsed. Pavlov et al. [89] use a coaxial pyrometer to measure and analyze the temperature in the laser impact zone. The authors in Refs. [90] and [91] use an IR camera to monitor an EBM process.

In addition to knowledge dissemination through the academic literature, there also exist several patents since most of the works on monitoring PBF processes involve the development of novel methods and apparatus. Inventions based on IR cameras have been most frequently utilized. In Refs. [92] and [93], a control system is invented to adjust the heating element, laser scan speed, and power through the measured input from an IR camera mounted on top (not coaxial to the laser beam) to observe a target area. Huskamp [94] use an IR camera to measure the temperature distribution over the part bed and use the information and a heater to maintain a consistent temperature. Grube and Beaman [95] and Beaman et al. [96] also utilize two IR sensors, one focused at the powder bed and the other at powder heater to serve as feedback for the control of the temperature. Patents and inventions based on other sensors also exist. For example, the inventors in Refs. [97] mount a thermocouple inside the powder bed in addition to the IR sensor on top. Similar to other works, they use the output signals from the sensor to keep a uniform temperature distribution of the powder bed.

3.2 DED Processes.

DED processes are similar in principle to PBF processes, with the main difference being the material feed mechanism. While in PBF, powder is fed from a feed piston to the build area using a blade or a roller; in DED, a deposition head is utilized to deposit material onto a substrate. The energy source (e.g., laser beam) comes out from the middle of the head and hits the substrate where material is to be added. The relative movement between the substrate and the deposition head is typically controlled using a CNC controller [2]. Notice that in DED, both metal powder and wire feed stock can be used as raw material, and that some additional process parameters are typically considered such as feedstock material delivery rate and nozzle standoff distance (distance between the tip of the nozzle and the substrate). With this similarity in mind, research on monitoring DED processes has also primarily focused temperature monitoring. A few research efforts have also investigated monitoring the height of each layer during the fabrication process.

It is worth noting that a variant of DED had been developed prior to PBF processes. The process is known as laser cladding, which uses the same principle in DED processes but is intended for coating existing parts with additional layers of metal rather than creating the 3D physical part. For this reason, research on monitoring DED processes is slightly ahead of PBF processes with more emphasis placed on implementing real-time process control. In Refs. [98] and [99], the authors develop a closed-loop controller that takes feedback from the monitored temperature of the part and uses it to adjust the laser power and achieve a homogeneous temperature distribution and better dimensional accuracy. They integrate a photodiode with the processing head of the machine and use its signal as input to the controller. Hu et al. [100–103] setup a thermal imagining system using an IR high-speed camera positioned coaxially with the laser beam to capture images from the melt pool. Next, they build a controller that received information from the analysis of the captured images and adjust the laser power to ensure uniform temperature distribution. In addition, they implement a system to monitor the powder delivery rate to the melt area using a laser diode and a photodiode. A low-power laser signal sent from the diode is received by the photodiode, and any change in the detected laser energy means that powder has gone past the sensor. This system was also filed as patents in Refs. [104–106]. There are many other studies that develop variant systems to monitor the melt pool temperature and/or powder flow (see for example papers [107–121] and patents [122–124]).

Hofmeister et al. [125–127] use a similar principle discussed for monitoring in PBF. They use a CCD camera placed coaxially to the laser beam, which through a set of optics and mirrors follows and obtains images from the melt pool, subsequently used to analyze and compare cooling rates. The research was also filed as patent [128]. Schuermann et al. [129] and Hoebel and Fehrmann [130] present an akin approach. There have been also numerous research methods [131–138] that used pyrometers to monitor and analyze the melt pool or the process zone and infer conclusions about different parameters such as variation in standoff distances or laser defocusing.

Some research efforts used design of experiments (DOE) in conjunction with process monitoring in DED processes. Ermurat et al. [139] make single tracks of material and use a high speed camera, with 20,000 fps, to monitor the nozzle and extract data about powder flow. The authors then use DOE to analyze the behavior of the track's geometry and size with the variation of other parameters such as the standoff distance and inert gas flow. Lee [140] use DOE to examine the powder deposition efficiency by monitoring powder delivery with a CCD camera.

Similar to PBF processes, some studies use process monitoring to validate analytical and simulation models to characterize DED processes. In Refs. [141–148], analytical models are developed to understand the thermal behavior of the process through physical relationships such as heat transfer models, energy conservation, and mass and momentum balance. Simulation was then performed using FEA and results were validated using experimental data from process monitoring. All of the developed models cited belong to the class of thermal models.

Thermocouples have also been used in monitoring DED processes. In Ref. [149], the author use this type of sensors to measure the temperature distributions along the substrate plate which were then compared to the values measured by a pyrometer. They conduct experiments with and without powder feeding under various processing conditions. Kelly [150] patented a fault detection method using thermocouples to monitor the nozzle temperature on the deposition head, and a controller is employed to maintain the temperature and prevent partial or total clogging.

In DED processes, powder flows out of a nozzle and is melted when it intercepts the laser beam. Due to this operating principle, it is necessary to ensure consistency of powder feed. Accordingly, some researchers devote their efforts into powder flow monitoring [151–153]. Most of the sensors used for this line of research are IR diodes or low-power lasers that send a signal to a receiver and estimate the powder flow as an inverse proportion of the received signal. In addition, high-speed cameras are also used for powder flow monitoring, as presented in Refs. [154] and [155] where the authors observe the powder flow right after it leaves the nozzle and characterize the particle speed and flux.

Displacement sensors have been frequently utilized in DED monitoring studies as well. In Ref. [156] and [157], a controller for the melt pool temperature is developed using a pyrometer as temperature sensor and a displacement sensor to measure track height profile. The authors were able to analyze and control both temperature and height profile of each layer. Boddu et al. [158] uses a setup comprising a pyrometer, a displacement sensor, and a coaxial CCD. They used the information from this setup to control the process and improve surface finish, cold spots, and porosity.

There are some works where the focus was primarily on monitoring the layer height in DED processes. Iravani-Tabrizipour and Toyserkani [115] use an optical system to measure the height of each layer during the process. The system is composed of three CCD cameras, positioned at 120 deg relative to each other, and tilted to the front at a 15 deg angle from the substrate plane. This system is then implemented into a recurrent neural network algorithm to monitor layer heights. Song et al. [159] use a system of three high-speed CCD cameras to monitor layer height in a laser cladding process, in addition to a pyrometer that measures the melt pool temperature. The monitoring system provided feedback to a hybrid controller to adjust the laser power, with layer height feedback having higher priority than temperature. In other words, as long as the height of the layer was within limit, the temperature was not taken into account. Similar methodologies are presented in Refs. [30,160–166] for layer height measurement and control.

A different approach for addressing the same problem of height monitoring and geometry control is proposed by Fathi et al. [167], Toyserkani and Khajepour [27], and filed as patents in Refs. [168] and [169]. The authors use a single CCD detector mounted normal to the process zone to detect the layer height and using it as feedback signal for the controller. With the fluctuation of the height measurements, they can estimate the roughness and surface quality obtained. A similar procedure is also presented in Ref. [170], where they adjust the power to control the height growth.

Other interesting studies on the monitoring and control of DED processes have been observed in the literature. Liu and Li [171] address the common assumption that the laser energy distribution follows a Gaussian distribution when it hits a perpendicular plane, hence when the build layer includes inclined planes, this energy distribution changes. To counteract this, the authors use a robotic arm that holds the base of the substrate and moves it to the orientation needed such that the laser is always incident at a 90 deg angle. Monitoring of the process was thus needed to control the robotic arm. The study investigation does not explicitly report which types of sensors were used. Liou et al. [19] develop a hybrid system with a laser head for the laser deposition process (additive) and a milling head (subtractive). They only use sensors for the additive process, with a pyrometer, a displacement sensor, and a coaxial CCD camera to measure and control the melt pool.

All of the works highlighted so far in DED processes use metal powder as raw material. As mentioned earlier in this section, there are also some DED processes that use wire feed stock, such as electron beam free form fabrication (EBF^3), for example. Very few studies have been devoted for monitoring this class of processes. Authors in Refs. [172–174] use an IR camera to image the melt pool and solidification areas. Medranoa et al. [175] place a CCD coaxial camera on the laser head and a series of six different types of IR pyrometers around the same head. The authors study the best location for monitoring the melt pool and the workpiece temperatures.

In Ref. [176], the laser metal deposition process is implemented on an industrial robotic arm with six axes of movement. The authors refer to the system as robotized laser metal-wire deposition (RLMwD). Monitoring of the process is key in the system because it provides feedback to control its motion. The system uses a camera located coaxially with the laser beam and views the melt pool through a dichroic mirror. A second camera is used to measure the layer height. Heralić et al. [177] extend this study by adding a laser scanner to the RLMwD system. After a layer is added to the part, the scanner scans the heights of the part and a new path is programmed to build the next layer. The authors report improvements in part accuracy. Two different apparatus are patented in Refs. [178] and [179] to conduct closed-loop control for this type of process through imaging of the melt pool.

3.3 Other Metal-Based AM Processes. The majority of research on monitoring and control of metal-based AM processes has been conducted for PBF and direct energy deposition (DED) processes. Considerably less research has focused on the remaining three process categories outlined in Sec. 1.

In sheet lamination processes, thin metallic sheets or foils that are welded on top of one another using ultrasonic welding, a process known as ultrasonic consolidation (UC). Since this is a solid-state joining process, the material does not need to reach its melting point. Little research has been done on monitoring sheet lamination processes. Schick et al. [180] use FEA to model and predict the process, then validate their model with experimental data collected using thermocouples located beneath the path of the ultrasonic welding head (the sonotrode). Next, they calculate the thermal diffusivity for the used material (aluminum) based on the model. Kelly et al. [181] and [182] build a thermal model and a mechanical model to characterize the process also using FEA. They use an IR camera to record the entire weld process and identify transient and steady-state thermal regions. Sriraman et al. [183] investigate thermal transients in the UC process. They also use thermocouples located underneath the sonotrode trajectory and measure peak temperatures and temperature transients under different process parameters such as vibration amplitude, normal force, and travel speed. Similarly, Yang et al. [184] use thermocouples placed between two successive deposited tapes (layers) to investigate improvements in bond formation during UC.

No works in the literature to date have been cited that investigate monitoring on binder jetting or material jetting processes for producing metal parts.

4 Categorization of Research Efforts

The studies surveyed in Sec. 3 were conducted using different metallic materials. In Table 1, we provide below a breakdown of the cited studies according to the type of material, in order to support future research efforts in rapidly identifying studies that investigate their material of interest.

Note that papers not listed in Table 1 did not specify the material used in the study and solely focus on describing the experimental setup or the methodology. By briefly scanning the list, it is clear that among the wide variety of metals that have been considered in different works, stainless steel, and titanium alloys were most frequently investigated.

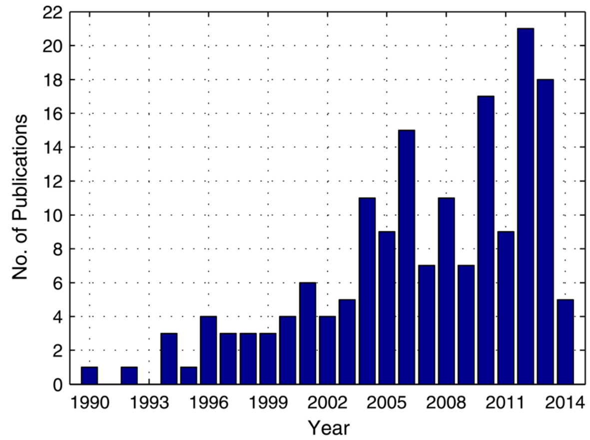

Fig. 1 Number of cited research efforts on the monitoring and control of metal-based AM by year

Commercially available metal-based AM systems emerged in the late 1990s. It is interesting to observe the growth in the number of studies by the time period in which they were conducted. Figure 1 shows a plot of the number of papers and patents published each year between 1990 and 2014. All the works depicted in the figure are cited in this review. It is easy to observe that less research on monitoring and control of metal-based AM existed before the year 2000. An obvious increasing trend in the number of research efforts over the next decade and up until this day is readily evident in Fig. 1. This can be attributed to the fact that shortly after commercializing metal AM in the late 1990s, the unique and promising capabilities that it offers helped brand it as a disruptive and potentially game changing set of technologies. Dictated by industrial needs of better part quality and higher repeatability, this research area gained and continues to gain increasing attention among the research community.

5 Insight and Future Research

It is evident from the discussion in Sec. 3 that the vast majority of research on process monitoring and control in metal-based AM focuses on temperature monitoring in PBF and direct energy deposition processes. This can be attributed to many factors. First, PBF and DED are characterized by the advantage of directly producing fully dense metal parts with mechanical properties that are comparable (and sometimes equivalent) to those of cast or wrought material. This is not always the case with the rest of the process categories outlined in Sec. 1 that can produce metal parts, where significant postprocessing is often needed to achieve the desired properties. Several proven industrial applications and case studies are cited that use PBF and DED processes to produce metallic end parts, and hence a growing need to improve part quality through process monitoring and control. Second, as mentioned in Sec. 1, the temperature field is an excellent proxy for part quality, since it has a direct impact on the resulting

Table 1 Publications breakdown by material

Material	Publications
Ti alloys	[38,46,56–60,63,66,70–72,74,76,87,88,91,113,118,119,137,148,154,172–174,176,177]
Ni alloys	[29,45,60,62,80,81,84,89,99,107–109,118,120,131,132,141,149,154,155,184]
Stainless steel	[24,25,27,28,46,57,61,62,68,73–79,82,86,98,99,110,115,125,126,132–136,138,139,142,144,145,147,149,151,152,159,174,175]
H13 tool steel	[68,75,100,101,103,114,125,127,156,157,160–162]
Co alloys	[110,112,116,117,140,146]
Mild steel	[59,80,81,85,102,121,143,146,149,158,167,171]
WC	[112,117,131,149,155]
Mo alloys	[64,65]
Al alloys	[60,112,161,167,180–184]
Cu alloys	[59,80,81,83,112,146,183]

microstructure, density, and mechanical properties of the part. Effective monitoring and control to ensure a homogenous temperature field significantly aids in improving quality. Finally, advancements in sensor technology for temperature measurement have facilitated and continue to facilitate collection of temperature data from PBF and DED processes. For example, as discussed in Sec. 2, pyrometry enables contact-free temperature measurement, which helps overcome many obstacles.

Further studies and investigations are needed for advance in monitoring and control of metal-based AM. For example, although much effort has been directed toward constructing experimental test beds to facilitate temperature measurement, there is still a significant lack of mathematical and statistical models and algorithms to model the monitored process variables and fully utilize this invaluable data to detect process anomalies at early stages and conduct predictive control to improve part quality. To date, all predictions in metal-based AM are based on simulation and physics-based FEA that are very difficult to solve and represent high computational burden. Efficient analytical and data driven models capable of processing large data streams are strongly needed for real-time control. On the other hand, almost all research efforts have been focused on single-tracks or very simple geometries, such as thin walls and cubes, which over-rides one of the most powerful aspects of AM; the ability to produce arbitrarily complex geometries that cannot (or are very difficult to) be produced using traditional manufacturing technologies. These include, for example, lattice structures that have a huge application potential in biomedical applications and devices [185]. More investigation needs to be geared toward monitoring and control in the presence of complex geometrical features such as overhangs, undercuts, and lattice and honeycomb structures. Very few efforts, such as Refs. [50], [52], and [53], have considered relatively more complex geometries, and more research needs to be conducted.

Despite the technological advances in temperature monitoring and the abundance of research studies within this scope, many challenges still need to be addressed. For example, we discussed in Sec. 2 that the emissivity of the material being processed is very difficult to determine, which often necessitates making assumptions that can yield inaccurate measurements. From the system development point of view, most commercial systems are not equipped with built in sensors, and these systems are typically very difficult to customize. Integrating process monitors with the AM process would greatly improve monitoring and control capabilities.

Although temperature monitoring represents an excellent path for controlling the quality of parts produced using PBF and DED, other process variables need to be investigated for use in real-time process control. For instance, it will be of great value to provide the capability to monitor part geometry layer-by-layer for real-time part qualification [5]. Sensors and controls for monitoring sheet lamination and material jetting processes have received less emphasis in the existing literature and need to be investigated in parallel with the ongoing developments in these processes for producing metal parts.

6 Conclusions

There has recently been consensus that the unique capabilities offered by AM processes qualify them to be game changing technologies. The design freedom, the ability to produce arbitrarily complex geometries, and reduced material waste, among other benefits, can have transformational roles across many industry sectors such as aerospace, healthcare, and automotive. However, there is also similar consensus among experts and stakeholders that the quality of metallic AM parts is still not sufficient to meet the stringent requirements of these sectors, which hampers the widespread adoption of AM as a viable method of manufacturing. This represents a major barrier toward fully exploiting the unique capabilities that it offers.

Basic and applied research are still needed to overcome this challenge and to serve increase the manufacturing readiness level of AM. In this review paper, we provided a comprehensive overview of research efforts conducted in the area of process monitoring and control for metal-based AM to increase part quality. In addition to provide a detailed discussion of the different types of sensors and systems developed for this purpose, we also categorized the works in the literature according to the type of process and type of material involved in the study. This review is the first to gather this information in one document and should serve to assist researchers get a clear vision of what has been investigated and what still needs to be investigated as outlined, for example, in Sec. 5.

Nomenclature

AM = additive manufacturing
CCD = charge-coupled device
CMOS = complementary metal-oxide semiconductor
DED = directed energy deposition
DMLS = direct metal laser sintering
EBF^3 = electron beam free form fabrication
EBM = electron beam melting
FEA = finite element analysis
IR = infrared
PBF = powder bed fusion
SFF = solid freeform fabrication
SLM = selective laser melting
SLS = selective laser sintering
UC = ultrasonic consolidation

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