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Nondestructive Testing for Metal Parts Fabricated Using Powder-Based Additive Manufacturing

by Lucas W. Koester*, Hossein Taheri†, Timothy A. Bigelow†, Peter C. Collins‡, and Leonard J. Bond§

ABSTRACT

Additive manufacturing (AM) presents unique challenges to the nondestructive testing community, not least in that it requires inspection of parts with complex forms that are not possible using subtractive manufacturing. The drive to use AM for parts where design approaches include damage tolerance and retirement-for-cause with high quality and where safety criticality imposes new QA/QC requirements is growing. This article reviews the challenges faced to enable reliable inspection and characterization in metal powder-based AM processes, including issues due to geometric and microstructural features of interest, the limitation on existing and emerging NDT techniques, and remaining technology gaps. The article looks at inspection from powder to finished part, but focuses primarily on monitoring and characterization during the build. In-process, quantitative characterization and monitoring is anticipated to be transformational in advancing adoption of metal AM parts, including offering the potential for in-process repair or early part rejection during part fabrication.

KEYWORDS: additive manufacturing, nondestructive testing, process monitoring, discontinuities, microstructure, standardization

Introduction

Additive manufacturing (AM) is defined as the process of joining materials to make objects from 3D (CAD) model data, usually layer upon layer, as opposed to using more traditional subtractive manufacturing methodologies. It has potentially numerous advantages for new design approaches including damage tolerance and retirement-for-cause, for particular high-value applications, and for forming parts that are unformable using traditional fabrication processes. However, in looking at AM parts throughout the fabrication and subsequent life cycle, there are significant challenges faced when seeking to ensure needed initial quality and then reliability throughout life in-service.

The inspection and characterization of powder metal parts at various points in the manufacturing process has been under consideration for several decades, with much of the attention focusing on nondestructive testing (NDT) of finished or near-finished parts (Bond et al., 2014). Over the years, some techniques have been demonstrated for application at interim fabrication steps and at other interim points during manufacture, such as with green parts (an intermediate state requiring additional processing, such as hot isostatic pressing or sintering, to achieve full strength). Recent increasing interest in employing advanced manufacturing, in particular for additive manufacturing, is causing the need for QA/QC processes to be revisited and specific challenges addressed. Other researchers (Chang and Zhao, 2013) have provided an extensive text that looks at the forming and shaping of metal powders, materials, and properties and densification of powder metallurgy components, including process optimization, and the currently used nondestructive evaluation tools. The text also includes discussion of various examples where metal powder-based materials are used.

The discussion in this paper focuses primarily on metal additive manufacturing that utilizes powder feedstock materials. Metal powder-based AM encompasses two versatile techniques of fabrication: powder-bed fusion (PBF) and directed energy deposition (DED). In the former, thermal energy selectively fuses regions of a powder bed layer upon layer to sequentially produce material in a part or prototype individually or items in a manufacturing lot. In the latter, focused thermal energy is used to fuse materials by melting as

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they are being deposited onto the build surface to sequentially produce material in a new part or to add material to an existing part (in the powder case, material is usually delivered with a nozzle). Both techniques generally result in a near-net shape component that requires little postprocessing, particularly material removal, to meet dimensional tolerances. PBF techniques may sometimes include building support structures that are later removed to enable forming "overhangs" and a postfabrication heat treatment may be necessary to relieve stresses or provide a final densification depending upon the application. NDE applied to parts formed using these processes is the focus of this article primarily because of rising industrial interest and the material or geometric challenges faced to qualify and inspect resulting parts and prototypes produced.

For advanced manufacturing, there are potential benefits of in-process powder-based materials monitoring by nondestructive evaluation (NDE) or noninteracting processing sensors, which move beyond current NDT. This can potentially lead to significant economic benefits resulting from the savings of time, materials, and processing expenses, including energy. Most quality engineers have focused on the final part inspection and efforts to automate and improve the adequacy of the final inspection to ensure the needed quality in products that are shipped to customers. This focus leverages many decades of progress in NDT techniques, not least the techniques for castings and in-process welding, and its benefits can be seen with successful examples of applications in various types of parts, including those formed with AM processes. However, the greatest benefits for powder-based materials and manufacturing that engineers can realize are from rapid optimization of powder-based processing techniques and by inspection/evaluation of precursor materials or in-process components, especially before the full processing sequence has added to the total, manufacturing cost of a part (Baumers et al., 2017). For AM, the three elements that all have a direct influence on the quality of a part include the following: the forming process, including the energy source; the manufacturing system that enables and controls the process; and the material employed, all of which need careful monitoring and control. With increasing adoption of AM parts, there are now also a number of codes and standards that are being formulated and adopted, and these address both the fabrication process and the QA/QC and inspection needs (ASTM, 2016; ASTM, 2018).

This paper reviews the current status and the potential for NDT tools needed to enable a total quality approach to parts fabricated using the various AM technologies. Significant capabilities exist, but new approaches to NDT and related measurements are needed throughout the fabrication process. NDT techniques must be adapted or created to provide characterization of items starting from the material feedstock to a finished part so as to reliably give needed part quality.

Background

Additive manufacturing's similarities to other manufacturing techniques, particularly those using powder processes and welding, have been mentioned and arise again in considering the needs to be addressed in QA/QC for AM. Critical to understanding NDT needs is material characterization and "allowables" (those naturally occurring material anomalies that are acceptable), such as some level of microporosity and grain variation that will not impact performance under some defined set of stressors. However, there are considerations unique to the various forms of AM that must be addressed. For example, the balling phenomenon represents a type of discontinuity that is generated in laser sintering–based AM processes resulting in irregular melt pool dynamics. A subcritical energy density and higher scanning speeds have been identified as the primary causes of balling, which result in insufficient material being present in the liquid phase to promote sintering or melting. Several different physical factors and process parameters can cause cracking in AM parts. Thermal gradients can generate cracks in the parts when there are differences in thermal properties between the substrate and the build material, or when there are steep thermal gradients in the molten pool while solidification is proceeding (hot tearing). In addition to these cracks that can form during production, components produced with AM have properties that can exacerbate crack formation during service. Understanding types of discontinuities, as with any NDT needs assessment, is central to defining inspection criteria. An exhaustive review on discontinuities and their formation mechanisms has been performed, and these results are summarized in other work (Taheri et al., 2017). An initial cursory examination of the geometric and microstructural features of interest in AM parts elucidates what existing NDT techniques may be applied and where new tools and characterization techniques may be necessary. While a full review of these topics is not possible in this short article, references are cited where these topics are discussed in more detail.

Geometry

In many cases, a finished AM part is first inspected using optical dimensional metrology for accuracy of the part's external dimensions and surface condition. Dimensional inaccuracy for an AM produced part can be problematic, particularly when considering a prototype or high-value part where the desired end product is a component requiring fine dimensional control (Smith et al., 2016a). The layering process used in AM techniques can result in rough surfaces and possible deviations from specified CAD model tolerances or other geometrical anomalies in the final part. Typically, the CAD model is converted to a stereolithography (*.stl) file format where the designed geometries and surfaces are discretized into geometric meshes. A macro-level "staircase" effect can occur on part surfaces due to this discretization (Moroni et al., 2014). In the AM process, melt pool dimensions and fluid flow have both been shown to influence the sidewall dimensions and surface finish in deposited parts (Gockel et al., 2015). To minimize geometrical anomalies, a stable melt pool size/shape is required (Lee and Farson, 2016). In addition, support structures may need to be fabricated to facilitate overhang fabrications for some geometries only to be ultimately removed.

Porosity and Lack of Fusion

Porosity is a common discontinuity that can occur at various scales and is found in additive manufactured materials. Many process parameters and feed material attributes have been associated with porosity formation. For sintering-based AM processes, microporosity (subpowder scale) is generally related to pores that occur inside the starting powder that are transferred to the final deposition. The occurrence of such micropores is illustrated with a radiographic image showing particle shapes and entrapped gas in Figure 1a. For both sintering-based and fusion-based AM, porosity that is present at the macroscale may be categorized into two main classes: gas porosity (Figure 1b) and lack of fusion (LOF) seen as larger, planar discontinuities in Figure 1c. These examples are for 17-4 PH stainless steel in the as-built condition (before any postprocessing such as heat treatment).

At the present time, most research articles attribute gas porosity not caused by entrapped porosity in the powder to in-process trapped shielding gas. In general, gas porosity arises from three sources. The first type is found in directed energy deposition (DED) techniques, where a high powder flow rate can lower the specific energy of the melt pool, resulting in increased gas entrapment. The second source is entrapped gas within the starting powder particles. The third is marangoni flow, which is defined as the mass transfer along an interface between two fluids due to surface tension gradients, which causes gas retention bubbles within the melt pool that potentially lead to large pores (Barua et al., 2014).

Porosity in structural applications is generally detrimental to part performance. Increasing the energy density can eliminate some of these smaller pores. However, other types of inhomogeneities can form at higher-energy densities (Bauereiß et al., 2014). An increase in scanning speed has been shown to initiate fragmentation of the build plane and sidewalls affecting surface roughness (Meier and Haberland, 2008).

When there is insufficient energy in the melt pool, the resulting inability to fully melt the powder particles can cause lack of fusion (LOF) porosity in AM parts. LOF can be divided into three categories (Liu et al., 2014): (a) separated surface with unmelted powder; (b) separated surface without unmelted powder; and (c) narrow and long shaped with unmelted powder. In general, it is found that increasing the scanning speed decreases the specific energy and, therefore, increases the risk of causing LOF discontinuities (Ng et al., 2009).

Thus, modifying process parameters to mitigate formation of one type of discontinuity (porosity or LOF, for example) often has effects on other properties that may be undesirable (for example, surface roughness caused by excessive energy

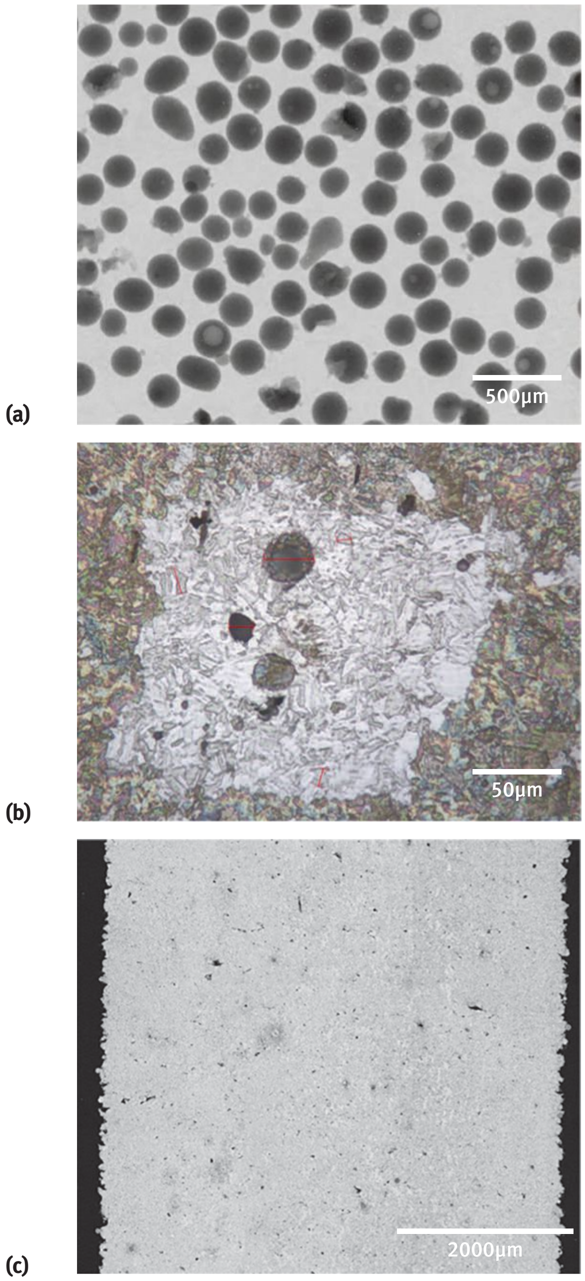

Figure 1. Examples of porosity: (a) porosity in metallic powder feedstock (Bond et al., 2014); (b) gas porosity observed in an etched metallograph; (c) SEM cross section showing a mix of volumetric discontinuities (porosity and lack of fusion) and sidewall roughness.

density), and an optimal processing window that leads to low porosity and fine surface finish may or may not exist for any given process that both minimizes microstructural discontinuities and results in fine dimensional control. Thus, postprocessing with hot isostatic pressing (HIP) is commonly used for components to reduce microporosity, depending upon the application. HIP can affect other microstructural features, including grain structure, and discontinuities may reappear after additional post-HIP processing (Seifi et al., 2016).

For the sake of completeness, it is useful to consider the formation of dispersoids of varying types in the microstructure. Impurities in powders can exacerbate the size of inclusions in the part. The number, size, shape (morphology), and distribution of inclusions over the part can significantly affect final part performance, particularly fatigue strength (Wilby and Neale, 2009).

Characterization is required at various scales. Current techniques of materials characterization such as scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD) are often destructive, requiring that the material be sectioned and appropriately prepared to quantify the microstructural features present. Some exciting new techniques, including spatially resolved acoustic spectroscopy (SRAS) (Sharples et al., 2006; Smith et al., 2016b), may provide a way to conduct large-scale analysis of variations in the size, shape, and orientation of grains and visualize discontinuities directly, providing a way to correlate processing with properties and performance. There are some nondestructive techniques to assess anisotropy, including X-ray based computed tomographic (CT) approaches, but they are sensitive to sample thickness and can be hindered by a rapidly spatially varying crystallographic texture. The use of ultrasonic backscatter is being investigated, but to this point it has not been routinely applied for anisotropy or texture in-situ.

Residual Stresses

Residual stresses in AM parts are introduced by rapid thermal cycles and temperature gradients during the forming process. Uneven distribution of residual stresses has a significant effect on the formation of high-stress intensity regions, nucleation of microcracks in the part, and recrystallization during the treatment process (Rangaswamy et al., 2005). Using the vickers microindentation test, evaluation of residual stress (Liu et al., 2011) showed that residual stress distribution is not uniform in laser rapid formed nickel-based superalloy Inconel 718 and is higher in overlapping regions of two adjacent passes. Understanding the thermal behavior of the AM processes can help monitor and predict the residual stresses. Various studies have been performed that have sought to predict and model residual stress by optimizing manufacturing parameters such as powder density, scan speed, and scan pattern using optimization algorithms or finite element modeling (Vastola et al., 2016; Wang et al., 2008). However, NDT measurements are necessary when there is no reliable predictive model. Neutron diffraction, X-ray diffraction, and contour techniques can give a characterization of residual stress, but such measurements are difficult to apply and may be impractical for in-situ implementation.

Microstructure

Changing the process parameters such as laser power and scanning parameters, specifically scanning speed and its effects on energy density, has been shown to cause a considerable change in the grain structure (Gong et al., 2014), the phases present (including the promotion of metastable phase formation), their distribution within the microstructure (Scharowsky et al., 2015), and tendencies for discontinuity generation (Zhong et al., 2015) in single-alloy AM parts and structurally graded AM parts (Liang et al., 2014). The variation in the temperature gradient in the melt pool results in variation in the solidification rate, resulting in concurrent variations in microstructure, including phase stability (Marya et al., 2015). Further, the atmosphere in the AM system can have an influence on phase stability, microstructural features/morphology, and discontinuities. For example, even a small amount of oxygen contamination can cause oxidation that changes the resulting texture and adds impurities to the microstructure in some AM techniques that are processed under inert gas shielding or environments (Murgau, 2016). Recent work, with results shown in Figure 2, demonstrates that additives can be used as an additional control measure for microstructure, for example with the addition of boron to titanium alloys (Mantri et al., 2017). Several studies have reported the anisotropy seen in material properties caused by the different scanning patterns and process parameters used (Shamsaei et al., 2015), and it has also been shown to be dependent upon the material employed (Carroll et al., 2015; Zhu et al., 2012).

Standardization

The standardization of process parameters, and their relationship to the properties of finished parts, is inherently problematic given the design flexibility in shape, material used as feedstock, process types, and needs for the end application. Efforts to apply existing characterization techniques have identified some areas of overlap for previously established techniques (Slotwinski and Moylan, 2015). The parameter space in AM, however, is vast and mostly uncharacterized in terms of impact on resulting bulk material properties, discontinuity formation, and ultimately part performance. Efforts to characterize and optimize processes to this point have been primarily focused on defining an operating envelope for a particular combination of material and manufacturing system through parametric studies and destructive characterization. Furthermore, the flexibility of AM processes likely precludes a "one size fits all" solution. Thus, the qualification of a new material and/or manufacturing system will likely prove time-consuming and expensive. An excellent review of the problems associated with materials qualification in AM was produced by other authors (Seifi et al., 2016).

There is a need for an enabling capability from nondestructive techniques to inform or validate multiscale models that are predicting solidification, composition, microstructure, and crystal plasticity together with finite element modeling of properties that lead to the penultimate predictions of part performance (Collins et al., 2016). However, existing characterization techniques, particularly in-situ characterization techniques, are primarily qualitative and relatively

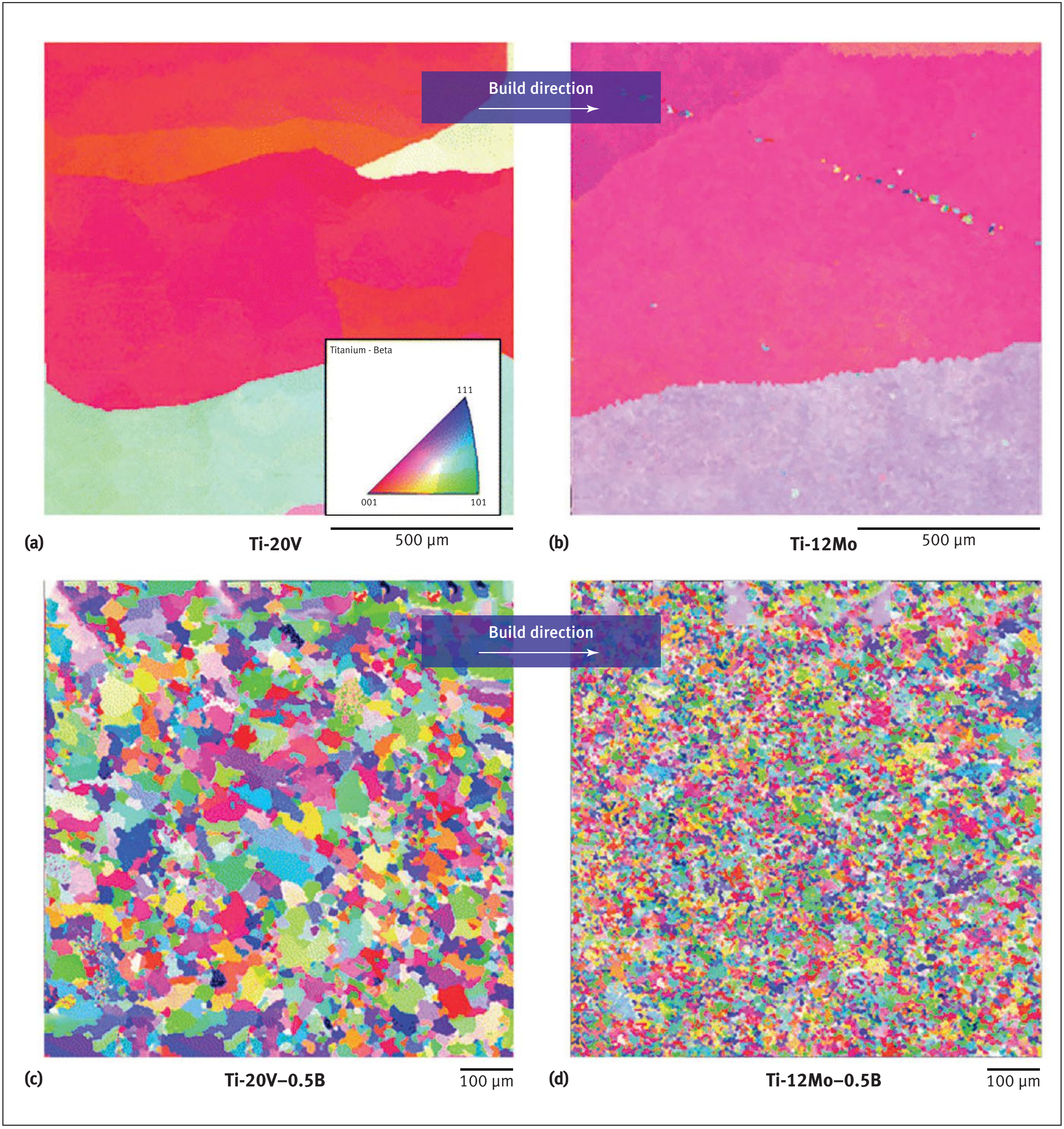

Figure 2. Example of texture manipulation (grain size refinement) in two AM titanium alloys determined by EBSD: (a) without boron in the feedstock powder for a titanium-vanadium alloy; (b) without boron in the feedstock powder for titanium-molybdenum alloy; (c) with boron in the feedstock powder for a titanium-vanadium alloy; and (d) with boron in the feedstock powder for titanium-molybdenum alloy. The color map corresponds to the crystallographic orientation defined in the inset of Figure 2a (Mantri et al., 2017).

undeveloped with the exception of optical and thermal imaging where resolution and utility as direct measures are, unfortunately, fundamentally limited.

The potential cost of validating a new material and/or additive manufacturing system has driven a shift from postproduction qualification to a "qualify as you go" scheme. The technique envisions a suite of capabilities from characterization of raw materials, real-time monitoring of process variability and material properties, and minimal postproduction testing to optimize the likelihood of a successful build and a deployable result (Seifi et al., 2016). Once characterized, an AM process is then "frozen" and multiple part production occurs with a specified feedstock and operating with set machine parameter ranges.

NDE for Additive Manufacturing

As mentioned in the previous section, a "qualify as you go" scheme is considered attractive as a way to address quality issues throughout the AM process. Thus, in-process NDT then plays a critical role in providing actionable data throughout the entire manufacturing process from powder to final part.

Feedstock Material Characterization

The material feedstock used in AM has a significant impact on the characteristics of resulting material in parts and can significantly impact production cost depending upon its form. For powder feedstock processes, characteristics such as powder composition, particle size distribution (PSD), apparent density, tap density, flowability, and particle morphology all influence final material properties. An example of entrapped porosity as seen in powder is shown in Figure 1a, and a compounding factor that can alter these powder properties is the recycling and reusing of residual powders. Recycling and reusing effects can cause changes in powder size distribution and contamination. Reusing of the powders can increase the oxygen content and increase the occurrence of irregular, nonspherical shaped particles, which can lead to the generation of discontinuities. Given that feedstock quality and recycling has a demonstrated impact on economics, discontinuity populations, and microstructure, the need for techniques to adequately measure powder properties is apparent, especially when using recycled powders. In looking at the economics of AM, single-use powder processes result in significant waste, and failure to recycle or otherwise reuse can make a process uneconomical. Many commercially available systems utilize sieving to maintain particle size distributions and remove large particles or contaminants from future builds. Several published studies show minimal effects on part microstructure with well-controlled recycling practices, but this remains a topic of study, particularly in terms of potential effects on microstructure changes and chemical composition as new and recycled powders are blended (Slotwinski and Garboczi, 2015).

In-Line Measurements and Monitoring

Investigating in-process measurements remains an area of active research at the industry and academic levels. The inspection and qualification of a component in real time during an AM process is challenging, given access issues and the in-process environment, and yet it is potentially a unique opportunity in the additive manufacturing space. Layer-wise construction of components allows access for inspection and characterization throughout the production of the part. Many investigators have acknowledged the opportunity for a "qualify as you go" scheme encompassing all aspects of production from raw material to finished component, with in-process measurements playing a key role (Everton et al., 2016; Seifi et al., 2016; Sharratt, 2015).

Much work is being conducted in this space given the transformational nature of any adequate solution, but at this point in time significant technology challenges and gaps remain (Fielding et al., 2016; Energetics Incorporated, 2013; Waller et al., 2014). In-process qualification offers the opportunity to potentially simplify an inspection by reducing the material path to potential discontinuities, and by avoiding the need to manage with complex surface geometry (in planar, layer-wise manufacturing such as powder-bed fusion). Significant barriers, however, remain to the application of nondestructive techniques in-situ, and these include managing the effects of build surface roughness, the harsh environments (high temperatures and molten metal), the limited space available for inspection-associated hardware, and the constraint of acceptable limitations on the inspection time as it impacts the total time for part build.

In-line, real-time quantitative inspection during an AM build is necessary for informed control of the AM process. Quantitative in-situ characterization and nondestructive evaluation enables real-time or near-real-time discontinuity detection and process monitoring. Early detection of discontinuities and undesirable process variations can enable real-time or near-real-time early part rejection to avoid wasted machine operation costs and postbuild processing on what is an ultimately flawed component. Rejected builds are essentially a multiplicative factor on the component cost, and individual rejected components in a build significantly add to the often high cost of other successful components in the build (Baumers et al., 2016). Furthermore, an ultimate goal of in-situ inspection and characterization is repair and closed loop control, both of which are predicated on quantitative in-situ characterization techniques. In-situ characterization is also a key factor in the "qualify as you go" scheme to avoiding generally expensive, statistically based qualification techniques common for less expensive, classical manufacturing techniques.

In-Process Monitoring Techniques

Layer-wise manufacturing in AM often necessitates many (potentially thousands) of submillimeter layers to construct a near net shape component. Thus, data management of any in-process measurement quickly becomes difficult. However, data reduction and location in space for each layer produces a pseudo computed tomography (CT) type dataset for both point and areal-based measurement techniques with a thermographic case illustrated in Figure 3 (Krauss et al., 2015).

Point-based monitoring techniques focus on melt pool optical and thermal emission monitoring. Measurement of the melt pool emission can be used to infer temperature and has been used to study general deposition quality and, more specifically, balling effects. Absolute thermal measurements are difficult as emissivity of the surface is often unknown and varying. Thus, most studies monitor relative changes in melt pool temperature rather than absolute measures. These types of single-point measurements for quality control have also been utilized by commercial equipment manufacturers in response to demand from customers (Everton et al., 2016).

Full field techniques generally require a high-speed, high-resolution camera either monitoring optical or thermal emissions. Full field imaging is desirable as it reduces the complications of a moving sensor and can be potentially employed on any machine with either a viewing window or ports for camera attachment. Again, data management has proven to be problematic, but can be achieved in real time with field-programmable gate arrays and data reduction. However, the techniques are often resolution limited and qualitative due to the same complications with emissivity mentioned previously. High capture rates also inflate the cost of the required cameras to provide full field coverage at a sampling rate sufficient to capture the dynamics of rapidly moving heat sources, particularly with laser and electron-beam heat source systems. Incorporating the imaging into laser optics of the system has enabled fine detail within the melt pool to be monitored, and the systems are fundamentally surface limited for optical emissions monitoring techniques (visible spectrum monitoring) or thermal diffusion limited (infrared camera monitoring) to surface or near-surface interrogation.

Full field techniques have shown a capability to monitor for larger discontinuities (generally >100 microns) through relative cooling rates affected by larger discontinuities, such as pores and lack of fusion zones. However, the techniques remain largely qualitative and require additional inspection to verify discontinuity morphology and size, and do not generally provide direct measurement of either discontinuity morphology or resultant microstructure. Work continues in this area, however, as the portability and cost of imaging systems show promise for wider application to AM quality control as opposed to more complex and potentially capable systems that require extensive system integration. An example of the capability to map grain orientations of additive materials is shown in Figure 4 (courtesy of Peter C. Collins).

Volumetric techniques hold promise in realizing quantitative discontinuity characterization but are more difficult to implement. Additionally, volumetric techniques generally exacerbate the data storage and throughput problems encountered in even point and planar techniques. Postbuild evaluation techniques such as radiography and X-ray computed tomography are promising techniques for inspection of completed components. In-situ inspection with these techniques is more complicated, given the generally long acquisition times and postprocessing to reconstruct three-dimensional volumes. Digital radiography (planar) could potentially be used in-line for process measurements, but to date it is not known to have been routinely used on metal additive systems in-line.

Ultrasonic techniques are used extensively postbuild to examine material properties including microstructure and discontinuities. In-line monitoring with ultrasonic transducers has been attempted by other authors, and they showed positive results in terms of quantifying porosity variation from data collected during building (Slotwinski and Garboczi, 2014). However, the technique utilized is limited to simpler structures and would require a noncontact variation for more complex geometries. Examination of the effects of porosity indirectly

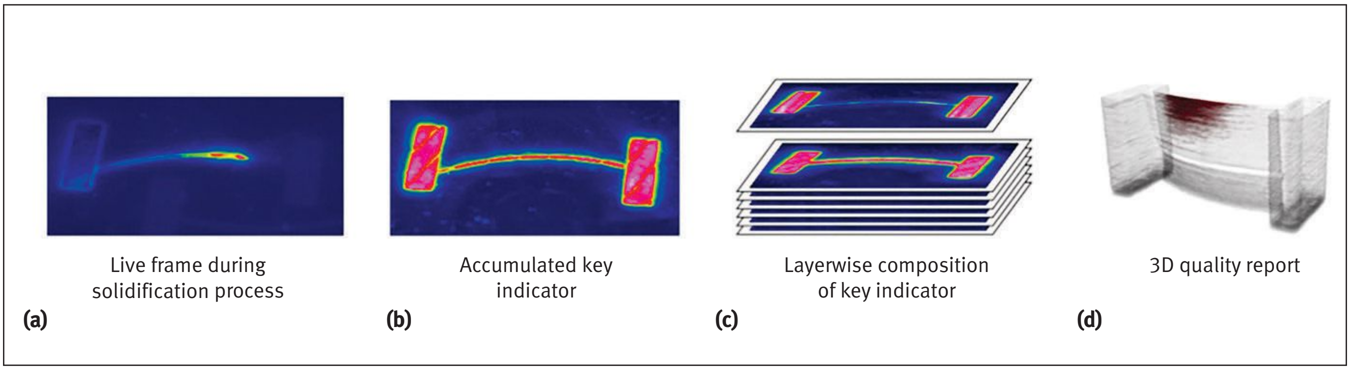

Figure 3. Tomographic dataset produced from an accumulated indicator using thermographic data collected during an additive manufacturing build. Reprinted from Krauss et al., 2015, with the permission of AIP Publishing.

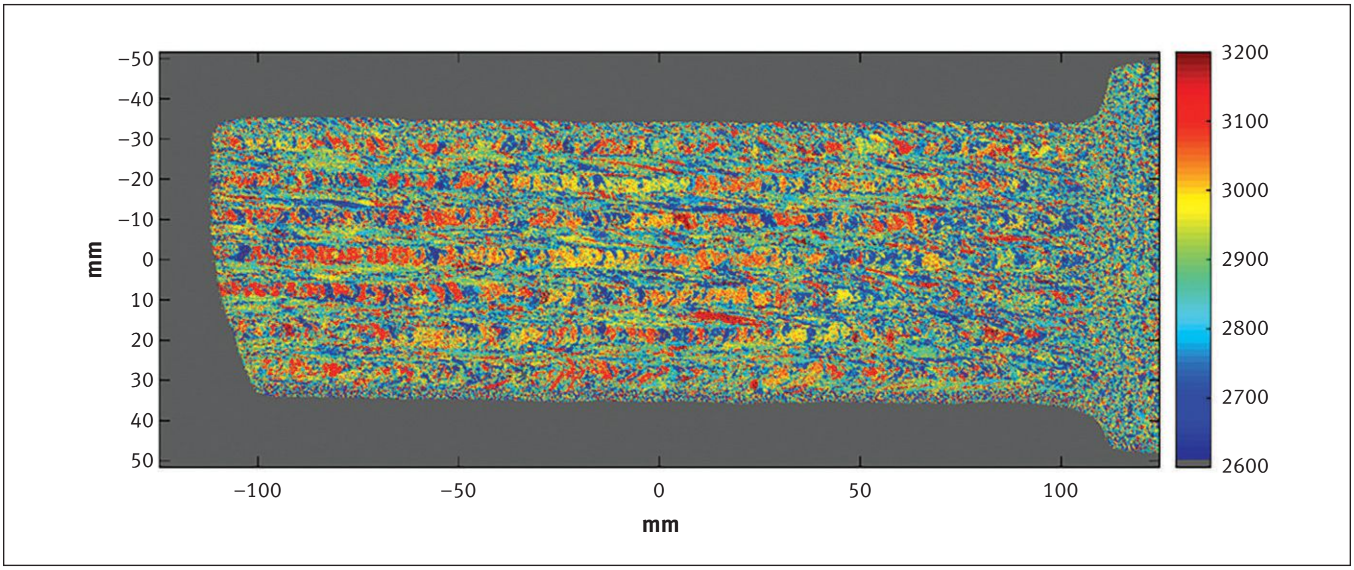

Figure 4. An emerging technique is surface acoustic wave velocity mapping by spatially resolved acoustic spectroscopy (SRAS) (courtesy of Peter C. Collins).

(through wave speed variation with porosity volume percentage) also requires sensitive measurement of the acoustic wave speed, which would prove difficult for complex geometries.

Passive monitoring of acoustic signatures has recently been performed for a directed energy process, showing variations in acoustic emissions signatures that correlate with varying process parameters (Figure 5). The technique is passive, requiring little modification for integration with AM systems and also gives good sensitivity to crack-like events. Noncontact ultrasonic techniques are also under investigation for in-situ process and material characterization, particularly for laser-based processes (Figure 6). This work often requires the production of custom equipment to allow for the incorporation of multiple lasers for melting, acoustic generation, and detection (Bigelow, 2017). Many of the environmental hazards in these systems have already been addressed; thus the addition of laser ultrasonic capabilities would likely require minimal hardware modifications, particularly if the current optics systems can be utilized or slightly modified. Further recent work underway examines acoustic backscatter from discontinuities generated in a noncontact manner to examine larger porosity that may be later consolidated by hot isostatic pressing, if necessary. Laser ultrasound, however, has drawbacks including sensitivity to surface roughness and optical absorption coefficient variation, sensitivity, and inspection time (Everton et al., 2015).

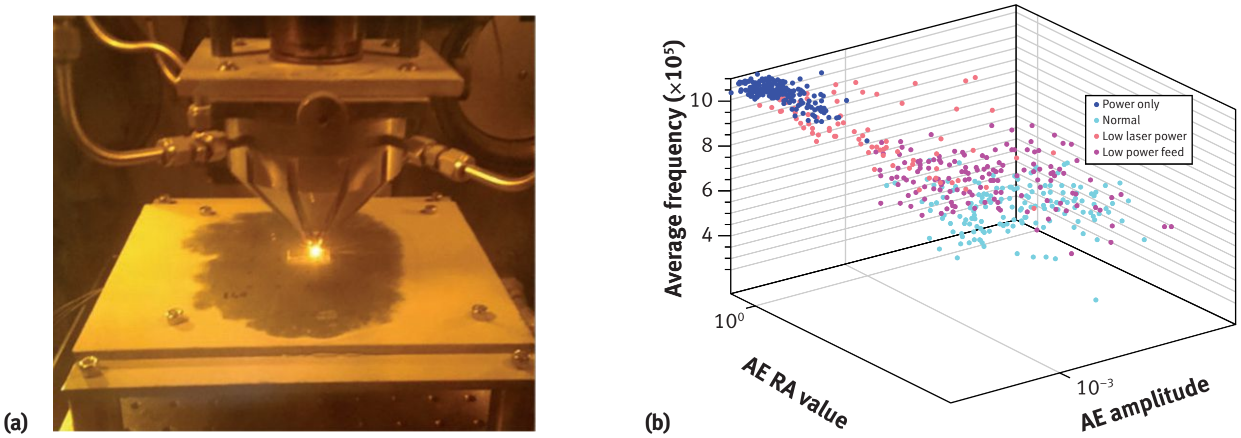

Figure 5. A volumetric technique using acoustic monitoring: (a) a directed energy deposition system instrumented build plate with acoustic emissions transducers below the build; (b) resulting clusters of acoustic emissions metrics depending upon build condition (courtesy of CNDE).

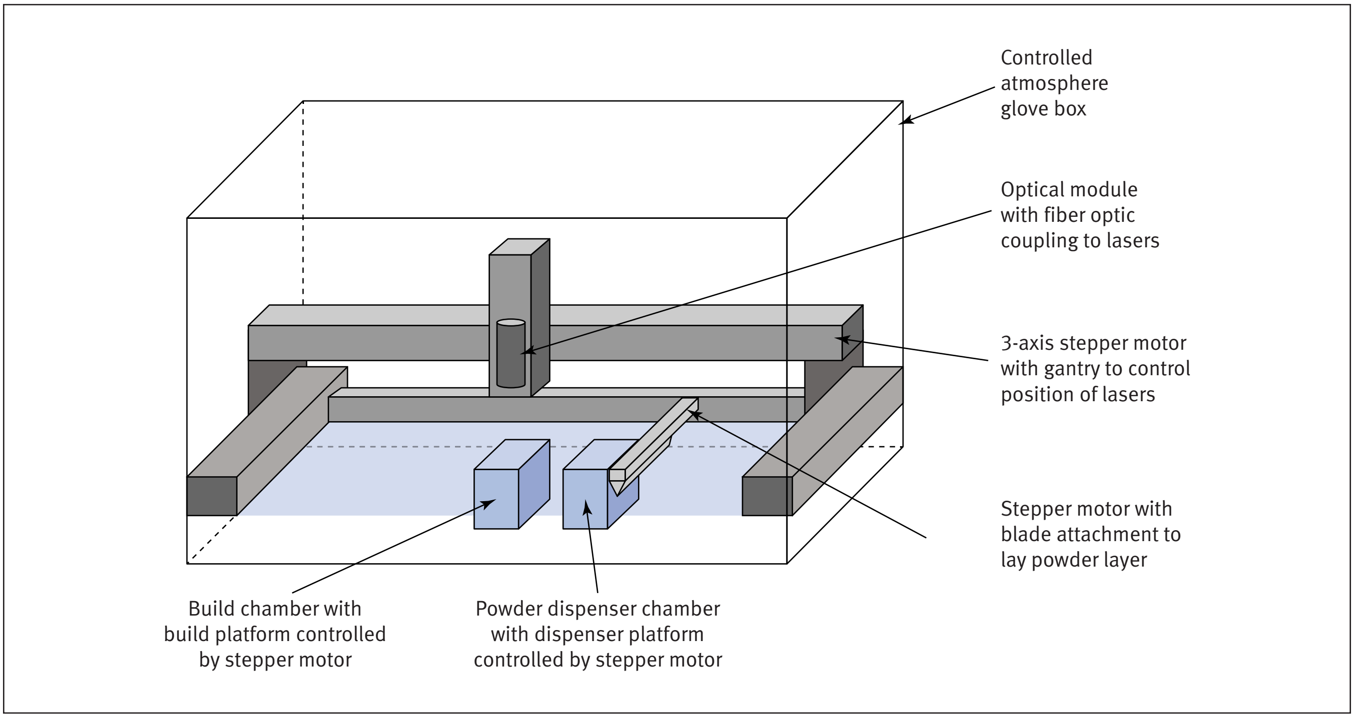

Figure 6. Sketch of basic powder-bed laser-sintering system to test in-line monitoring of porosity in laser powder-bed fusion (Bigelow, 2017).

Postproduction Inspection

Reliable inspection of completed components remains a major barrier to wider utilization of AM components. Obstacles to reliable NDT remain, including challenging geometries and microstructures, identification of critical discontinuity sizes and types, and a lack of standardized test techniques. AM is particularly attractive for complex geometries with high "buy to fly" ratios and complex internal features that would be difficult or otherwise impossible to achieve with subtractive techniques. A review of current techniques for similar processes has identified some areas of overlap where existing NDT techniques may be utilized, but significant gaps remain. Rough surfaces and complex internal or external geometries limit the applicability of classical NDT techniques.

Digital radiography and particularly X-ray CT remain the most promising techniques, but penetration quickly becomes problematic for larger components made from alloys with high X-ray absorption. Two properties of X-ray CT make it a capable candidate for use in AM: the ability to image inaccessible structures and the ability to perform dimensional metrology on external surfaces (Thompson et al., 2016). X-ray CT has also shown to be capable of determining porosity distributions, rather than an average determination of porosity content (or equivalently, density) obtained by Archimedes's method. Other techniques, such as those used in ultrasonic testing, can potentially interrogate deeper into these components for some materials, but such inspections can be limited by complex surface topography, complexity of internal structures (that can include air gaps), "grain/microstructure" scattering, and attenuation at higher frequencies and anisotropy. The incorporation of fine internal features, particularly when embedded deep within large and dense parts (which can be enabled by AM), all complicate inspection.

The challenges faced in implementing QA/QC programs, including finished part inspection, have limited design flexibility and applications of AM fabricated components to primarily noncritical, statically loaded applications to avoid potential fatigue failures. However, some parts are now being flown in aviation and space applications. These quality challenges will likely remain in the near future until extensive "effect of defect" studies have been performed to inform design allowables and there is a better understanding of material property variability, including microporosity, between processes and material systems (Seifi et al., 2016). Furthermore, the inspection at such a late stage resulting in rejection is a multiplicative cost factor for otherwise successfully built and validated components.

Conclusion

Significant guidance for NDT of AM parts can be drawn from experience in developing and qualifying metal manufacturing systems such as powder metallurgy, laser welding and processing, and casting. Applicability of NDT techniques used for other metal processes has been examined by a number of researchers, and significant technology gaps remain. In-process measurements and monitoring are seen as potentially transformational if such signatures and measurements can be related either directly or indirectly to process operating envelopes, parameters, and reliable detection and characterization of discrete discontinuities. Then, predictors of final product quality and performance can be given using multiscale modeling, revolutionizing AM application and part qualification. From the nondestructive examination point of view, significant work remains to be performed to meet the needs of the industry, to enable reliable quantification of geometric and material properties in all the various AM process and material systems. Given the breadth of technologies represented by AM, even within metal AM alone, there will likely be no "one size fits all" approach to AM component quality assurance. However, NDT applied from powder to the finished part, particularly in process, offers numerous opportunities for innovation.

ACKNOWLEDGEMENTS

Contributions of original work from the authors on emerging techniques and their respective sponsors are greatly appreciated. Acoustic monitoring of additive manufacturing processes was funded as an Industry-University Core Project by the Center for NDE (CNDE), Iowa State University, and was initiated while CNDE was a Phase III NSF Industry University Cooperate Research Center (IUCRC). Work on laser-generated ultrasound for porosity assessment was supported by NSF CMMI Award Number 1661146.

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