A PERSPECTIVE OF THE NEEDS AND OPPORTUNITIES FOR COUPLING MATERIALS SCIENCE AND NONDESTRUCTIVE EVALUATION FOR METALS-BASED ADDITIVE MANUFACTURING

ЗАТРЕБУВАНІСТЬ І ПЕРСПЕКТИВИ ПОЄДНАННЯ МАТЕРІАЛОЗНАВСТВА ТА НЕРУЙНІВНОЇ ОЦІНКИ МАТЕРІАЛІВ ДЛЯ АДИТИВНОГО ВИРОБНИЦТВА МЕТАЛОПРОДУКЦІЇ

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This paper presents a perspective of the needs and opportunities associated with the multidisciplinary problem of nondestructive evaluation (NDE) of additive manufacturing (AM). Recognizing the multidisciplinary nature of the problem, as well as the need to bridge knowledge between the different communities, the paper is structured to provide brief backgrounds and details relevant to both communities, as well as present an assessment of the state of the art. This paper, in some respects, is meant to be a primer of the different landscapes, as well as a catalyst for making future connections. At the end, it will be clear that there is much more work to be done, but that the work that is ongoing is exciting, and the potential to exploit NDE techniques for metals-based AM is very high.

У цій статті представлено перспективи, пов'язані із задоволенням потреб та можливостями, що можуть бути досягнуті на основі застосування міждисциплінарного підходу в галузі неруйнівного оцінювання (NDE) адитивного виробництва (AM). Визнаючи міждисциплінарний характер питання, а також необхідність взаємообміну знаннями між цими різними спільнотами, стаття структурована таким чином, щоб надати стислий опис основ та подробиць, що стосуються обох спільнот, а також представити оцінку сучасного стану. Ця стаття у певному розумінні може сприйматися у якості спільної основи для різних областей, а також каталізатора для створення майбутніх зв'язків. Зрештою стане зрозуміло, що попереду ще багато роботи, але робота, яка триває, є захоплюючою, і потенціал для використання методів NDE для AM металовиробів дуже високий.

Keywords: additive manufacturing, nondestructive evaluation, materials state, measurement techniques, materials physics
Ключові слова: адитивне виробництво, неруйнівна оцінка, стан матеріалів, вимірювальна техніка, фізика матеріалів

Introduction

Increasingly, there is an awareness that the paradigm-changing nature of additive manufacturing (AM) requires a reassessment of both materials science and nondestructive evaluation (NDE). Traditionally, these technical specialties/disciplines are separated, as their role in the development, manufacture, and use of parts and components in advanced technical systems, such as vehicles, aircraft, defense, and energy systems, is notably different. However, it is also becoming clear that there is a significant opportunity if these traditionally separate subject matter experts can collaborate in the area of AM.

The causes associated with why these technical experts are separated is worth a brief discussion. First, there is the typical role that these experts play in any organization. A materials scientist plays important roles in the development and optimization of new materials, often long before those materials are qualified and become part of the design and manufacturing ecosystem. A materials engineer may then be highly involved in certain aspects of the manufacturing ecosystem, providing subject matter expertise related to process controls and destructive testing to assure specific metrics of quality (for example, mechanical testing or microscopy). The NDE experts often receive a handoff of parts and components, and then apply their skill sets to ensure that the quality of parts is known to an acceptable degree of uncertainty, monitoring parts over their lifetime in service. In certain organizations, the NDE experts can play a role in the design of the parts if philosophies such as design for inspectability are part of the organization's culture. Second, there are the types of data these different subject matter experts typically manage. For the materials scientist or engineer, the spatial domain dominates the characterization techniques, enabling the direct observation of grains, texture, precipitates, and defects. For the NDE expert, the tools invariably rely upon measurements involving time, and are thus in the frequency domain, which can be converted into the spatial domain using various techniques. Lastly, the NDE experts are trained to use statistics (that is, probability of detection) to pursue rare events and are, by their occupation, risk averse. Conversely, the research of many materials scientists is primarily focused on the initial stages of new materials development, where it is not uncommon to imagine in an almost unbridled sense the possibilities of the new materials under study.

AM is, without question, a new manufacturing paradigm. In its most unconstrained, futuristic sense (see Figure 1), AM is capable of producing net or near-net shapes:

- whose features span across length scales (Zhou et al. 2015; Riveiro et al. 2019; Kumar and Maji 2020; Marini and Corney 2020);
- whose topology may be topologically optimized or, emergently, generatively designed (Meng et al. 2020; Liu et al. 2018);
- whose local materials state[1], and thus properties/performance, may be controlled spatially by tuning

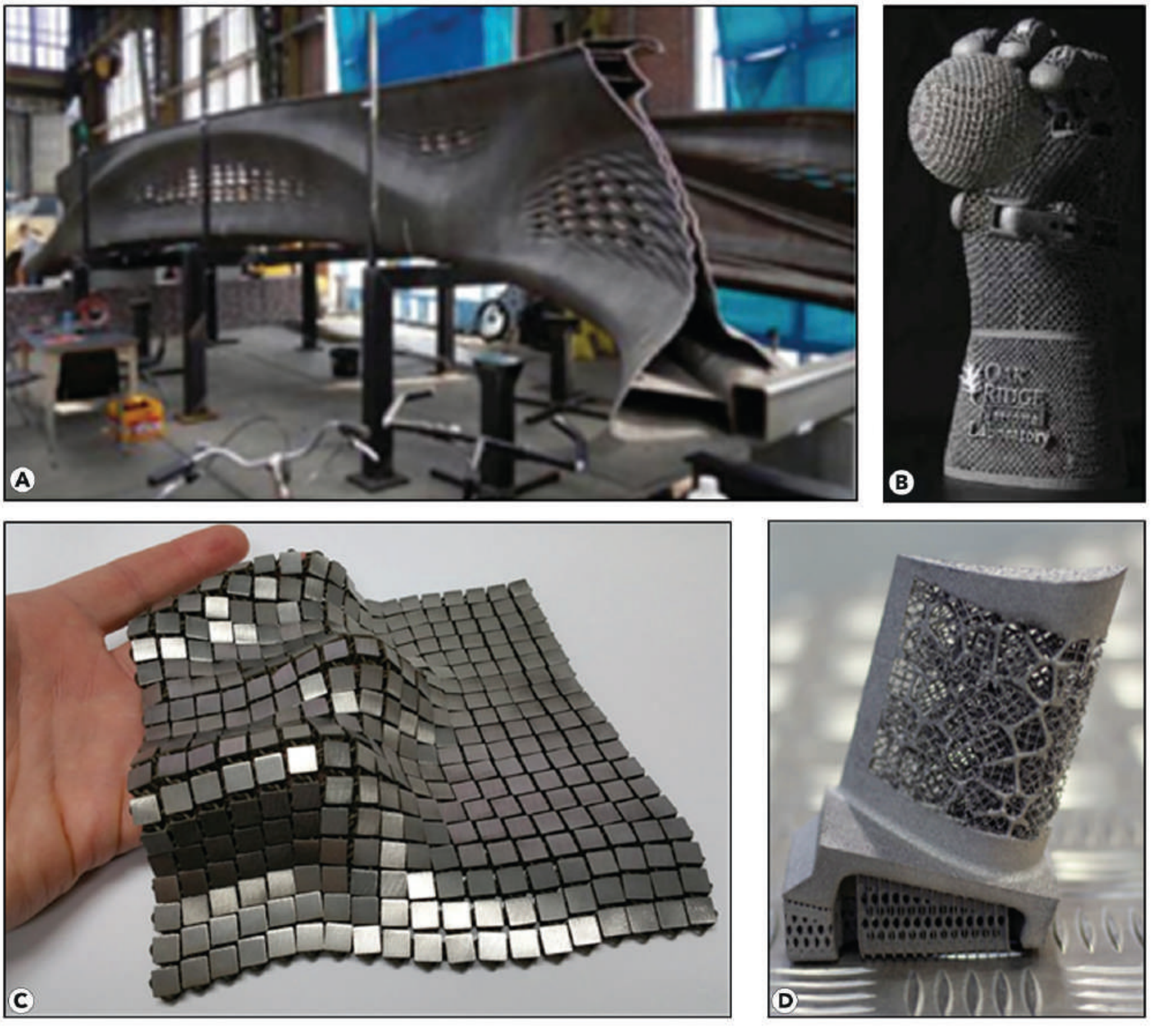

Figure 1. Wide variety of applications of AM techniques: (a) additively manufactured bridge using the wire arc additive manufacturing (WAAM) technique; (b) hydraulic hand 3D printed by Oak Ridge National Laboratory that houses electric motors and hydraulic components inside; (c) 3D-printed metallic "space fabric" designed and manufactured by NASA; and (d) AM meso-structures in a turbine blade. (Figure 1a is reprinted with permission from Feucht et al. [2020]; Figure 1b is reused from Love et al. [2013] under Creative Commons Attribution License (CC BY); Figure 1c is reused from Good and Landau [2017] under Creative Commons Attribution License (CC BY); and Figure 1d is reprinted courtesy of The University of Sheffield.)

[1] Materials state includes, but is not limited to: composition, solute distributions, microstructure (phases, their size, distribution, and correlations), crystallographic texture, and the presence of defect structures (e.g., dislocations, porosity, interfaces, cracks), across all length scales. This definition follows from materials state awareness (MSA), which is defined as "digitally enabled reliable nondestructive quantitative materials/damage characterization regardless of scale" (Buynak et al. 2008). The materials state is what a manufacturing process produces (or what evolves during service) and is also what governs the performance of the material (Buynak et al. 2008; Jacobs 2014; Aldrin and Lindgren 2018).

the process, post process, and/or composition spaces (Tammas-Williams and Todd 2017; Li et al. 2020); and

• where the local materials state may be both designed and measured during component manufacture, providing a digital record/twin that can be used to both verify/validate the process space and predict the properties/performance of the part during service.

To ensure that the material is of a sufficient quality with respect to the design metrics (such as dimensions, properties, and performance), it is necessary to develop and bring to bear new advanced metrology and evaluation tools during the manufacturing process. Among the most promising techniques are those that are based upon conventional NDE approaches, yet their applicability requires a direct connection with the materials state.

Within AM, there are new physics that operate, which scientists and engineers (and companies/organizations) need to understand. For example, as most AM techniques are fusionbased processes, the composition of the as-deposited material may be different than the composition of the starting powder or wire, through either the preferential loss of some volatile elements or the gettering of other elements from the surrounding atmosphere (Carroll et al. 2015; Sato and Kuwana 1995; Semiatin et al. 2004). And, while much is known about the dynamic nature of the AM process, other research is leading to new insights into the formation and evolution of defects (Kenney et al. 2021; Quintana et al. 2021), the importance of fluid dynamics (Tammas-Williams et al. 2015; Hojjatzadeh et al. 2019) on the molten pool and presence of any keyhole, and the competition between molecular flow of gas and the vaporization of elemental species and their combined effect on the proximal powder (Yoder et al. 2021; Ahsan and Ladani 2020). These new physics are being discovered in sophisticated experimental facilities, including high-energy beam lines, where both high spatial and temporal data can be obtained (micrometer and microsecond). The state-of-the-art measurements are beginning to be correlated with some NDE approaches, as these are promising methods to correlate the physical mechanisms associated with AM with signals that can be measured during the AM process.

It is clear that for both the realization of many of the promises of AM as well as the determination of different physical domains that the NDE approach has an important role to play. This paper consists of two primary components. First, it provides a brief review of some of what is known about the composition–process–materials state–performance relationships in AM. Elements of this first section will include some aspects of NDE techniques, as relevant. New connections between aspects of the materials state and NDE techniques will be presented. Second, it provides a review of the applicability of different NDE techniques for both ex situ and in situ assessments of the materials state, and by extension, initial metrics of the quality of the as-manufactured materials and components.

A Review of Additive Manufacturing

Jim Williams, an internationally renowned expert on titanium, physical metallurgy, and microstructure-property relationships, as well as a former dean at both Carnegie Mellon University and Ohio State University, once provided the most pithy yet useful definition of AM: “It is the opposite of subtractive manufacturing.” In addition to its brevity, this “definition” is useful for two reasons. First, it is implicitly broad, as it does not invoke any of the prototypical details that are typically invoked yet constrict our perspective, such as the heat source (such as laser), geometries of the material that is added (such as molten pool), or incoming material type (such as powder). Second, it implies a capability that is important for the NDE community: the addition of volumes of material means that those volumes can be probed in a manner paralleling (following) the AM technique itself, providing a highly detailed perspective of the materials state.

The intellectual property history of AM can most clearly be understood based upon this definition. From a certain perspective, civilization’s earliest methods of manufacturing involved AM, as exemplified by coil pots, which permitted individuals to make clay pottery prior to the advent of the potter’s wheel. However, from a modern perspective, the earliesttechnical basis for metal-based AM is found in a 1920 patent by Ralph Baker (1920), who patented a method to produce decorative articles using electric arc welding to deposit beads of material onto previously deposited beads of the same metal. While this method was cited in other welding techniques in the 1960s, the next notable patent came in 1979 from Brown et al. (1979) while working at the United Technologies Corp. on a US Navy–funded project. In 1979, the inventors disclosed a process for the subsequent deposition of metallic layers that would be capable of producing bulk, rapidly solidified metals. In their work, they termed this technique “LAYERGLAZE,” and in their patent, they included the possibilities of multiple heat sources (including both electron beams and lasers) and of multiple material forms (including both powder and wire). While this was not pursued fully at the time, there is a direct connection between this patent and Sandia National Laboratories’ work on a directed energy deposition system with a powder-blown delivery system and a laser energy source known as Laser Engineered Net Shaping (LENS™), which resulted in the first commercial company for metals-based AM, Optomec, and the first commercial sale in 1998 to Ohio State University. Other key technology patents in the 1980s that have benefited the AM community are rooted in polymeric materials, including the work of Hideo Kodama in 1981 (Kodama 1998), Charles Hull's work in stereolithography in 1984 (Hull 1984), and Charles Hull's first 3D printer in 1987 (3D Systems 2021). In the earliest days of metals-based AM using LENS systems, there were simultaneous efforts to understand the processing-property space, including the first appearance of metrics that combined key "feed and speed" parameters into energy density terms (Yin and Felicelli 2010; Hofmeister et al. 2001); understand the composition–microstructure–property space, including the use of elemental blends (Schwender et al. 2001; AlMangour et al. 2017); and produce the initial work into producing compositionally graded structures (Zhang and Bandyopadhyay 2019; Bandyopadhyay and Heer 2018; Obielodan and Stucker 2013; Balla et al. 2009). Industries and agencies began to fund work to develop the first processing–structure–property databases and began to place AM metallic parts into service (Collins et al. 2014, 2016). Within the past decade, there have been sustained efforts in developing and integrating computational tools to predict the geometry (including distortion and residual stress), microstructure, properties, and performance of AM parts (Smith et al. 2016a; King et al. 2015). The level of sophistication and availability of machines is now sufficiently robust that in 2019, it was even shown that it was possible to 3D print and "fly" a certain superhero suit (All3DP 2021).

It is difficult to bound the variations of AM systems. The scale of the systems ranges from aerosol jet-like processes, which have submicrometer resolution and are used to manufacture functional devices, to large-area AM, which produces parts with dimensions of multiple meters (Lim et al. 2012; Williams et al. 2016). While most metals-relevant AM systems involve fusion (pools of liquid metal), there are other innovative AM techniques that are solid state (such as the MELDprocess [Yoder et al. 2021; Griffiths et al. 2019, 2021]) and rely upon frictional or ultrasonic methods of joining. The heat sources for fusion-based techniques include lasers, electron beams, plasma sources, and, most recently, resistance-based techniques (such as Joule heating [Huang et al. 2014; Batista et al. 2020]). The incoming material to be added is prototypically wire or powder, but can also include thin sheet or ribbon (Kobryn et al. 2022; Hascoet et al. 2014). The atmospheres can be equally varied, ranging from vacuum to inert shield gas to deposition in controlled atmosphere glove boxes. This variability has an impact on the composition of the as-deposited materials in fusion-based systems. AM systems can be additive only, or hybrid involving the recursive operation of both additive and subtractive (machining), or other techniques, such as laser peening for local control of the residual stress (Hackkel et al. 2018; Madireddy et al. 2019). Systems can be equipped to deliver material from a single feed source or from multiple feed sources to enable the spatial control of the composition in a preprogrammed manner (Kelly et al. 2021; Schwartz and Boydston 2019). The as-deposited structures can be free form or supported using lattice structures such as in powder beds (Collins et al. 2016; Davis et al. 2009; Zalameda et al. 2013; Vaissier et al. 2019; Hussein et al. 2013). Similarly, the architectures can be designed to be fully dense, lattices, or with variations of controlled internal cavities (Juechter et al. 2018; Wang et al. 2018; Tao 2016; Gardan and Schneider 2015). Figure 1 provides a broad overview of the types of structures, systems, and processes that exist. Considering these capabilities in aggregate, and imagining future systems where the "material effectors" are selectable to achieve a particular materials state with a particular function in a particular location (a logical fusion of concepts found in AM and metamorphic manufacturing [Xie et al. 2016; Daehn and Taub 2018; Feucht et al. 2020; Love et al. 2013; Good and Landau 2017]), one can begin to conceive of new materials and desirable topologies across a range of length scales.

In general, the types of physical processes of fusion-based AM techniques involve:

- the transfer of energy from the heat source into the material, which includes consideration of the material's reflectivity to the particular energy wavelength and adjusted for particular configurations that correspond to the efficiency and redundancy of energy-impingement events;
- the heat-transfer mechanisms within the part, including radiation, conduction, and convection (Raghavan et al. 2013; Gutowski et al. 2017);
- the heat-transfer mechanisms associated with the material's thermodynamics, including phase transformations and any attending enthalpy of mixing of different species (Kumara et al. 2020; Zhang et al. 2019b; Kenel et al. 2017);
- the fluid dynamics of the liquid, including Marangoni convection, buoyancy, gravity, and other complex melt-pool dynamics (Hojjatzadeh et al. 2019; Gan et al. 2017; Khairallah et al. 2016);
- possible secondary processes in proximity to the molten pool, including capillarity, wetting, sintering, and thermal grooving (Blank et al. 2019; Mullins 1957, 1958);
- dynamics mediated by the liquid/vapor interface, including volatilization or gettering of elemental

species, and the gas dynamics, including kinetic motion of molecules (Sato and Kuwana 1995; Semiatin et al. 2004; Collins et al. 2014);

- physical processes at the liquid/solid interface, including melting and solidification;
- solid-state phase transformations; and
- the current evolution (and retention) of elastic-plastic deformation processes induced by either phase transformations, phase evolution, or transients in thermal gradients.

These processes are further complicated by the motion of the heat source, inducing so-called thermal gyrations into the part whose magnitude and frequency are functions of the part geometry and the build scan strategies (G-code). Each of these is sufficiently complex so as to merit their own treatment, and as such lies beyond the scope of this paper. However, an understanding of such broad categorizations is helpful to understand the types of measurements that will be useful in understanding key metrics of the materials state that influence the properties and performance of the material. Table 1 provides correlations between these general types of physical processes and a hierarchy of materials state parameters that govern the properties and performance of materials. For some materials, these correlations have been quantified, and the most important factors have been determined.

Important Materials State Factors

From the perspective of failure in most metallic systems (assuming a reasonable level of ductility), the principal aim is to understand the presence of defects and damage and their evolution during service. Thus, concepts such as fatigue and fracture go hand in hand with materials state awareness and any attempt to link NDE methods with AM, whether ex situ or in situ. In AM materials, the dominant macroscopic defects include porosity, lack of fusion (LOF), cracking/tearing, and balling.

After the macroscopic defects are considered, two other variables demand our attention. The first variable, residual stress, can couple with defects, leading to unexpected failure. Explicitly, it is necessary to state that residual stress is the gradient in the local density of dislocations, which are the atomic-scaled line defects responsible for an alloy's ductility, and which can lead to considerable strengthening of the material. Thus, a material can have a low average dislocation density but a high residual stress (large gradients), a high dislocation density but a low residual stress (small gradients), or other permutations. The second variable involves grains, their size, and any preferential crystallographic orientation, also known as texture. Texture is increasingly recognized as having an important role on the properties and performance of materials. Texture is very common in AM materials, owing to the steep thermal gradients and rapid solidification (Quintana et al. 2020; Saville et al. 2021; Kamath et al. 2021; Kunze et al. 2015; Dinda et al. 2012; Song et al. 2014), though it can be controlled through processing. The presence of periodic texture has been linked with some challenges in inspectability.

The final two broad categories, materials composition (both average and local) and the "rest" of the microstructure (typically phases, their size and distribution) are critically important to setting the baseline mechanical properties of engineering alloys (such as strength, ductility, and fracture toughness). At a minimum, there are local compositional fluctuations in AM components (Kenney et al. 2021; Collins 2004;

Table 1. Materials state variables linked to different physical processes related to AM

Physical process	Materials state variables					
	Composition		Phases (size, fraction)	Grain size/ texture	Defects (pores, cracks, lack of fusion, balling)	Residual stress
	Average	Local				
Heat input		×	×	×		
Macroscopic heat transfer			×	×		
Materials thermodynamics		×			×	
Fluid dynamics within the molten pool					×	
Fluid processes adjacent to the molten pool	×	×			×	
Liquid/vapor interface processes		×		×	×	×
Liquid/solid interface processes			×			×
Solid-state phase transformations				×	×	×
Elastic and plastic deformation, gradients		×	×	×	×	×
Thermomechanical gyrations				×	×	×
Euclidean deposition (i.e., G-code) effects		×	×	×		

Hayes et al. 2017), which can lead to variations in the elastic stiffness tensor (*Cij*), and thus should be relevant for the NDE community.

These five categories of variables are described briefly in the following sections. Interestingly, there is a coupling between these variables that provides potential strategies to better identify them using NDE techniques. Some examples of coupling between variables will be introduced.

Defects

There are at least five types of macroscopic defects associated with a volumetric variation of some sort: spherical porosity, LOF porosity, balling, cracking or hot tearing, and fish scaling (Zhou et al. 2015; Tammas-Williams et al. 2015; Pogson et al. 2004; Sochalski-Kolbus et al. 2015). Figure 2 provides examples of these four types of macroscopic defects.

Often and erroneously, spherical porosity (Figure 2a) is assumed to indicate an existing gas pore. The correct interpretation is that the pore formed when it consisted of a gaseous species inside the pore. However, there are two sources for such gas. The first source is gaseous elements, such as argon, that are contained in some powder particles prior to deposition or that are captured by liquid dynamics from the surroundingatmosphere. These elemental species will remain in the pores and are unlikely to be healed permanently through other post-deposition processing steps (Kenney et al. 2021; Collins et al. 2016; Collins 2004; Zhang et al. 2019a; Chlebus et al. 2015). The second source is alloying elements that are vaporized and create a keyhole (Kenney et al. 2021; Hojjatzadeh et al. 2019; Collins et al. 2016; Petrov et al. 1998; King et al. 2014). These elements have surface Rayleigh instabilities whose dynamics can result in spherical pockets of vapors of the constituent metal elements that behave as a gas, resulting in spherical pores, and which then condense on the surface of the pore, leading to a pore that is under vacuum. The thermophysical properties, including density, of these two types of spherical pores will differ. There is emerging work that is using high-energy X-rays to image experiments that emulate powder bed systems to study the origins of these defects (Menasche et al. 2021; Xavier et al. 2020; Jop et al. 2020), whileother work is studying the importance of Marangoni convection on the capture and retention of these particles in molten pools with an extended tail (Hojjatzadeh et al. 2019; Gan et al. 2017; Khairallah et al. 2016). Such work is in alignment with evidence that raster scan powder bed strategies are more likely to contain these spherical pores that arise from alloy constituent vaporization, while spot-scan strategies are less likely.

LOF defects (Figure 2b) are features caused by partial melting of the material by insufficient heat and can be classified by poor overlap within layers, inadequate wetting, or shallow melt pools that do not interact with previous layers (Polonsky et al. 2020; Calta 2019; Martin et al. 2019; Cunningham et al. 2019). Scanning strategies play an important role in the creation of this type of defect. LOF defects are common in linear raster strategies, especially in those locations when the heat source reduces speed to make turns, making the zones near the edges particularly common places to observe these defects (Zhou et al. 2015). This points to the need to better understand—and potentially measure—signals of the depth of penetration of the molten pool, as opposed to the current method, which is commonly a preprogrammed function related to power and acceleration/deceleration speeds. Such information would better represent the process physics. The formation of LOF defects can also be responsible for "turbulence events" that hinder fluid flow and can promote even more heterogeneities in chemistry. Furthermore, the local cooling rates can be related to the shape of LOF defects or be identified as the cause of their formation (Kenney et al. 2021; Bayat et al. 2019; Wolff et al. 2017). NDE techniques, such as X-ray computed tomography, can be very powerful tools to first determine if LOF defects are present in the part and also their location and approximate sizes, depending upon the resolution of the technique, the depth of penetration, and other shape factors.

Excessive heat can form other defects such as those associated with the "balling phenomenon" (Figure 2c) in which liquid droplets of metal are ejected from the melt pool, cool rapidly, and then land on the melt pool (potentially becoming incorporated) or other regions of the part (Khairallah et al. 2016; Gunenthiram et al. 2018; Haghdadi et al. 2021). These droplets once they cool and if they are captured, may effectively modify the local properties (topological, mechanical, chemical, texture, thermal, etc.) and influence subsequent layers.

Cracking (Figure 2d) is a dynamic process where the rates of heat transfer and the concurrent stresses and strains due to thermal expansion/contraction, or phase transformations, compete with the ability of the material to accommodate the strains, typically defined by the ductility of the material. The problems associated with cracking are well known in the welding community and are often associated with concepts such as the "brittle range" (the temperature range that a material will still have strength but without any measurable ductility) and the nil ductility temperature. Such cracking problems exist for AM materials for two reasons. First, AM is effectively a spatially controlled welding process, with the same physics, although with different degrees of severity. Second, the 3D nature of the builds often results in thermal cooling differentials, where the base plates are at a colder temperature and result in higher heat extraction rates and degrees of thermal cycling for the first layers of a build, which reduces as the builds get to be larger/taller, and further removed from a "cold" substrate relative to the molten pool. In addition to these conventionally understood cracks, differences in the local material's state and porosity levels (whether intentional or not) will result in changes in heat flow and will lead to gradients in stresses and strains that can lead to local cracking, even in otherwise ductile material.

The final defect discussed in this review is the so-called "fish scaling" (Figures 2e and 2f). This defect is observed in the planes parallel to the build direction and are a result of variations in solute concentrations or chemical variations in the melt pool, or variations in precipitate formation and morphology (Sochalski-Kolbus et al. 2015; Tang et al. 2015; Brandl et al. 2012). This is typically a result of solidification processes, such as solute rejection in columnar and/or dendritic solidification, and/or solute trapping for fast-moving solid-liquid interfaces. During destructive metallographic analysis, this fish scaling can be used to distinguish individual melt pools. This defect is also a discontinuity in properties such as the local elastic stiffness tensor (*Cij*), density, composition, and other aspects of the material's state. The ability to measure these using any NDE method will be limited in many respects, as the wavelength of the measurement devices is much larger than these local variations.

Texture

In polycrystalline materials, texture is a phenomenon where there is a preferential bias in how the crystal structures (that is, atomic planes and directions) of each individual grain are arranged. Crystallographic texture has long been known to exist in traditional manufacturing processes, including deformation processes, casting/solidification, and welding. For those crystallographic textures whose origins are due to solidification, the literature is full of data and models that show a preferential growth of grains where certain crystallographic directions are parallel to the maximum thermal gradients, effectively balancing both the growth rates of the crystals and the heat transfer. Classically, solidification models and data show the [001] grain growth is parallel to the maximum thermal gradient for cubic alloys, though it can be influenced by anisotropy parameters and other crystallographic variables related to grain growth, which can even occur in the [110] direction (Chalmers 1964; Morris and Winegard 1969; Ferry 2006; Liu et al. 2013; Boettinger et al. 2000; Henry 1943; Henry and Rappaz 2000).

In AM, the process parameters such as melt-pool size, scanning strategy, and layer height influence the maximum thermal gradient, and thus are mainly responsible for texture and grain morphology, which can result in equiaxed grains (Figure 3a) or elongated columnar grains (Figure 3b) (Haghdadi et al. 2021). The [001] growth can have deviations up to ~10° to 20° from the build direction as a result of the spatially varying heat source that modifies the thermal gradient, and this texture persists with subsequent layers (Quintana et al. 2020; Saville et al. 2021; Kamath et al. 2021; Stephenson et al. 2020; Haghdadi et al. 2020; Shao et al. 2020; DeMott et al. 2021; Kumar et al.

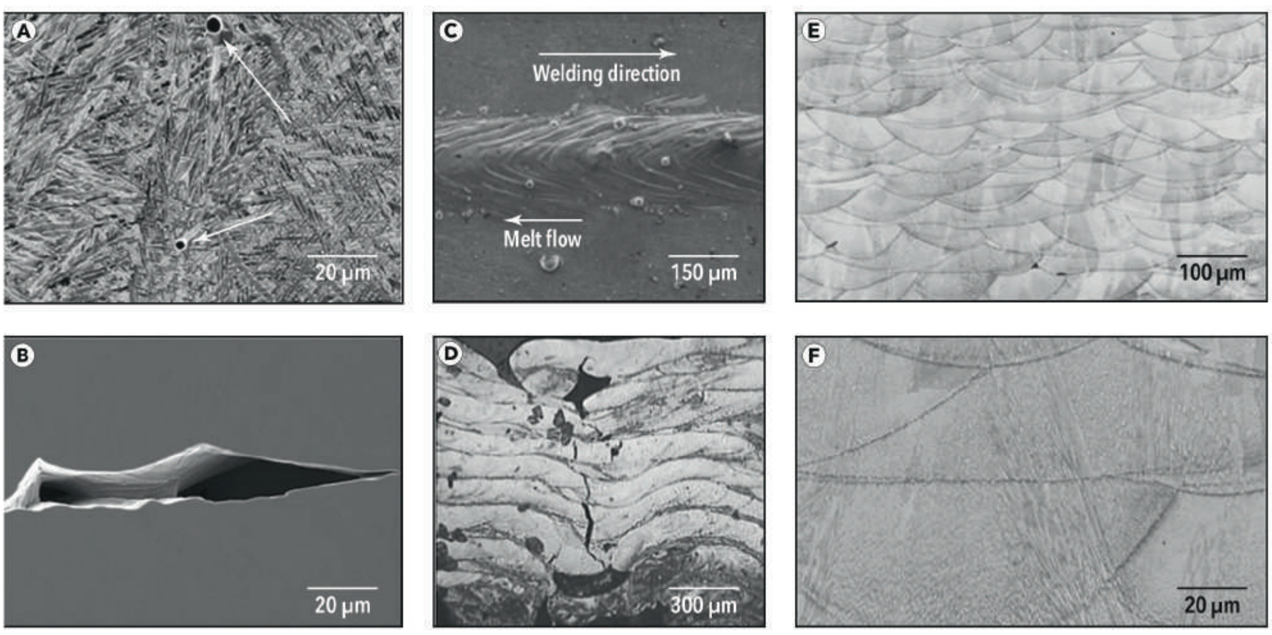

Figure 2. Defects commonly observed in AM: (a) spherical porosity (indicated by arrows); (b) lack of fusion caused by insufficient energy input to melt the stock material; (c) balling; (d) hot tearing caused by excessive energy input, creating ejecta of material and thermal stresses; and (e) and (f) fish scaling, at two different magnifications. (Figure 2a is reused from Tammas-Williams et al. [2015] under Creative Commons Attribution License (CC BY); Figure 2c is reprinted with permission from Zhou et al. [2015]; Figure 2d is reprinted with permission from Pogson et al. [2004]; and Figures 2e and 2f are reprinted with permission from Sochalski-Kolbus et al. [2015]).

2021). Texture in AM parts has been reported for alloys such as titanium-based (Bermingham et al. 2015; Vilaro et al. 2011; Wu et al. 2002; Qiu et al. 2015), nickel-based (Kunze et al. 2015; Dinda et al. 2012; Bi et al. 2014), and aluminum-based high-entropy alloys (Joseph et al. 2015; Sun et al. 2014), among others (Song et al. 2014; Zecevic et al. 2015). As texture is directly related to heat flow, the presence of defects such as spherical pores or LOF (Kenney et al. 2021) can modify the heat vector and the orientation of the columnar grain growth and in some cases, the columnar grains can stop at the "floors" of these defects. This local disruption is an example of a correlated microstructural feature that may help to identify defects—even those that are subsurface—in AM components.

Residual Stress

During AM processing, parts can experience cyclic expansion/ contraction during the thermal gyrations of heating/cooling, which can result in inhomogeneous and anisotropic stresses that can result in permanent microscopic domains of plastic deformation. This is known as residual stress. To be specific, residual stress refers to gradients in the dislocation densities (which accommodate stresses and lead to strains). Suchresidual stresses can lead to distortions, cracking, and failure (Cottam et al. 2014). Within AM deposited parts, residual stresses can vary within a layer. They have been reported to be different at the bottom of a layer to the top (Denlinger et al. 2014, 2015; Michaleris 2014; Mercelis and Kruth 2006), and have been reported to reach magnitudes such as ~400 to 800 MPa in nickel-based superalloys (Denlinger et al. 2014; Vilaro et al. 2012) or as low as ~25 MPa for aluminum alloys (Brice and Hofmeister 2013). Not surprisingly, given the gradient nature of the local stress/strain states and the typical balancing of stress states, these stresses can be either compressive or tensile in nature, depending upon location (Denlinger et al. 2015; Brice and Hofmeister 2013). Roberts et al. (2009) reported that residual stresses are directly related to thermal gradients in the melt pool, and thus can be controlled by thermal gradients by modifying the printing parameters and scanning strategy. Such residual stresses would be potentially suitable for nonlinear NDE techniques post deposition, although it may be possible to use image-based techniques and machine learning to predict the local residual stress of a component.

Compositional Variations

In AM, compositional variations can be induced either intentionally (such as through controlled modification of the incoming material feed) or unintentionally (such as through volatility of an elemental species in the presence of a vacuum and exposed to significant superheats). In addition to these macroscopic changes in composition of the local melt pool or its surface, the complex fluid flow can convey the different compositional domains (often at flow rates of 0.1 to 1.0 m/s). In addition, for powder bed processes, it has recently been shown that the fluid dynamics are coupled with the convective forces within the molten pool, which can have a considerable influence on the local composition of the solidified material. These fluid dynamics are a function of thermal gradients in the liquid pools and are thus a function of the scan strategies (for example, raster or spot scan strategies). Of the competing fluid-flow mechanisms, Marangoni convection has been shown to be the dominant factor in raster melt pools, as it is driven by temperature gradients. Hojjatzadeh et al. (2019) defined three distinct regions in the raster melt pool: circulation, transition, and laser interaction. In comparison, spot melting melt pools would have only laser interaction regions. This difference explains why gas bubbles more easily escape the melt pool in spot melting strategies and can remain entrapped (and form pores) in raster strategies (Kenney et al. 2021; Quintana et al. 2021). In addition, this coupled effect between defects (gas pores) and compositional fields has been recently confirmed (Kenney et al. 2021), providing another possibility to relate two defects that may be interpretable using different measurement modalities.

Fluid flow, in combination with preferential elemental vaporization, is also responsible for a phe-

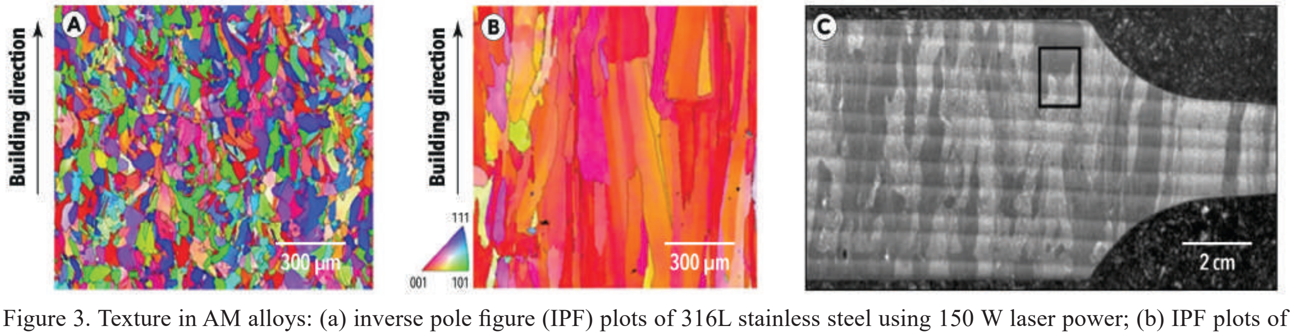

Figure 3. Texture in AM alloys: (a) inverse pole figure (IPF) plots of 316L stainless steel using 150 W laser power; (b) IPF plots of 316L stainless steel using 1000 W laser power; and (c) columnar growth and banding in a Ti-6Al-4V tensile coupon. (Figure 3a is reprinted with permission from Laleh et al. [2019]; Figure 3b is reprinted with permission from Niendorf et al. [2013]; and Figure 3c is reprinted with permission from Carroll et al. [2015].)

nomenon known as banding (Figure 3c) and can be observed in optical microscopy (usually as light and dark bands perpendicular to thebuild direction) and energy dispersive spectroscopy (capturing bands and chemical turbulent signatures in the presence of defects).

Phases

Structural, multicomponent engineering alloys often rely on second phases (or phase transformations) for strengthening purposes. Such alloys include $\gamma - \gamma'$ nickel-based superalloys, precipitate hardened steels, precipitate hardened aluminum alloys, and $\alpha + \beta$ and β titanium alloys. While in traditional manufacturing processes, materials experience a specific sequence of temperature excursions to optimize the phase transformations sequence and evolution of the second phase precipitates, the nature of AM forces the alloys to experience an externally governed number of thermal cycles (through the slicing algorithm) of a rather extensive range of possible temperatures, ranging from remelting to "optimal phase transformation windows" to lower temperature heating/coarsening, all of which influence crystallographic texture, grain size, formation–dissolution–formation of precipitates, phase fraction, and formation of nonequilibrium phases, including noncrystalline phases in some cases. Traditional phase transformation models are not fully valid for AM systems and require modification to incorporate these thermal cycles and their influence in the already printed layers. Compositional variations and banding can also be related to different phases in different locations within a layer, as different chemistry can be related to different regions in a phase diagram. The presence of certain phases, morphologies, phase distributions, or phase fractions can be achieved in some cases only by post-deposition heat treatments. This domain is, on the one hand, perceived as the most difficult to couple with NDE modalities because it is the least mature, and due to the size/ scale of the precipitates. However, it may be that indirect methods can be used to assess phase formation, as the precipitation of one phase will change the crystal chemistry of the parent phase, resulting in changes in the local elastic stiffness tensor, a property that is determinable using NDE techniques.

A Review of the Application of NDE Techniques for Additive Manufacturing

NDE is a collection of qualitative and quantitative testing methods that are used to evaluate certain characteristics of the subject under test without permanent damage or alteration. NDE can provide critical information regarding certain material properties, which plays an important part of providing confidence for qualification and better quality control of the material being used or produced. NDE can also be used on a routine basis to continuously monitor mission-critical (high-value) parts and systems over their lifespans. Rigorously speaking, nondestructive evaluation (NDE), nondestructive testing (NDT), and nondestructive inspection (NDI) do not correspond to the exact same concept, but it has become an acceptable practice to use these three terms interchangeably. NDE techniques rely on electromagnetic radiation, electromagnetic wave, electromagnetic diffusion process, mechanical wave, visible and invisible light, or a combination of those physical phenomena (for example, laser induced phased array [LIPA] and electromagnetic acoustic transducer [EMAT]) to indirectly or directly examine samples. It is worth noting that NDE is much more than just "detecting cracks," as it is very common to use NDE techniques to evaluate the properties of perfectly working subjects at the micro-, meso-, and macroscale. Based on specific physical processes and principles, NDE techniques can be broadly divided into six modalities: visual testing (VT), ultrasonic testing (UT), acoustic emission testing (AE), electromagnetic testing (ET), radiographic testing (RT), and thermal/infrared testing (IR).

Each of these modalities has different strengths and weaknesses, and their performance is bounded by their respective physical basis. In the potential application of NDE techniques in AM, there are two resolutions to consider: spatial resolution and temporal resolution. This paper considers only the first, given its immediate translatability and greater disparity between the materials science and engineering/additive manufacturing (MSE/AM) processing needs (micro- to mesoscale) and NDE possibilities. Interestingly, the temporal resolution is far more likely to have a match between the MSE/AM needs and NDE possibilities. Considering spatial resolution, for VT and UT (both wave propagation methods), the Rayleigh criteria determines their resolution limit due to diffraction limits. For VT, expected resolution will be no better than ~0.2 μm for optimized optics, and this number is 0.2 mm for UT in most cases. There are intrinsic tradeoffs between metrics. For example, there is a tradeoff between resolution and depth of focus for VT, and there is a tradeoff between spatial and temporal resolution for UT. For ET, RT, and IR, the resolution limit of these modalities is mainly empirically determined by the equipment, mechanical setup, and testing samples. For ET methods, spatial resolution is no better than 0.2 mm; for IR, this number is 20 μm (Ida and Meyendorf 2019).

Since the quality of AM parts is very sensitive to process windows and complex and competing physics, there is an obvious need for NDE on AM. It is imperative to include NDE in the AM process loop (whether in situ or ex situ) so that feedback information from NDE techniques can not only improve the process but also play an important role in the overall quality assurance paradigm. Table 2 (Taheri et al. 2017) summarizes the matureness of NDE techniques on AM in 2017 and their evolution in the following four years.

Given that there have been significant efforts extended on the general subject of AM NDE, the remaining section of this paper will cover the latest developments regarding NDE application on AM, and the reasons why the information in Table 2 was updated.

Visual Testing

VT techniques include, but are not limited to, contour mapping, fringe projection (structured light), laser profilometry, digital image correlation, and optical imaging and tomography. These techniques are mainly used to evaluate geometric accuracy, surface roughness, and residual stress (Sharratt 2015), although there are ongoing efforts to correlate these types of data with other volumetric defects determined following completion of the depositions. One way to determine residual stresses by comparing the build before and after removal from the substrate is by using a coordinate measurement machine (CMM) or other type of high-accuracy 3D scanning technology (Denlinger et al. 2014). Recent progress in computer vision may also provide another way of measuring residual stress by Eulerian video magnification (Wu et al. 2012), which is relatively low in cost because it is camera based. VT (camera based) techniques are useful for in situ AM process monitoring due to their low cost, ease of use, and numerous software support packages (such as computer vision and machine learning). The basic application of camera-based techniques in AM process monitoring is flaw detection. LOF defects can be identified from optical data by correlating multiple images with different lighting conditions and from multiple layers (Abdelrahman et al. 2017).

With the help of supervised machine learning, it is also possible to extend the detection capability of cameras beyond LOF defects (Gobert et al. 2018), although it remains difficult to differentiate LOF, porosity, cracks, and inclusions. Mechanical properties

Table 2. Comparison of potential and capabilities for application of NDE methods for defect detection and materials evaluation for finished AM parts, and the changes to these techniques in the last four years

NDE method	Proposity		Crack		Microstructural anomalies		Geometrical anomalies		Mechanical properties		Electromagnetic properties		Residual stress	
	2017	2021	2017	2021	2017	2021	2017	2021	2017	2021	2017	2021	2017	2021
Visual	C	B[1]	C	B[1]	A		A		N	B[2]	N		N	B[3,4]
Ultrasonic	A		A		A		B		A		N		B	
Electromagnetic	B		A		D		B		N		A		C	
Radiography	A		A		C		A		N		N		A	
Thermal/infrared	D	B[5]	B		D		B		N		N		N	

Note: A = applicable; B = possible/needs development for use in AM; C = low probability of successful application to AM; D = not applicable to AM; N = not applicable

[1] Gobert et al. 2018; [2] Lu et al. 2019; [3] Sharratt 2015; [4] Wu et al. 2012; [5] McNeil et al. 2020

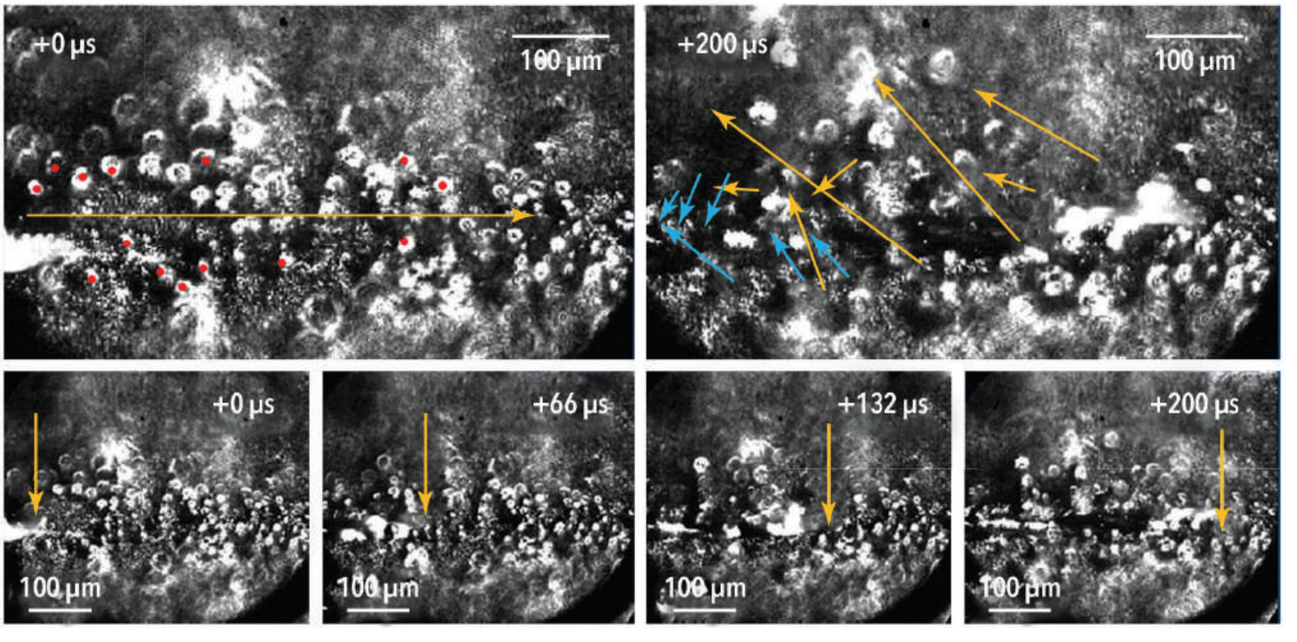

Figure 4. High-speed imaging of melt track progression and powder movement under the influenceof hot vapor Bernoulli effect (reused from Matthews et al. [2016] under Creative Commons Attribution License [CC BY]).

such as density and ultimate and yield strengths can also be inferred by optical images captured during in situ monitoring of the selective laser melting (SLM) process (Lu et al. 2019).

Besides measuring material properties, optical imaging can also provide new insight into the physical phenomena that occur during the AM process. High-speed imaging with microsecond resolution can help in establishing new understandings of the competition between the volatilization of elemental species and the surrounding gas flow to regulate the dynamics of powder motion in powder bed systems away from the molten pool (Matthews et al. 2016), as shown in Figure 4. Research has demonstrated that by including spatters as the process signature driver, a significant increase in the capability to detect under-melting and over-melting conditions is possible (Repossini et al. 2017).

Ultrasonic Testing

UT is widely used for materials characterization and can be used to evaluate material characteristics such as grain size and the presence and quantity of inclusions and porosity, along with material properties such as elastic modulus and (directly or indirectly) the material's hardness, strength, and fracture toughness (Nanekar and Shah 2003). Wave speed, attenuation, backscatter amplitude, and critical angles are commonly used metrics in UT. In the context of AM, porosity can be correlated with ultrasonic wave speeds, and the resolution limit of such a method is ~0.5% (Slotwinski et al. 2014). This presents certain difficulties for the materials scientist, where accurate measurement of porosity fractions below 0.5% may be desired. Laser ultrasound is a noncontact UT technique that induces a laser-induced thermal stress that is sufficient to generate ultrasonic waves within a sample. Laser ultrasonic methods are suitable to perform in situ or in the online inspection of parts with very complex geometry in a high-temperature environment (Levesque et al. 2016). Recent progress in laser induced phased arrays (LIPA) (Pieris et al. 2020) has demonstrated that LIPA is a viable remote, nondestructive, UT technique capable of being implemented as part of an online inspection of AM as seen in Figure 5. It is worth noting that the LIPA system described by Pieris et al. (2020) had some difficulty sizing the defects, but that the positional accuracy was quite good. This issue of sizing may be improved by either optimizing the shear wave frequency or through more sophisticated data processing, perhaps through models that can handle multiple modalities.

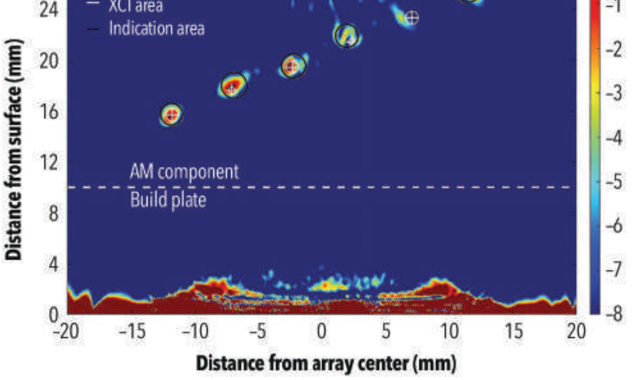

Figure 5. Normalized TFM image using shear–shear wave arrival (reused from Pieris et al. [2020] under Creative Commons Attribution License [CC BY]).

Spatially resolved acoustic spectroscopy (SRAS) is an acoustic technique that uses surface acoustic waves to map the grain structure of a material (Smith et al. 2014), including local crystallographic orientation and texture. The use of surface acoustic waves has been correlated with build quality of SLM parts (Smith et al. 2016b). In some respects, SRAS results provide a high spatial assessment of the material's state, and thus can serve as so-called ground truth when other (cheaper) NDE methods are used and, potentially, fused. Figure 6 provides an example of SRAS grain size and orientation measurement.

Acoustic Emission Testing

Acoustic emission testing (AE) is an NDE method that measures the elastic energy released in the form of acoustic waves in materials that undergo some type of change (such as plastic deformation, cracking, or rupture) (Ida and Meyendorf 2019). Passive monitoring of acoustic signatures has been performed for a directed energy process, showing variations in acoustic emission signatures that correlate with varying process parameters. Because the technique is passive, little modification is required for integration with AM systems, while exhibiting good sensitivity

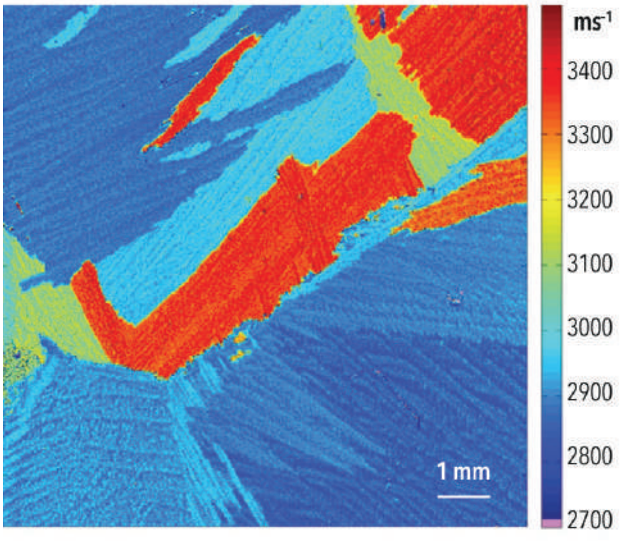

Figure 6. Image of TiLG685 showing the internal structure within the large grains. The crystallites are clearly visible, and spatial resolution is about 50 μm (reused from Smith et al. [2014] under Creative Commons Attribution License [CC BY]).

to crack-like events (Koester et al. 2018). One of the exciting demonstrations of the application of UT to AM involves the assessment of a type of hybrid AM, where the material state has been tuned through the nonuniform application of a secondary peening process (Sotelo et al. 2021). This work shows that UT can be used to spatially assess differences in the material state, providing a promising pathway for future efforts where the composition and material state may change within a single unitized structure. The attenuation map shown in Figures 7a and 7b suggests that the microstructure of these samples is mostly homogeneous, despite the known heterogeneity introduced by the AM process, and Figure 7c exhibits a pronounced cyclic behavior, which is primarily attributed to microstructural changes imparted by the hybrid process.

Electromagnetic Testing

From low frequency to high frequency, this family of NDE techniques comprises alternative current potential drop (ACPD), eddy current testing (ECT), and microwave and millimeter wave techniques as well as Terahertz measurement technology. ECT is arguably the most promising technique of these four candidates for metal powder–based AM processes because it offers a noncontact and high-speed way to inspect surface and near-surface features of samples under test. Due to the skin effect that depends on the working frequency and the material's electrical properties, it is very difficult for ECT to probe deep features (for example, 20 mm deep cracks) for ferromagnetic materials. However, such depth measurements are possible for nonferromagnetic materials if a special coil design is used (Janousek et al. 2005). Traditional coil-based ECT systems have been proven applicable for surface and nearsurface (depth = 1.2 mm, minimum length = 0.2 mm, material = Ti64) cracks in an AM manufacturing environment (Du et al. 2018). Advancement in magnetometer technology has helped to improve the performance of ECT in terms of minimum detectable defect size. A heterodyne ECT system based on a magnetoresistive sensor has been shown to be able to detect surface defects in the order of 100 μm (Ehlers et al. 2020), as seen in Figure 8.

Eddy current in array form (ECA) has recently been used for AM process monitoring due to its superior performance compared to its single-channel counterparts. ECA techniques can detect discontinuities, surface irregularities, and undesirable metallurgical phase transformations in magnetic and nonmagnetic conductive materials additively manufactured using laser powder bed fusion (Todorov et al. 2018).

Electromagnetic techniques in general are sensitive to bulk electrical properties of the samples under testing, which, based upon current work, makes them unsuitable for evaluating microstructural anomalies as well as mechanical properties.

Radiographic Testing

X-ray imaging (2D) and X-ray computed tomography (CT) (3D) are very powerful tools for detecting internal defects embedded inside of the sample for both in situ and ex situ scenarios. The output results

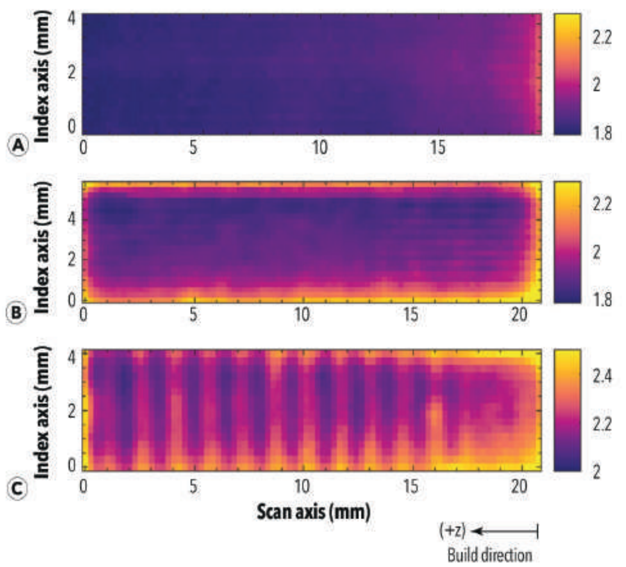

Figure 7. Attenuation, α (Np/m), maps for: (a) wrought; (b) AM; and (c) hybrid AM samples. Note the differences in scale (reprinted with permission from Sotelo et al. [2021]).

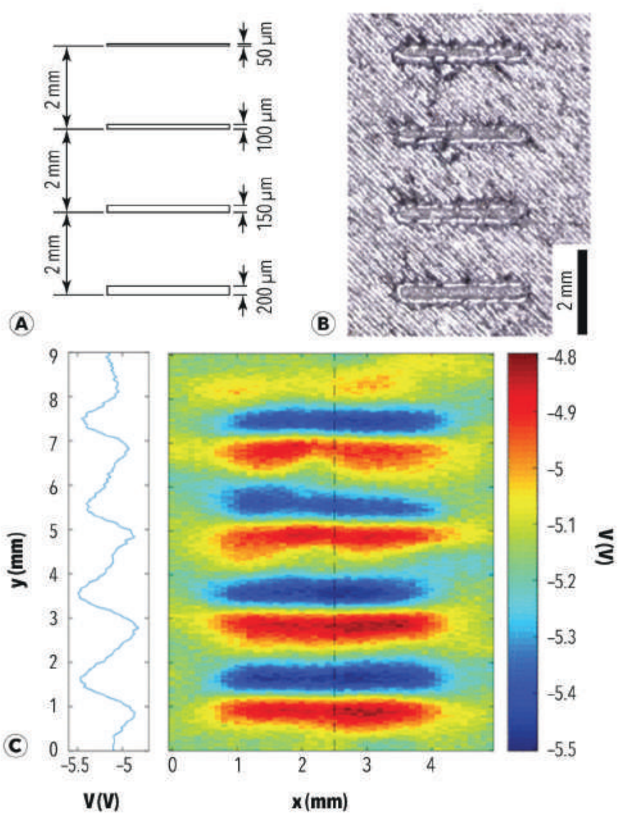

Figure 8. Heterodyne ECT system based on a magnetoresistive sensor: (a) CAD drawing of desired defect geometry (depth 200 μm); (b) microscopic picture of artificial surface defects; and (c) ET data of artificial surface defects (reused from Ehlers et al. [2020] under Creative Commons Attribution License [CC BY]).

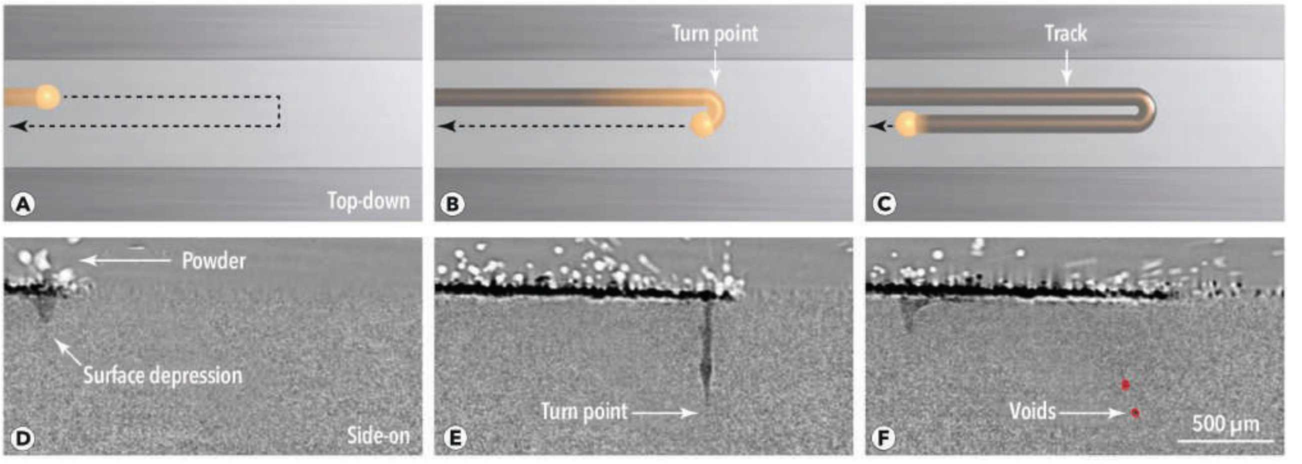

Figure 9. Illustration of the experimental geometry for laser turn point experiments: (a–c) illustration of the laser turnaround point studied here; (d–f) time difference X-ray images of a turnaround in Ti-6Al-4V performed at a laser power of 200 W and set scan speed of 1000 mm/s; (d) laser scanning from the left to right with spatter and powder above a melt depression due to vapor recoil below; (e) laser entering the turn point region and the vapor depression digs deep into the substrate; (f) laser moving right to left after the turnaround. Keyhole voids at the turnaround location are highlighted in red. (Figure is reused from Calta et al. [2019] under Creative Commons Attribution License [CC BY].)

are usually intuitive visualizations of the inspected volume, making data interpretation a relatively easy task compared with other modalities.

With its high spatial resolution, micro CT has been demonstrated to be able to detect low volume fractions of porosity (du Plessis et al. 2015), LOF, and inclusions, making micro CT an ideal tool for developing AM process improvements and ensuring the quality of certain high-value components.

The combination of the resolution and penetration depth of X-ray imaging makes it an ideal technique to image and scientifically study the subsurface physical phenomena associated with the dynamic behavior of the laser powder bed fusion process. Subsurface melt-pool dynamics, including keyhole dynamics and collapse, vapor bubble formation and motion, and the effect of laser turnaround parameters on the depth of the molten pool and associated generated defects can all be observed using imaging using X-rays (or other high-energy particle techniques, such as neutron or protons), which permits some fundamental studies to be conducted that are otherwise exceptionally difficult, if not impossible, for surface-sensitive process monitoring tools (Calta et al. 2019). Figure 9 demonstrates the possibility of using in situ X-ray imaging to observe the dynamics of pore formation at the laser turnpoint, which is helpful for designing an effective mitigation strategy.

Similar work has been done by Hojjatzadeh et al. (2019), where direct observation and quantification of melt-pool variation during the laser powder bed fusion AM process under constant input energy density is done by in situ high-speed, high-energy X-ray imaging. The results, shown in Figure 10, are important for understanding the laser powder bed fusion AM process and guiding the development of better metrics for processing parameter design.

Thermal/Infrared Testing (IR)

IR is an imaging technique that uses the thermal radiation of an object to determine its characteristics (Ida and Meyendorf 2019). Compared with other NDE methods such as UT and RT, IR is fast and can be used to inspect large areas simultaneously (in other words, scanning is not required). The measured surface radiation can reveal the existence of disconti-

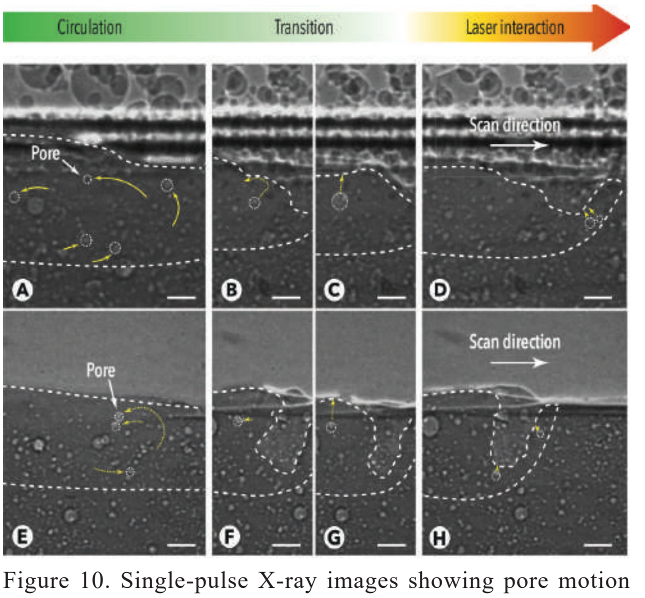

Figure 10. Single-pulse X-ray images showing pore motion within melt pools: (a–d) pore dynamics during the laser powder bed fusion process; and (e–h) pore dynamics during melting of a bare substrate. Pores follow circular patterns during circulation (10a and 10e); they present irregular movement during transition (toward the surface and escaping) (10c and 10g); or circulating in the melt pool (10b and 10f). They move toward the depression zone and escape the melt pool during the laser interaction (10d and 10h). The dotted arrows (10b, 10c, 10d, 10g, and 10h) show the future trajectories of the pores, while the solid arrows (10a, 10e, and 10f) indicate the history of the trajectories. The dashed line indicates the boundaries of the melt pool and the depression zone in 10d and 10h. (Figure reused from Hojjatzadeh et al. [2019] under Creative Commons Attribution License [CC BY].)

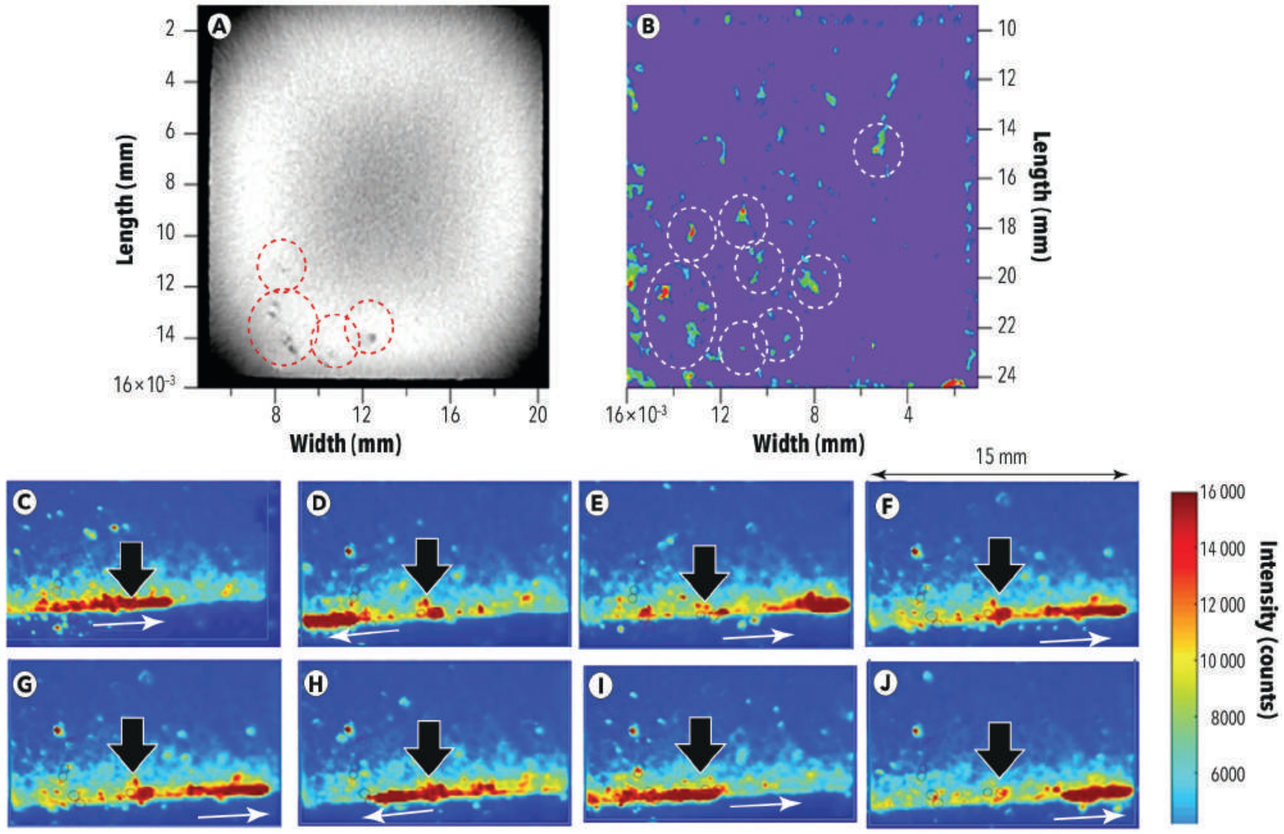

Figure 11. X-ray computed tomography (XCT) is used as an ex situ characterization technique to provide the cross comparison with data acquired by in situ techniques such as thermal/infrared testing (IR) and optical imaging: (a) ex situ XCT data for layer 309; (b) in situ optical images from the same location showing contrast, which is related to surface irregularities; (c–f) in situ IR frames from the same layer within the defect location shown in Figure 11a, captured when the laser completes the raster. (Figure reprinted with permission from McNeil et al. [2020].)

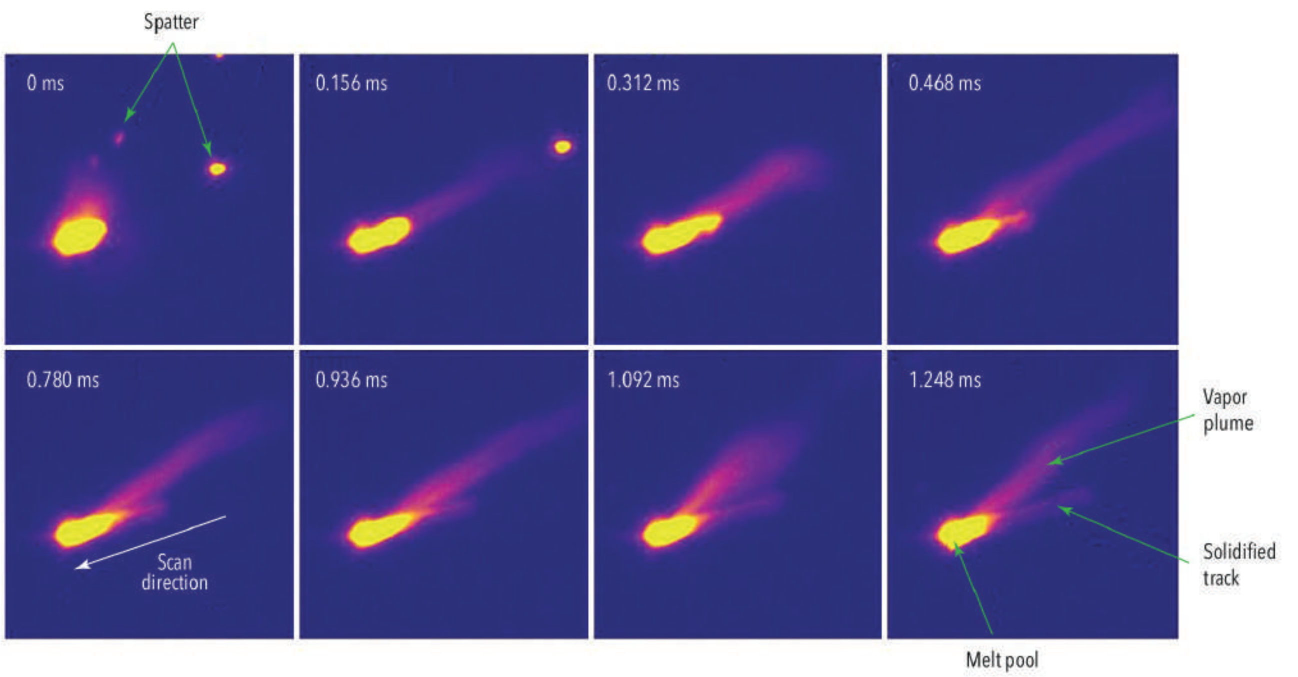

Figure 12. High-speed thermal images collected by the melt pool monitoring camera at LLNL (reused from Calta et al. [2019] under Creative Commons Attribution License [CC BY]).

nuities that affect heat conduction in metal AM parts since surface temperature and its distribution depend on the thermal diffusion of the material as well as the geometry and location of the discontinuities (Mandache 2019). Analyzing layer-by-layer thermal images in terms of the spatial and temporal variations of thermal signatures (for example, peak intensity, decay, and number of gyrations) can be used as a surrogate for defect formation tendency during laser powder bed fusion processing (McNeil et al. 2020). Further, Figure 11 demonstrated that the in situ conclusions can be crossverified by ex situ X-ray CT (XCT) measurement results (McNeil et al. 2020).

If high-speed thermal cameras are used, it is possible to closely observe the behavior of the melt pool in a time-based series, which could provide invaluable information that helps to understand the AM process. Recent research (Calta et al. 2019) demonstrates that high-speed camera images can be used to resolve thermal emission from spatter events, fluctuations in the melt pool itself, the vapor plume, and the solidified track as it cools, as seen in Figure 12.

Conclusions

This paper has given an overview of both the materials science aspects of AM, as well as the prospects of NDE techniques to provide key information regarding the process. The fundamental physics associated with AM are complex, and the relevant length scales range from nanometers to centimeters, while the time scales range from sub-microsecond to many seconds. Relevant velocities include not only the obvious "travel speeds" of the AM process, but also the velocity of the solid-liquid interface and the convective flow within the liquid state. Each of these parameters is associated with details of the process and phase transformations that govern the materials state, including deposited composition, grain structure, texture, defects, and residual stress. While it will be impossible to directly measure all of these parameters, there is the prospect that some multilength scale processes will have measurable signatures that can be probed using NDE techniques. A variety of methods and techniques, ranging from visual, ultrasonic, and radiographic (wave-based methods) to electromagnetic and thermographic (diffusion based) have been presented, and have all been shown to offer some benefit, whether it is to understand process variations or make discrete measurements of the materials state. This field remains active.

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