Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification*

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Abstract

As the metal Additive Manufacturing (AM) industry moves towards industrial production, the need for qualification standards covering all aspects of the technology becomes ever more prevalent. While some standards and specifications for documenting the various aspects of AM processes and materials exist and continue to evolve, many such standards still need to be matured or under consideration/development within standards development organizations (SDOs). An important subset of this evolving standardization domain has to do with critical property measurements for AM materials. While such measurement procedures are well documented with various legacy standards for conventional metallic material forms such as cast or wrought structural alloys, much fewer standards are currently available to enable systematic evaluation of those properties in AM-processed metallic materials. This is due in part to the current lack of AM-specific standards and specifications for AM materials and processes, which are a logical precursor to the material characterization standards for any material system. This paper summarizes some of the important standardization activities, as well as limitations associated with using currently available standards for metal AM with a focus on measuring mission-critical properties. Technical considerations in support of future standards development, as well as a pathway for qualification/certification of AM parts enabled by the appropriate standardization landscape, are discussed.

Keywords: metal additive manufacturing, standardization, qualification, certification

Disclaimer

The views presented in this paper are those of the authors and should not be construed as representing official Federal Aviation Administration (FAA), National Aeronautics and Space Agency (NASA) and National Institute of Standards and Technology (NIST) rules interpretation or policy.

Qualification and Certification Needs and Perspective

Additive manufacturing (AM) has garnered tremendous attention from industry, particularly the aerospace, medical devices and defense sectors. While many sections of this manuscript apply to a broad range of material systems produced by AM technology (both metallic and non-metallic), the primary focus of this paper is on metal AM processes due to the projected higher level of criticality for metal AM parts. It is anticipated that using metal AM processes, companies will be able to fully produce essential, but otherwise unavailable, parts on-demand in days rather than months. In addition to significant lead-time reduction, a number of other business drivers are commonly acknowledged, including weight reduction, part count reduction, high levels of geometric complexity, etc. That is the promise of AM, and not surprisingly, industrial leaders are making targeted investments in AM capabilities with the goal of improving readiness and sustainment of AM technologies for a broader range of businesses. One notable example involves General Electric recently establishing a new business unit, GE Additive, with a plan to produce 10,000 AM machines in the next 10 years [1], thus becoming both the end user and AM machine manufacturer. The continuing investments by other major original equipment manufacturers (OEMs) indicate the general readiness of industry to implement AM technologies at significant growth rates. For instance, most of the major aerospace companies are actively evaluating AM technologies and/or starting to move towards full-scale production of AM parts. Development of industry-accepted specifications and standards is especially essential in this rapidly evolving environment and can facilitate faster and more robust qualification which, in turn, could expedite device/product certification by regulatory agencies. Previous publications [2], [3] have outlined approaches for qualification of metal AM and the corresponding structural integrity considerations. This paper extends the concepts outlined previously [2], [3] and focuses on technical considerations concerning the standardization efforts.

Traditionally, the level of qualification and certification (Q&C) requirements for aircraft parts has been linked to the level of part criticality, defined with various degrees of specificity. For instance, the FAA rule for Materials (14 CFR 25.603) used in transport category aircraft components defines its applicability as "*parts, the failure of which could adversely affect safety*". The FAA Advisory Circular 25.571-1D, Damage Tolerance and Fatigue Evaluation of Structure, defines principal structural elements (PSEs) as elements "…*whose integrity is essential in maintaining the overall structural integrity of the airplane*", including "*all structures susceptible to fatigue cracking, which could contribute to a catastrophic failure*". The FAA rule 14 CFR 37.70 for Engine Life-Limited Parts, or LLPs (formerly known as engine safety-critical parts) defines LLPs as parts "…*whose primary failure is likely to result in a hazardous engine effect*."

While the specific definitions relative to commercial aircraft applications may vary depending on the application type (e.g. airframe structures vs. propulsion engine components), there is a common denominator in that appropriate damage tolerance assessment needs to be performed for parts of high criticality. Two elements of such assessment, fatigue crack growth analysis and NDI (non-destructive inspections), traditionally relied on industry-accepted standards and methodologies that are further discussed in this paper.

The rule for Fabrication Methods (14 CFR 25.605) states that "*each new aircraft fabrication method must be substantiated by a test program*". However, the rule-level certification requirements often do not define the specific *acceptable* testing procedures or compliance methods. This level of detail needs to be defined by an applicant (e.g. OEM) as a part of the MoC (means of compliance) definition, and reviewed and approved by certification authorities. Therefore, standardization of the test methods and specifications can be viewed as an enabler for efficient and robust certification (or qualification) process. For AM, being a relatively new manufacturing technology, the specific testing procedures still need to be developed, reflecting the unique nature of AM material systems including anisotropy, inherent material anomalies, location-specific properties, residual stresses, etc. [2], [4]–[7].

As the level of criticality of AM parts in aviation is expected to continuously increase [3], more efforts need to be focused on the characterization and understanding of fatigue and fracture properties of AM materials, and the corresponding testing methodologies. In addition to "conventional" crystallographic fatigue crack initiation mechanisms in homogeneous substrate materials, crack initiation due to the presence of inherent AM material anomalies such as porosity, lack of fusion defects, or inclusions also needs to be considered [5], [8]–[13].

Due to the random nature of material anomalies (not specific to AM materials), the FAA Advisory Circular 33.70-1 defining damage tolerance requirements for engine LLPs states that "*the probabilistic approach to damage tolerance assessment is one of two elements necessary to appropriately assess damage tolerance*". To support such assessment, the appropriate characterization of material anomalies is needed, in addition to conventional fatigue and fracture properties of substrate materials. Such characterization should focus on developing the size distribution and frequency of occurrence of material anomalies. This information can be used to define an exceedance curve for a given class of material defects, which is the key input into probabilistic fracture mechanics based assessment, such as the one defined in the FAA Advisory Circulars 33.14-1 and 33.70-2 for specific types of material or manufacturing defects. One approach to defining material anomalies exceedance curves is based on the EIFS (effective initial flaw size) distribution (see, e.g. [14], [15]) which relies on the accurate characterization of crack growth properties in the entire range of da/dN vs. ΔK curves.

It should be noted that characterization of material anomalies for fracture critical aircraft or engine components needs to be based on realistic variation in material properties, microstructure, and material defect characteristics representative of the full-scale production environment. Failure to do so may result in "lessons learned" similar to those experienced during the early days of powder metallurgy (PM) when an undetected non-metallic inclusion in a PM turbine disk was found responsible for the failure of a fracture critical component that caused the crash of an F-18 aircraft (see [3] for details).

Due to the broad range of potential AM applications in aviation that include design and production of new parts, replacement parts and repairs, the FAA has recently issued several documents, including *internal* memoranda providing guidance to the regional ACOs (aircraft certification offices) and MIDOs (Manufacturing Inspection District Offices) regarding the engineering and manufacturing considerations for certification of AM parts, as well as the Notice for the FSDO (Flight Standards District Offices) inspectors [16] to provide an introduction and awareness regarding the use of AM technology in the maintenance, alterations and repairs of aircraft and engine components. The latter notice [16] also cites the "*lack of industrywide standards for AM*" as one of the current challenges.

In addition to the FAA, other government agencies like NASA [17] and the FDA [18], [19] have released documents to address quality standards and initial technical considerations for deployment of AM technologies for higher criticality applications (e.g. spacecraft, biomedical devices). These considerations include design for AM, process control, post-processing, part/component testing, inspection, and material and process qualification. A NASA standard [17] also offers AM parts classification based on the consequence of failure and risk level, as shown in Figure 1 below. Such classification is established "…*to levy appropriate levels of process control, qualification, and inspection*".

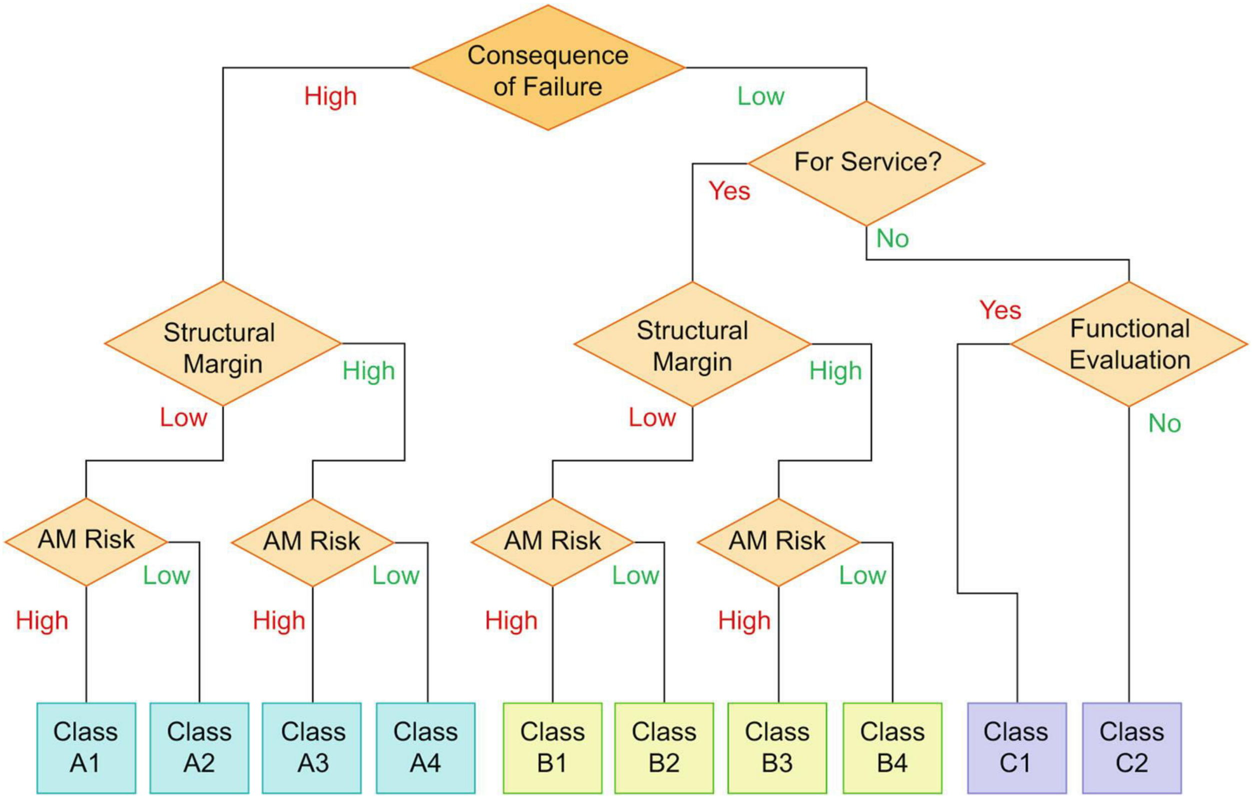

Figure 1. AM parts classification (adapted from [17]*)*

All of these recommendations (or requirements) issued by various agencies are likely to evolve as more information and field experience becomes available in the future. It is important to note that the Q&C requirements are different for aircraft, spacecraft, and biomedical device applications, with specific technical considerations depending on the application type and level of criticality. Although a number of existing standards and specifications may be applicable and relevant throughout the phases of AM process chain, this is not always the case due to the lack of industry experience and uniqueness aspects of AM processes. New developments from the SDOs are needed in this area to facilitate effective Q&C procedures for metal AM parts.

The schematic in Figure 2 below illustrates high-level elements of the Q&C landscape. In the early phases of technology implementation, the industry usually has to exclusively rely on the internal proprietary materials and processes specifications for both the internal qualification work and certification by the regulatory agencies. Development of such in-house documents is usually lengthy and expensive. As the SDOs develop appropriate specifications and standards, the companies can choose between the internal and external documents. The use of industry-accepted external specification and standards, in general, can simplify the work of regulatory agencies, and to enhance safety by "leveling the playing field" in terms of establishing the minimally acceptable requirements across the industry for the key elements of new technology such as AM. For instance, smaller size companies that are interested in using the technology, but may not have sufficient resources to develop comprehensive in-house specifications or standards, could use the external documents to enable robust Q&C process.

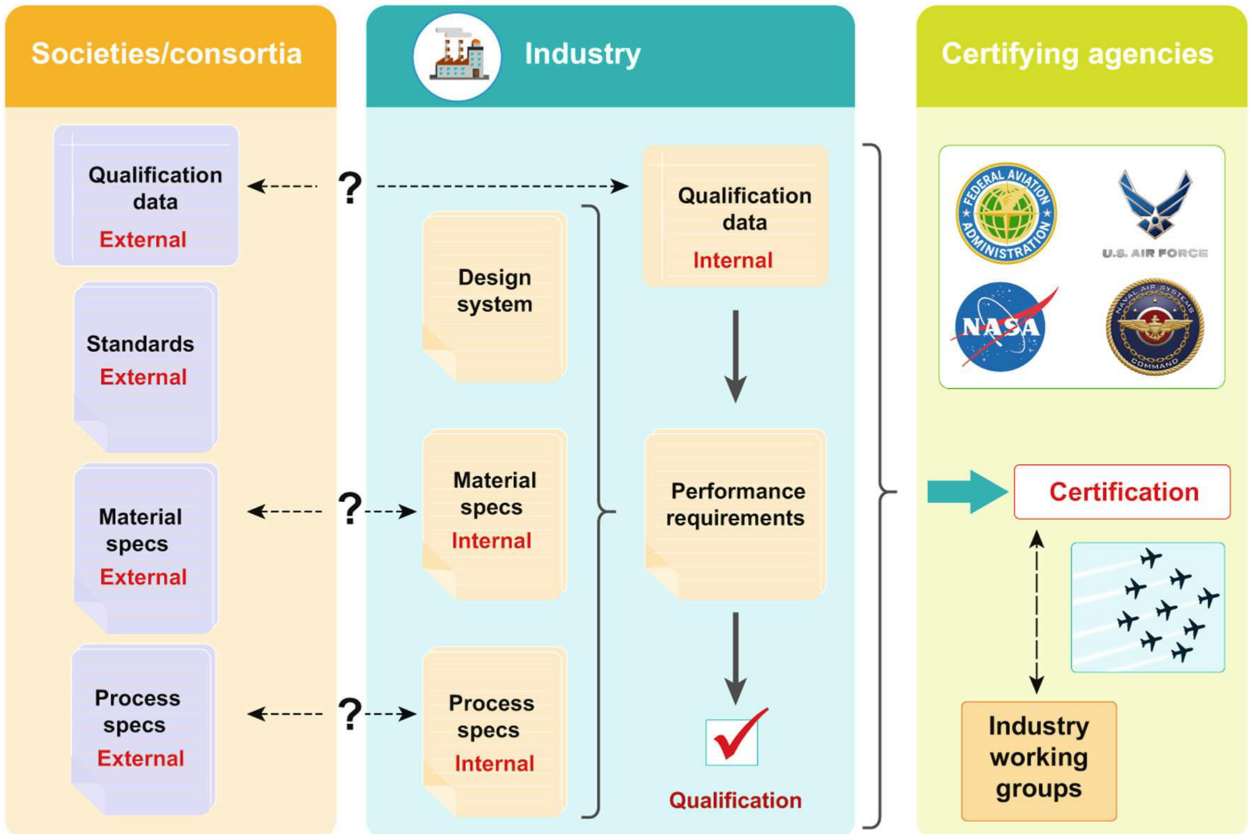

Figure 2. Schematic representation of the Q&C landscape (adopted from [20]*).*

Summary of discussions at recent joint FAA/AFRL workshops

The rapidly expanding applications of AM and their business potential have given rise to a large number of AM consortia, conferences, special journal issues and society forums. Such consortia and organizations tend to focus on promoting AM technology, developing new application areas, and enablers for a broader range of companies to become active technology users. However, in the authors' observation, such organizations put less emphasis on the issues related to developing effective Q&C methodologies. In part to address these shortcomings, the FAA and AFRL collaborated on developing a series of workshops specifically focused on AM Q&C issues. The first such workshop was held in Dayton in September 2015 and brought together over 60 people from the government, industry, and academia. The detailed workshop proceedings and summary can be found in [21]. The second joint FAA – AFRL workshop was held in September 2016 in Dayton [22], and provided a forum for continuing discussions regarding the evolving Q&C framework for AM, and reflected recent developments in this area. Some of the key workshop outcomes included discussion of the major industry trends (such as the increase in the level of AM parts criticality, the transition to full-scale production, and rapid evolution of AM supply chain environment), and significant quality and manufacturing issues for AM processes that must be rigorously addressed for Q&C. Specific areas were identified and addressed by multiple presenters, including:

- *Process variation, controls, and in-process monitoring*
- *Characterization and control of process-related defects and anomalies, and their impact on parts durability*

- *Effects of post-deposit processing such as stress-relief, HIP, and heat treatment*
- *Quality and control of feedstock (raw material)*
- *As-built and post-deposit finishing processes and their effect on part durability*
- *NDE requirements and capability*
- *Orientation- and location-dependent properties.*

Since some of the above considerations for AM part/process Q&C are location-dependent within a part, one of the workshop's recommendations was to consider potential methods and approaches for zoning of AM parts to address defects, variation, and risk. The more detailed discussion of AM part zoning considerations and potential approaches can be found in [3].

Summary of discussions at a recent ASTM/NIST workshop

A recent workshop (ASTM/NIST Workshop on Mechanical Behavior of Additive Manufactured Components, May 4-5, 2016, San Antonio, TX) endeavored to identify current needs to achieve more widespread acceptance and usage of AM metals in fatigue and fracture critical applications. Valuable input was gathered from over 150 attendees from all major areas of the AM community: industry (aerospace, medical device, AM machine manufacturer, etc.), academia, and government (regulatory and research agencies). A more detailed summary of the workshop findings can be found elsewhere [23], but some of the findings provide direct motivation for the current paper.

One of the main needs identified during the workshop was to address the current lack of a comprehensive understanding of the relationships between processing, material microstructure (including defects), and fatigue and fracture properties. This was also highlighted in recent reviews [5], [24] that covered both powder bed fusion (PBF) and directed energy deposition (DED) AM processes across a range of alloy systems. Relevant action items included the need to evaluate existing fatigue and fracture standardized test methods to determine if they are appropriate for metal AM. This provides one motivation for the evaluation of test methods undertaken in this paper. Current standardized destructive test methods [25] may be inappropriate for metal AM as they typically assume material homogeneity and often require specific size and design of test specimens that may not be practical for AM materials. Because of the known lack of homogeneity (e.g. microstructure, density) in metal AM, it was suggested during the workshop [23] that fatigue crack growth test methods with better crack growth rate resolution were needed. It was recommended that existing test methods (e.g. fatigue crack growth tests conducted in a scanning electron microscope (SEM)) utilized by other industries (e.g. nuclear) be considered, but no specific standards were cited. In-situ tomography monitoring during testing may also be useful in determining the role of process-induced defects in fracture/fatigue initiation and growth.

Another major need identified during the workshop [23] was both traditional and rapid qualification frameworks. The need for an extension of traditional qualification frameworks for AM is more immediate, and many at the workshop [23] felt that regulatory agencies should play a leadership role in these efforts. The use of traditional qualification frameworks would involve adapting/extending current validation and verification techniques to standardize best practices for use with metal AM. The appropriate design and use of witness coupons manufactured along with AM parts were one of the major points of discussion within this need. Most agreed that while such witness coupons can be very effective in documenting process variations during a build, the differences in specimen size, thermal history and local build parameters near the witness sample are not necessarily representative of the actual component(s) built as a part of the same build. The development of rapid qualification techniques remains of great interest to the AM community as part of the strategy to decrease product development time and cost, and therefore time to market for new AM parts and components, as summarized recently [2], [26]. Further discussion of Q&C of metal AM parts is provided in later sections.

A separate workshop sponsored by ASTM committee F04 on Medical and Surgical Materials and Devices (workshop on additive manufacturing for medical applications, May 3rd, 2016, San Antonio, TX) was held with around 150 attendees to provide a platform to discuss the present state of additive technologies, their applications in the medical industry and standardization needs. The outcomes of that workshop and recommendations will likely be covered in a separate publication.

Considerations for fracture critical property measurements of metal AM components

Although monotonic properties of AM parts are often comparable to, and sometimes better than their cast or wrought counterparts [2], [4]–[6], [27]–[31], significant variability in AM material behavior under cyclic loading conditions presents a major challenge for implementation in critical applications such as biomedical, aerospace, and defense. AM process-induced defects can impact both low cycle fatigue (LCF) and high cycle fatigue (HCF) behavior [5], [9], [13], [32], [33] while also inducing significant scatter on fatigue properties, although some reports [29], [34] show improved performance with careful control of the process. To ensure more widespread adoption of AM parts in various applications, the factors affecting their fatigue resistance should be better understood [35]. As indicated in recent publications [2], [3], [5] and highlighted above, various concerns regarding process-induced defects may necessitate the use of probabilistic methods applied to site-specific regions in parts in order to estimate their fatigue life and risk of failure based on the local microstructural features and defect statistics [36]–[38]. Successful integration of these efforts will enable wider utilization of AM in applications with higher criticality levels.

With regard to the above, there are four main considerations for fatigue and fracture characterization specific to AM materials: (a) presence of defects, (b) anisotropy, (c) surface roughness, and (d) similitude between the test coupons (used for fatigue and fracture characterization) and actual parts. Each consideration is briefly discussed below:

(a) Material defects are not likely to have a significant effect on “bulk” properties such as crack growth rate (da/dN vs ΔK), consistent with recent work [2], [4], [5], [22], [38]–[41], but can cause substantial fatigue debit and serve as crack initiation sites under some circumstances [2], [5], [6], [8], [9], [42]–[46]. Their effects on fatigue need to be understood and defect populations characterized, including the frequency of occurrence and size distribution that can be combined into exceedance curves (see [3], [15] for more details).

(b) The layer orientation may also affect the mechanical performance of AM parts and cause anisotropic behavior in monotonic and cyclic/fatigue properties [2], [5], [32], [47]–[51]. Many studies have demonstrated directional mechanical behavior in AM parts with horizontally-built specimens (i.e. long axis of sample perpendicular to build direction) exhibiting higher mechanical strengths (i.e. tensile and fatigue) as compared to specimens fabricated in vertical (i.e. long axis of sample parallel to build direction) and diagonal orientations [5], [32], [48], [49], [52]. Anisotropy in fatigue and fracture behavior can be characterized using conventional testing methods (e.g. ASTM) [2], [4], [5], [38], [48], [49], [52], [53]. However, the main challenge is how to use this information for design and qualification work. The easiest approach is to use the most conservative directional properties (e.g. determined along the build direction for AM parts) and treat the material as isotropic. However, this approach may prove too conservative in some cases. The alternative is to use direction-specific properties, but this is complicated by the following considerations:

- Real-life designs with a high degree of geometric complexity (as expected for many AM parts) result in complex multi-axial stress states. While the multi-axial fatigue prediction framework is complex enough even for isotropic properties, the anisotropy in fatigue properties presents additional challenges. Predictive frameworks need to be further developed.
- In the case of crack propagation analysis, even the relatively simple crack models (e.g. planar crack growth with two degrees of freedom) would need to invoke the use of anisotropic da/dN properties in two directions. Full-scale 3-D fracture mechanics problems will require the use of direction-specific da/dN properties in all three directions and conventional fracture mechanics (FM) tools may need to be adjusted and validated for such analysis.

(c) In addition to the process-induced defects (lack of fusion, porosity, microstructure heterogeneity, etc.) often found in AM materials/parts, their fracture and fatigue behavior can be significantly affected by the feedstock material [54], microstructure, surface roughness, etc. resulting from the process [2], [5]. While sub-surface defects can often be eliminated via post processing such as HIP [2], [5], [38], [46], [55]–[59], the resulting microstructural changes and/or coarsening can produce strength reductions [5], [30], while subsequent heat treatment may lead to the reappearance of defects [60]. It is also known that surface roughness negatively affects fatigue resistance of metallic materials. Thus, reducing the surface roughness should improve the fatigue resistance of AM materials [34], [61]–[64]. Significant reductions in fatigue strength and endurance limit of as-built AM 316L SS [61], 17-4 PH SS [62], and Ti-6Al-4V [63], [65] have been reported in comparison to identically AM-processed but surface polished counterparts. While this is consistent with the claims of the importance of surface roughness for fatigue of common structural alloys, much more work is needed to understand surface effects across a broad spectrum of AM materials and techniques, process parameters, and part geometries. In particular, the difference in surface roughness among different AM techniques [2], [5], along with the challenges associated with machining/eliminating the roughness of internal surfaces, cannot be underestimated.

(d) The issue of similitude between the AM parts and test coupons is complex but needs to be understood and addressed as a high priority item due to its potentially significant impact on the fidelity of AM process and parts qualification. The commonly used coupon types include coupons directly excised from AM parts, or purpose-built coupons such as witness coupons or prolongations. The main technical challenge is that, for AM parts, *local* material properties may depend on specific build parameters which, in general, may be different between the part and the purpose-built coupon. This may also result in a different defect distribution in coupons versus components as will be discussed later in this paper. The specific approach and technical considerations may vary depending on whether test coupons are used for initial part (or process) qualification, manufacturing QA process, or for the development of design-pedigree properties databases. One key factor affecting the degree of similitude between the part and witness coupon is the in-process thermal environment [2], [5], [26], [61]. Depending on the material and AM method utilized, the geometry and number of parts on the build plate may significantly affect the resulting monotonic [66]–[68] and cyclic [69] mechanical properties of AM materials. This has been attributed to the different microstructure and defect statistics in the fabricated parts and their dependency on the thermal history (i.e. maximum temperature, cooling rate, etc.), part geometry and/or the number of fabricated parts per build [5], [32]. Residual stress level is another important consideration, and may vary significantly depending on the AM process type [2], [5].

Considering all of the above-mentioned challenges in fabricating reliable parts using AM technologies, there is an immediate need for developing/updating standards pertaining to microstructural characterization and mechanical testing methods [5], [35], [70] in order to facilitate comprehensive characterization of AM materials [70]–[73]. Considering the localized nature of fatigue failure, standards should also focus on how porosity/defects within an AM part are measured. Special requirements of AM specimens, including surface quality, post-build machining, size, geometry, and build orientation should be addressed in such standards [5], [30], [32], [68], [70]–[75].

Applicability of current mechanical testing standards to metal AM

While evaluation of mechanical properties of many AM materials can be conducted using the guidelines developed for conventional materials with existing testing standards, the coordinate systems (e.g. rolling direction, transverse, short, etc.) and nomenclature (e.g. RD, LT, ST, etc.) specific to conventional materials testing (e.g. ASTM E399, ISO 12135 and ASTM E647) are not adequate to cover the full spectrum of parts that can be produced by metal AM ([4], [5], [38], [70], [76], [77])**,** although ASTM standard F3122 addresses some of these differences [25]. In addition, fracture critical properties measured from a standard test coupon might not be the same as those present in a finished component for the reasons indicated earlier. These include differences in defects frequency, shape and size distribution due to the difference in the geometry of a witness sample versus actual part, as shown in Figure 3. This figure depicts color-coded defect volumes on a test witness coupon and a turbine blade manufactured from gamma Ti-Al pre-alloyed powder using EBM technique. Non fracture-critical properties (e.g. yield strength, ultimate tensile strength) are expected to have a much lower dependency on the defect distribution in comparison to fatigue, as discussed earlier.

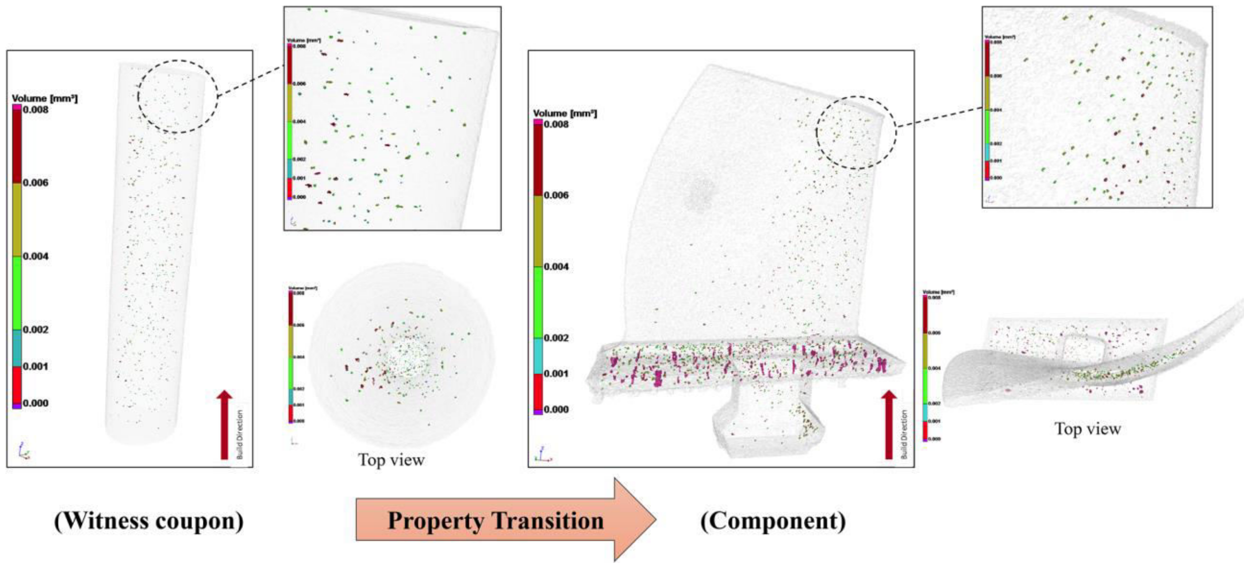

Figure 3. Challenging property transition from coupon to the real component, 3D visualization can be accessed on the online version of this paper. Color-coded dots exhibiting the presence of defects [78].

Role of Non-Destructive Testing (NDT) for AM, and its opportunities and challenges

The wide range of AM processes, process parameters, input materials (feedstock), process equipment, and post-processing can contribute to significant property variation. Against this backdrop of property variation, mitigation against AM part failure relies heavily on NDT to detect defects, and destructive (e.g. proof or fatigue) tests to assess the effect of defects on part performance. Some of the challenges associated with mechanical (destructive) tests are discussed in the previous sections. The challenges associated with NDT techniques not only include part variation, but may also arise from part complexity, surface roughness, and access to the inspection surface or volume, as discussed here.

There are longstanding NDT standard defect classes for welds and castings. The defects characteristic of these processes will generally not be similar to those developed in the AM process. Therefore, it has not been recommended that existing physical reference standards for welding and casting be used to determine NDT capability when inspecting AM parts [79]. This implies, that until an accepted AM defect catalog and associated NDT detection limits for AM defects are established, the NDT techniques and acceptance criteria for AM parts will remain part-specific point designs.

As reviewed previously, the AM process parameters and disruptions during a build may induce a variety of flaws (anomalies) in AM parts that can be detected, sized, and located by NDT [80]. Table 1, co-developed by ASTM Committee E07 on NDT [80] and ISO TC 261, represents a much-needed AM defect catalog listing the various defect types that may be present or may evolve in metal AM parts during the build, post-processing, and service. Some of the flaws listed in Table 1 are unique to metal AM (e.g. DED or PBF), while others are common across all the manufacturing techniques, including closely related conventional manufacturing techniques such as welding. Some of these defects such as layer defects, cross-layer defects, trapped powder and unconsolidated powder are unique to parts made by powder bed fusion (PBF).

Table 1. Nondestructive Test Detection of Typical Additive Manufacturing Flaws [80].

Flaw/Artifact[B]	Observed in PBF or DED?	Why?	Post-Process Detection
Porosity	both	Poor selection of parameters, moisture or contamination of feed material or process environment, inadequate handling, storage, vaporization of minor alloying constituents depending on material feedstock. Errors in precision of beam delivery.	Depending on sample geometry and size of porosity may be detected using CT/PCRT/RT/UT
Voids	both	Powder run out, changes in the energy density of the impinging beam creating keyhole melting or vaporization conditions that entrap voids or create spatter (spherical molten ejecta) leaving holes, and voids that may be covered by subsequent layers of fused materials. System drift or calibration issues may come into play to create conditions of LOF. Bridging of powder in the hopper / poor flow properties.	Depending on sample geometry and size of voids may be detected using CT/PCRT/RTR/UT
Layer defects	Unique to PBF[E]	Interruption to powder supply, optics systems errors (laser) or errors in data. Contamination of build environment purity (inert gas interruption or other process interruption such as changing the filament emitter within and electron beam gun. Powder supply blending or mixing between one batch and another, a new lot of filler wire, etc.	Depending on sample geometry and size of flaw may be detected using CT/PCRT/RT/UT
Cross-layer defects	Unique to PBF[E]	Poor selection of parameters, contamination or degradation of the processing environment. Discoloration (e.g. DED-plasma arc of Ti alloys) as detected visually can indicate a process out of control. Error in the precision of the beam delivery.	Depending on sample geometry and size of flaw may be detected using CT/PCRT/RT/UT
Under melted material/unconsolidated powder (LOF)	Unique to PBF[E]	Poor selection of parameters, poorly developed and controlled process or a process out of control creating a poorly resolved flaw state. Errors in the precision of beam delivery.	Most probably CT, and PCRT, detectability depends on sample geometry and size PCRT
Cracking[C]	both	AM PBF failure to completely clean one alloy powder from the build environment prior to processing another, DED large assemblies extensive solidification stresses present within large buildups, There is a host of metallurgical issues associated with crack susceptibility. Extremely large range of potential thermal and mechanical conditions present, across all AM processes, that may lead to cracking are poorly characterized.	Depending on sample geometry and size of crack may be detected using CT/PCRT/ECT/RT/UT
Reduced mechanical properties	both	New powder out of spec or degraded through reuse, poorly developed/controlled process, interruption of feedstock supply.	Check powder (x-ray diffraction) at end of process and mechanical properties of finished part, PCRT individual frequencies may correlate also.
Poor accuracy	both	Scaling/offset factors are effected by part geometry , beam intensity and the density of the powder bed or SLM –scan head/optics problems EBM – presence of EMF interference. build platform shift.	Usually easy (visually) as part has step on surface but localized defects may require laser CMM and internal deviations with CT compared to CAD or possibly PCRT compared to the model.
Inclusions	both	Debris from AM or post processing equipment.	Depends on the nature of the contamination and complexity of part, some inclusions are detectable using UT/PCRT/RT/CT
Residual stress/warpage	both	Poor selection of parameters.	Usually easy (visually) as part has step on surface but localized defects may require laser CMM and internal deviations with CT compared to CAD possibly PCRT compared to the model.
Stop/start flaws[D]	both	Consequence of long builds or interruption of feedstock leading reduced mechanical properties.	Check mechanical properties of finished part, PCRT individual frequencies may correlate also.
Surface flaws	both	Includes partially fused powder, linear or planar conditions or irregularities. Similar to spatter, undercut, irregular top bead, ropey bead, and slumping noted for welded parts.	PT, MET
Trapped powder	Unique to PBF[E]	…	Most probably, CT or PCRT detectability depends on sample geometry and part size.

[A] *Abbreviations used: … = unknown or not applicable, AM = additive manufacturing, CAD = computer aided design, CMM = coordinate measuring machine, CT = computed tomography, DED = directed energy deposition, EBM = electron beam melting, ECT = eddy current testing, EMF = electromagnetic frequency, HIP = hot isotatic pressing, LOF = lack of fusion, MET = optical metrology, PBF = powder bed fusion, PCRT = process compenated resonce testing, PT = penetrant testing, RT = radiographic testing, SLM = selective laser melting, UT = ultrasonic testing.*

[B] *discontinuities that are not necessarily rejectable.*

[C] *due to rapidly quenching which may also lead to metastable or nonequilibrium morphologies.*

[D] *issue during long builds.*

[E] *ISO TC 261 JG59, Additive manufacturing – General principles – Nondestructive evaluation of additive manufactured products, under development.*

The sources of these defects also differ depending on the type of AM process and process parameters used, while post-processing techniques may or may not be able to fully mitigate all of the defects listed. Application of the NDT procedures discussed in [80] on as-built and post-processed parts are intended to reduce the likelihood of material or component failure during its intended service application. This could mitigate or eliminate the attendant risks associated with loss of function, and possibly, the loss of ground support personnel, crew, or mission, as well as minimize any adverse effects on range safety (due to failure of AM spaceflight hardware) or patient safety (due to failure of AM medical implants). Another best-practices guide is under development by ASTM Committee F42 describing how to intentionally seed flaws of prescribed type, geometry, and location. The physical reference specimens so produced are then used to confirm that the flaw of interest can be detected by NDT [81].

Figure 4 is provided to illustrate the range of NDT and optical measurement techniques according to defect location and spatial resolution [82]. Each NDT technique has its own limitations. Process history, flaw type, flaw size, flaw distribution, part dimensions, effects of material/microstructure on signal attenuation, and part complexity are all relevant considerations for selection of an appropriate NDT techniques as part of an inspection plan. One major and promising NDT technique to assess the structural integrity of products made by AM is X-ray computerized tomography (XCT). Detection of defects by XCT systems has a direct correlation with the size, thickness, and complexity of the object being analyzed. Recent work [53], [83]–[86] has shown the significant progression of quantitative XCT technology as a tool for assessing feedstock materials (e.g. metal powders) and integrity of structural components. However, in-situ defect detection and mitigation during processing remains a critical task for continuing/future efforts by the AM community [87]–[90].

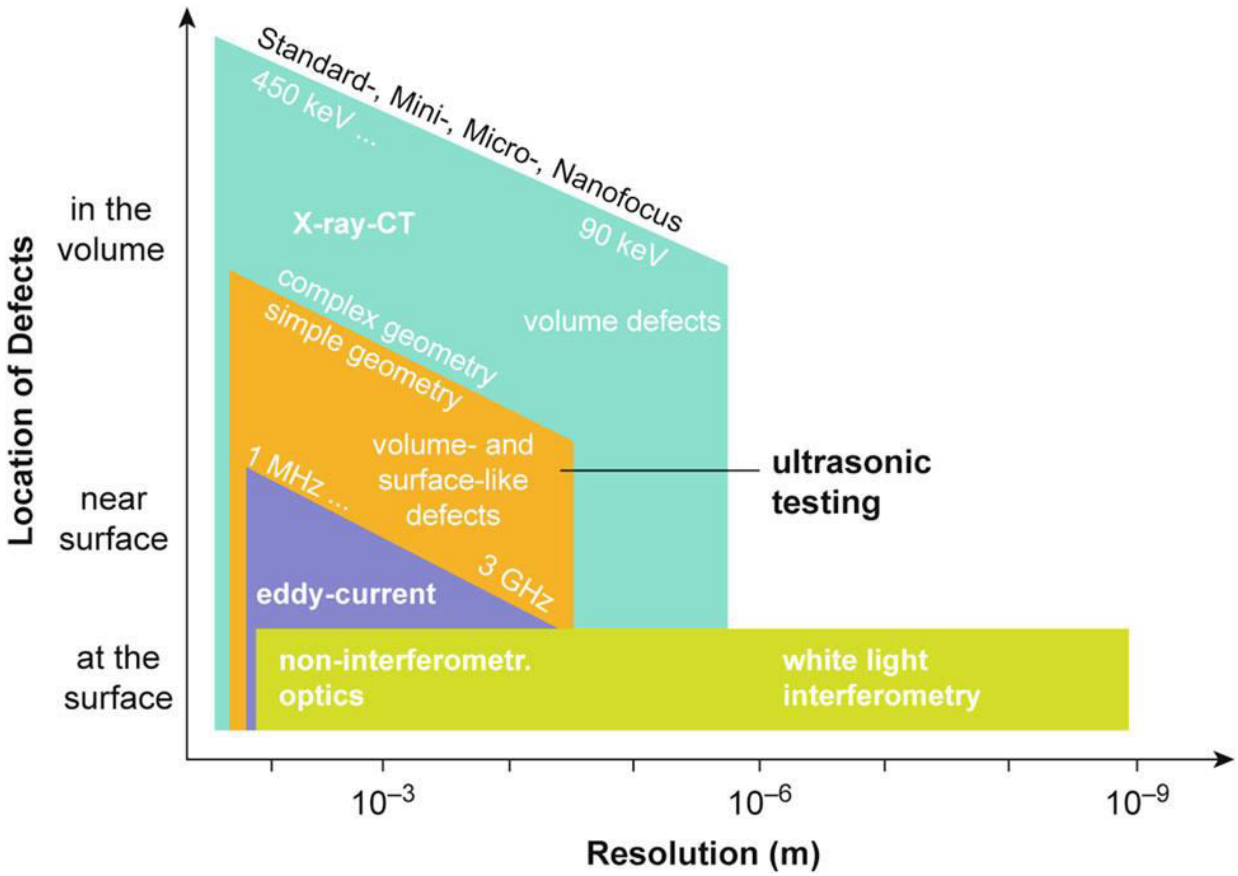

Figure 4. Classification and comparison of chosen NDT techniques and optical measurement techniques according to detectable defect location and spatial resolution reproduced from [82].

Figure 5 demonstrates the dependence of resolution limit (voxel size) versus object size and provides relevant information regarding the limitations of defect detection in typical AM parts. In that regard, it is critical to understand the defect types and sizes responsible for failure in different loading scenarios in order to establish the appropriate detection strategies with a consideration of the object size and scale of resolution needed. These considerations determine what technique to use and may justify the use of higher resolution synchrotron-based XCT [58], [91], [92]. Industrial applications often require inspection of large components and depending on the size of the object, certain techniques may be more relevant (see Figure 5). For example, while XCT can be utilized on sub-size samples to detect micrometer-sized and sub-micrometer sized defects, these may not be directly relevant to the life-limiting defects in actual parts. In addition, as with any defect detection strategy, it is also important to ask: 1) what is the largest defect that can go undetected, 2) what is the effect of a given defect type, size and distribution on part performance and safety, and 3) what is the consequence of catastrophic part failure stemming from such inspection misses.

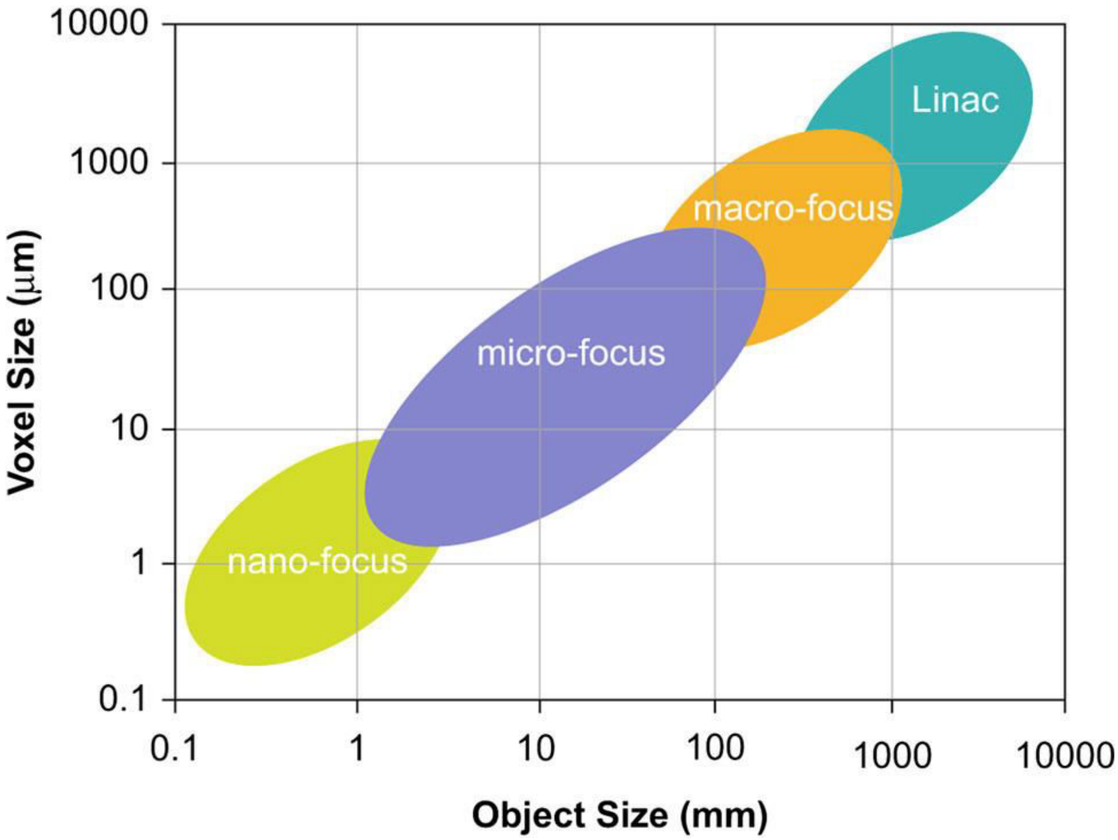

Figure 5. Resolution vs. object size limitations reproduced from [93].

Perhaps the key challenge confronting NASA [17], the FAA, Department of Defense (DoD), and the commercial aerospace sector [94] is the qualification of fracture critical AM parts using either NDT or proof tests, especially in applications where structural margins are low and the consequence of failure is high. Such parts use a damage tolerant rationale and require careful attention. At this time, it is not clear that defect sizes from NASA-STD-5009 [95], which were derived from conventionally made metal hardware, are applicable to AM hardware, particularly when the as-built AM part surface is still present and surface sensitive NDT techniques such as eddy current and dye penetrant testing are used. To quantify the risks associated with these parts, it is incumbent upon the structural assessment community, such as ASTM Committee E08 on Fracture and Fatigue, to define critical initial flaw sizes (CIFS) for the part in order to establish the objectives of the NDT. A demonstration of adequate life starting from the NASA-STD-5009 flaw sizes is generally inappropriate for fracture critical, damage tolerant AM parts. Knowledge of the CIFS will allow the fracture control and NDT community to evaluate risks and communicate meaningful recommendations regarding the acceptability of the risk. It is recognized that parts with high AM Risk[1] may have regions inaccessible to NDT. For understanding these risks, it is important that inaccessible regions are identified along with the corresponding CIFS.

[1] As defined by NASA, AM risk is a function of the following criteria: 1) all volumes and surfaces can be reliably inspected or proof tested, 2) the as-built surface can be fully removed on all fatigue-critical surfaces, 3) surfaces interfacing with sacrificial supports are fully accessible or can be fully improved, 4) structural walls or protrusions are ≤ 1mm in cross-section, and 5) critical regions of the part require sacrificial supports.

Many AM parts will require the use of multiple NDT techniques to achieve full coverage. A combination of radiographic, dye penetrant, eddy current, or ultrasonic techniques may be common and should be considered. Surface inspection techniques may require the as-built surface be improved to render a successful inspection, depending on the defect size of interest and the signal to noise ratio. Also, removal of the as-built AM surface merely to a level of visually smooth may be insufficient to reduce the NDE noise floor due to the propensity for AM near-surface porosity and boundary artifacts.

The AM process offers a unique opportunity to build hardware that will enable demonstration of defect detection directly in the part. For example, a demonstration part with simulated CIFS defects, surface connected and volumetric, can be built. Part-specific demonstrations of NDT detection capability will be expected, while the accepted probability of detection defect sizes are established applicable to AM parts and materials. The physics of the layered AM process tends to prohibit volumetric defects with significant height in the build (Z) direction. The concern instead is for planar defects, such as aligned or chained porosity or even laminar cracks, that can form along the build plane. This mechanism has a number of implications: planar defects are particularly well suited for growth; the primary defect orientation of concern is defined, which may be meaningful in analysis or with detection methods dependent upon alignment with volumetric defects; AM planar defects will generally exhibit very low contained volume; the limited Z-height of planar defects can be demanding on incremental step inspection processes such as computed tomography.

Along with an accepted AM defects catalog (Table 1), and establishment of associated NDT detection limits for AM defects, a list of NDT-related recommendations to overcome technological gaps preventing the infusion of AM in NASA and Commercial Space applications were identified in a 2014 gap analysis [96]. This Technical Memorandum [96] also contains a summary of NASA agency & prime contractor AM efforts (Figure 6) and related NDT activities. The following technology push areas specific to AM and related to NDT were identified and elaborated:

- Develop mature NDT techniques for as-built and post-processed AM parts
- Apply NDT to understand effect-of-defect, including establishment of associated NDT detection limits for AM defects
- Apply NDT to understand scatter in design allowable database generation activities
- Fabricate physical reference standards to verify and validate NDT equipment and AM processes
- Develop in-situ process monitoring to improve feedback control, to maximize part quality and consistency, and to obtain certified parts that are ready-for-use directly after processing
- Develop better physics-based process models using and corroborated by NDT
- Develop NDT-based Q&C protocols for flight hardware
- Develop SDO standards for NDT of AM parts and fabrication of representative seeded flaws for detection by NDT

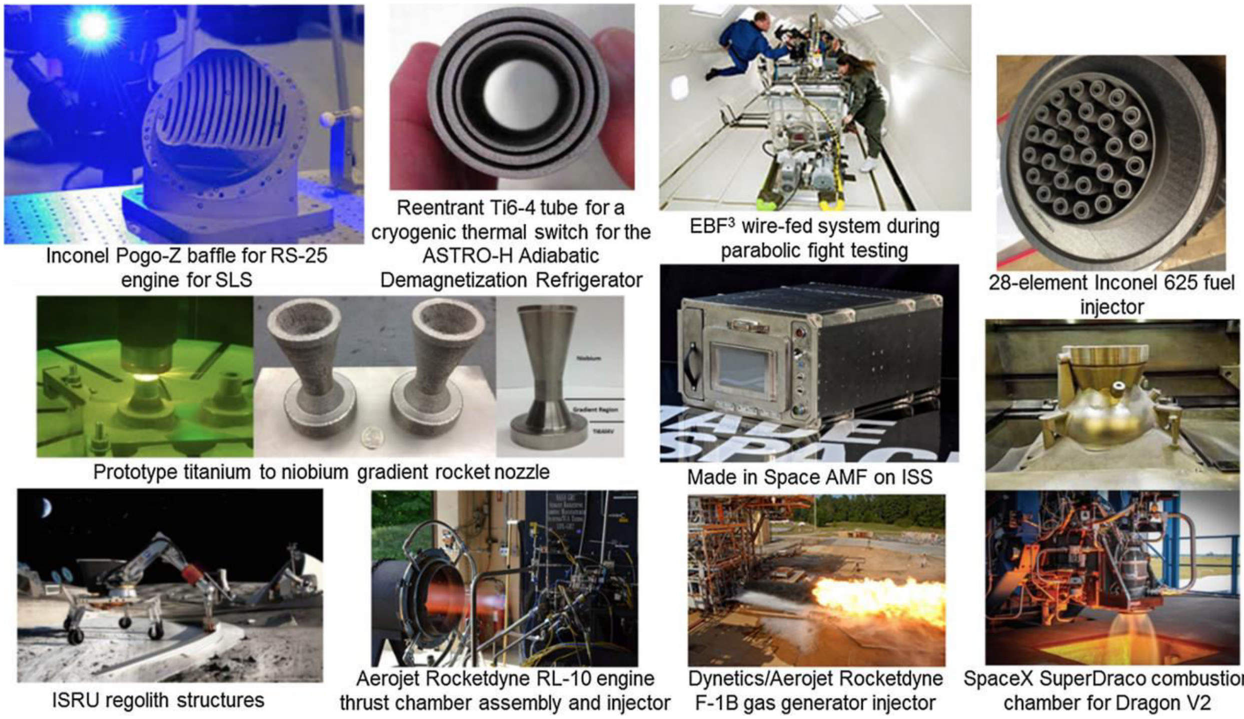

Figure 6. Representative NASA agency and prime contractor additive manufacturing activities [96].

Current activities and status of SDOs for standardization of AM

In addition to the various technical challenges described earlier, there are a number of SDOs concurrently working toward similar goals, with little interaction. Such fragmentation is counter-productive, and the effort to improve communication, reduce duplicate activities and work toward consistent and non-contradictory AM related standards was deemed necessary. The recent creation of the Additive Manufacturing Standardization Collaborative (AMSC) [94] under the sponsorship of America Makes and ANSI is intended to address this need.. The AMSC working group was established in March 2016 to coordinate and accelerate the development of industry-wide AM standards and specifications consistent with stakeholder needs and thereby support the rapid growth of the AM industry. The AMSC mission is not to develop standards, but rather to provide a roadmap that will include a gap analysis for standards and specifications, and outline relevant published standards and specifications, as well as those in development. The first public draft of this roadmap [94] is available for review at the time of this article. Recommendations are provided for additional R&D and/or standards and specifications, as well as priorities for their development, in addition to listing the organization(s) that potentially could perform the work. It is essential that the AMSC roadmap be widely promoted in order to disseminate the identified recommendations as they can be used as a guide to prioritize development of the specifications and standards across the multiple SDOs and to direct funding opportunities for AM research required to facilitate standardization. It is also important that the key government agencies with a certification authority, that normally reference public specifications and standards in their regulatory documents, provide prioritization input into this planning activity. Ultimately, the aim of such an effort would be to provide a means to continue guiding, coordinating, and enhancing AM standardization activity, and to enable the market for AM to thrive.

ASTM F42 and ISO/TC 261 recently announced a new standards development framework shown in Figure 7. This figure illustrates that standards can be developed at three levels:

- general standards (e.g. concepts, common requirements, guides, safety);
- standards for broad categories of materials (e.g., metal powders) or processes (e.g., powder bed fusion); and,
- specialized standards for a specific material (e.g., aluminum alloy powders), process (e.g., material extrusion with ABS), or application specific (e.g., aerospace, medical, automotive).

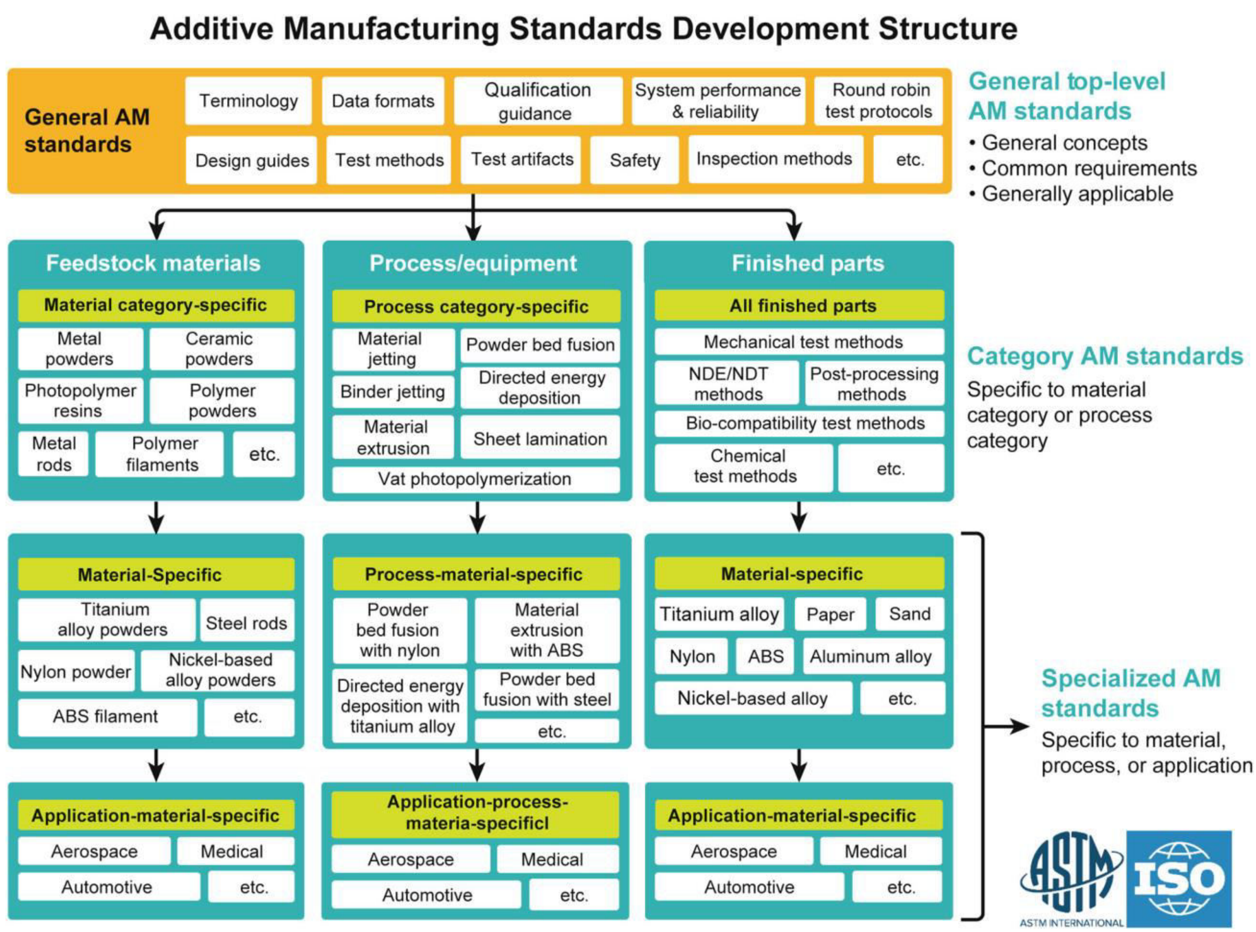

Figure 7. Additive manufacturing standardization framework (Developed and Approved by ASTM F42/ISO TC261).

Both ASTM and ISO have a number of technical committees that can coordinate with each other to address such a comprehensive framework. It is essential to maximize collaboration between technical committees to make sure the appropriate expertise is captured to influence industry-wide standards. This framework does not confine the scope of the work for any standards organization but provides a framework in which the majority of standards needs can be met. A guidance document describing the framework and strategy is also under development by ASTM/ISO to accompany this structure.

In addition to the above activities, the American Welding Society (AWS) formed the D20 committee on AM in 2013 to develop a standard that would integrate requirements for the AM of metal components. AWS assigned a stand-alone task group to study whether or not AM falls within its charter and whether there was a need for AM standards to be developed by AWS. It was emphasized that there should not be a duplication of efforts, and the AWS committee would develop broader application codes/standards that would integrate requirements for AM of metals, including qualification of design, materials, processes, and personnel. Similarly, in July of 2015, the Society of Automotive Engineers (SAE) established a new SAE AMS-AM committee on Additive Manufacturing under its Aerospace Materials Systems (AMS) Group. This committee is chartered with developing and maintaining the aerospace material and process specifications and other SAE technical reports for AM, including precursor material, additive processes, system requirements and post-build materials, pre-processing and post-processing, nondestructive testing, and quality assurance. The American Society of Mechanical Engineers (ASME) has also established an AM standards committee (Y14.46) currently focused on geometric dimensioning and tolerancing (GD&T) issues.

Technical interchange across the AM industry can be fostered by focused meetings/workshops organized/sponsored by these organizations on the subject of AM standardization that are broadly attended by the industry, academia, and government representatives.

Ongoing challenges towards standardization for fracture/fatigue critical properties

One of the elements toward establishing the confidence in components fabricated using AM is to employ recognized standardized tests for measurement of the key mechanical properties including tensile strength and fatigue resistance. As indicated earlier, there is currently a concern regarding the level of similitude between the purpose-built test coupons and the actual components for the measurement of these mechanical properties. Any change in part geometry, the number of builds per plate, design parameters (laser patterns, layer orientation, support structure) can significantly affect the thermal history, which ultimately alters microstructural details and defect type statistics [38], [66]. This, in turn, can greatly affect mechanical properties, especially fatigue behavior of AM parts. Therefore, establishing process-structure-property-performance relationships for metallic AM materials and parts is the central factor which must be addressed as the efforts for standards development move forward [35]. The ICME (Integrated Computational Materials Engineering) framework is viewed as an enabler for such developments by multiple companies and several government agencies [2], [97]–[99].

Another challenge is determining the extent to which additional AM standardization work is needed, and to what level currently existing standards, developed for conventional materials, can be adopted directly for AM materials. It is likely that a better understanding of the mechanical behavior of AM components is needed before this can be fully addressed. The AM process typically generates very large cooling rates which produce unique microstructures, large residual stresses, material anomalies and anisotropy. All of these attributes could be much different than what is observed in a conventionally manufactured coupons [94], [100].

The proprietary nature of AM process variables provides an additional challenge when considering the development of standards. While AM process variables directly affect the thermal history, microstructure, defect formation, and consequently, fatigue and fracture resistance, commercial AM machine vendors may be reluctant to share internally optimized process variables. There may also be additional process variables that cannot be easily altered or even accessed by the user. Clearly, these limitations are now starting to change and open platform machines could be accessible within the industry. While such machines may be of significant use for fundamental studies of process-structure-property relationships, it is unclear how open access machines will impact process/product consistency.

Future pathway and proposed focus areas

Based on the technical considerations presented in this paper, the following focus areas are recommended by the authors for a path forward in developing the specifications and standards landscape for AM:

- Continued development of AM standards as an enabler for effective Q&C processes, that cover all essential aspects outlined in [94] – AM design, design allowables, data and data format, AM equipment calibration and operator training, input and precursor, material specifications, process monitoring and control, benchmark parts, NDT, dimensional accuracy, predictive physics-based 3D models, post-processing and finishing and assembly guidelines, cleanliness of finished parts, maintenance and repair, mechanical testing, terminology, safety and health.
- For parts used in higher criticality applications (up to and including safety-critical parts) , the authors recommend an emphasis on the development of standards or industry best practice documents for each of the following areas:
    a. Generation of a defects/anomalies catalog with defect definitions added to [101], for example
    b. Development of manufacturing guidelines for seeding natural flaws (LOF, porosity, etc.) to determine the effect of defects/anomalies on fracture and fatigue properties [81]
    c. Establishment of intentionally added features (watermarks, embedded features, etc.) in parts used to demonstrate NDT capability
    d. Establishment of NDT detection limits for the range of AM defects/anomalies identified in Item (b) on parts produced in Item (c) and assign appropriate probability of detection statistics (i.e. develop acceptance criteria used in ASTM Test Methods, for example)
    e. Development of robust in-situ monitoring techniques and implementation of closed-loop process control to prequalify parts before post-processing and/or assembly
    f. Characterization of material defects/anomalies, and their effect on fracture and fatigue properties (effect-of-defect)
    g. Generation of an acceptable anomalies catalog with anomalies definitions, based on Item (a)
    h. Characterization of fatigue and fracture properties, microstructure, and residual stresses
    i. Development of robust in-situ monitoring techniques and implement closed-loop process control
    j. Definition and promulgation of NDT needs for first articles, versus reference or witness coupons, production parts, and spares
    k. For production parts, refinement and validation of conventional and emerging NDT methods for as-built and post-processed AM parts
    l. Development of accurate methods for dimensional metrology, especially for internal features

m. Characterization of static properties and design allowables for AM materials (contingent on having a comprehensive set of industry- accepted public specifications and standards for AM materials and processes)

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