Additive Manufacturing Materials and Technologies

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SCIENCE, TECHNOLOGY AND APPLICATIONS OF METALS IN ADDITIVE MANUFACTURING

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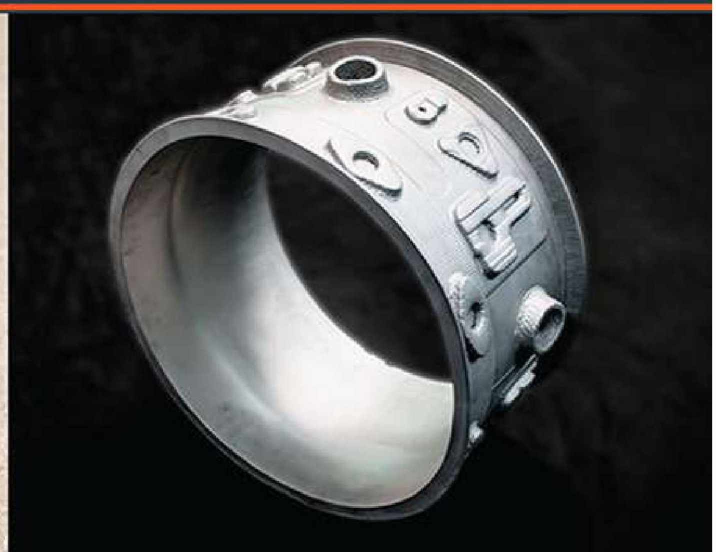
and Bradley Jared



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Science, Technology and Applications of Metals in Additive Manufacturing

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Contents

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CHAPTER 7

Design for metal additive manufacturing

Abbreviations

AMF	additive manufacturing file
CT	computed tomography
CAD	computer-aided design
CAM	computer-aided manufacturing
CNC	computer numerically controlled
DED	directed energy deposition
E-PBF	electron beam-powder bed fusion
EDM	electrical discharge machining
GE	General Electric
HPC	high performance computing
HIP	hot isostatic pressing
ICME	Integrated Computational Materials Engineering
IGES	Initial Graphics Exchange Specification
LEAP®	Leading Edge Aviation Propulsion
L-PBF	laser-powder bed fusion
PBF	powder bed fusion
PSPP	process—structure—property—performance
RP	rapid prototyping
SO	shape optimization
STEP	Standard for the Exchange of Product data
STL	Standard Tessellation Language
3D	three-dimensional
TO	topological optimization
2D	two-dimensional
UAM	ultrasonic additive manufacturing
XML	eXtensible Markup Language
XRD	X-ray diffraction

7.1 Motivation and opportunities

Metal additive manufacturing is a disruptive technology with the potential to radically alter product design and to introduce paradigm changes across a broad range of industries. It is being applied to numerous applications associated with design, prototyping, test hardware, limited quantity production, tooling, fixturing, part repair, and part modification. The digital

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nature of metal additive manufacturing (AM) processes provides accelerated product development cycles which reduce risk by reducing the time and cost associated with nonrecurring engineering, setup, and fabrication. The complexity afforded by metal AM processes also has exciting potential to add value to products by introducing the ability to realize part topologies that are optimized for performance, not manufacturing, and to engineer material structures at scale inaccessible through conventional manufacturing means. Mass customization through AM is already present within the consumer domain for custom medical implants [1] (Fig. 7.1), and will certainly grow across a broader sector in the years to come.

While expectations that metal AM will completely supplant traditional metal manufacturing methods are speculative and exaggerated, AM does represent a compelling supplemental and complementary new tool for designers and manufacturers. In the near term, most adopters involve those desiring products that are highly customized, require low volumes, and/or necessitate rapid fabrication cycles. Prudent users will adopt and implement metal AM motivated by a beneficial business case and the value added by its adoption.

Additive processes generate material and geometry concurrently in a layerwise fashion [2], and introduce the unique possibility to generate and locally control geometry and material at every volume element or "voxel" in a part. Thus complex freeform geometries, internal and re-entrant features, architectured materials, and multifunctional,

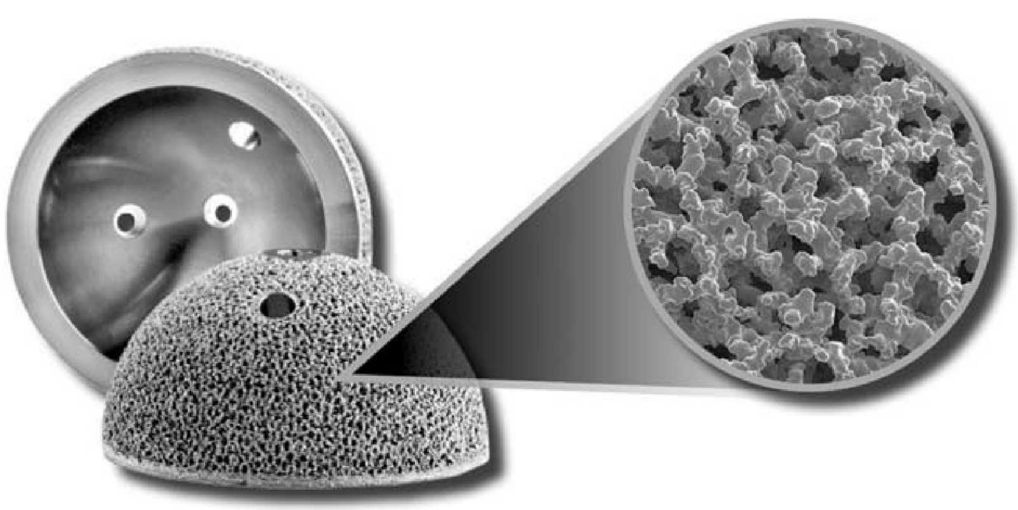

Figure 7.1 Titanium acetabular cups with integrated trabecular structures produced by electron beam-powder bed fusion. *Photo Courtesy: General Electric (GE) Additive.*

multimaterial parts all become realizable and enter the design space for engineers, scientists, and even consumers.

7.1.1 Geometric complexity

The mantra that "complexity is free" [3] is most commonly expressed within the context of part geometry as AM offers unprecedented opportunities to design and build complex structures optimized for performance envelopes inaccessible under conventional manufacturing constraints. In principle, voxel level geometrical control introduces the capability to fabricate arbitrarily complex geometries containing both internal and external freeform features. Features at multiple scales, overhangs, re-entrant geometries, internal geometries, and architectured structures can all be produced using a range of metal additive techniques (Fig. 7.2). While traditional machining and casting can produce complex geometries, they possess more restrictive process constraints and are incapable of producing many

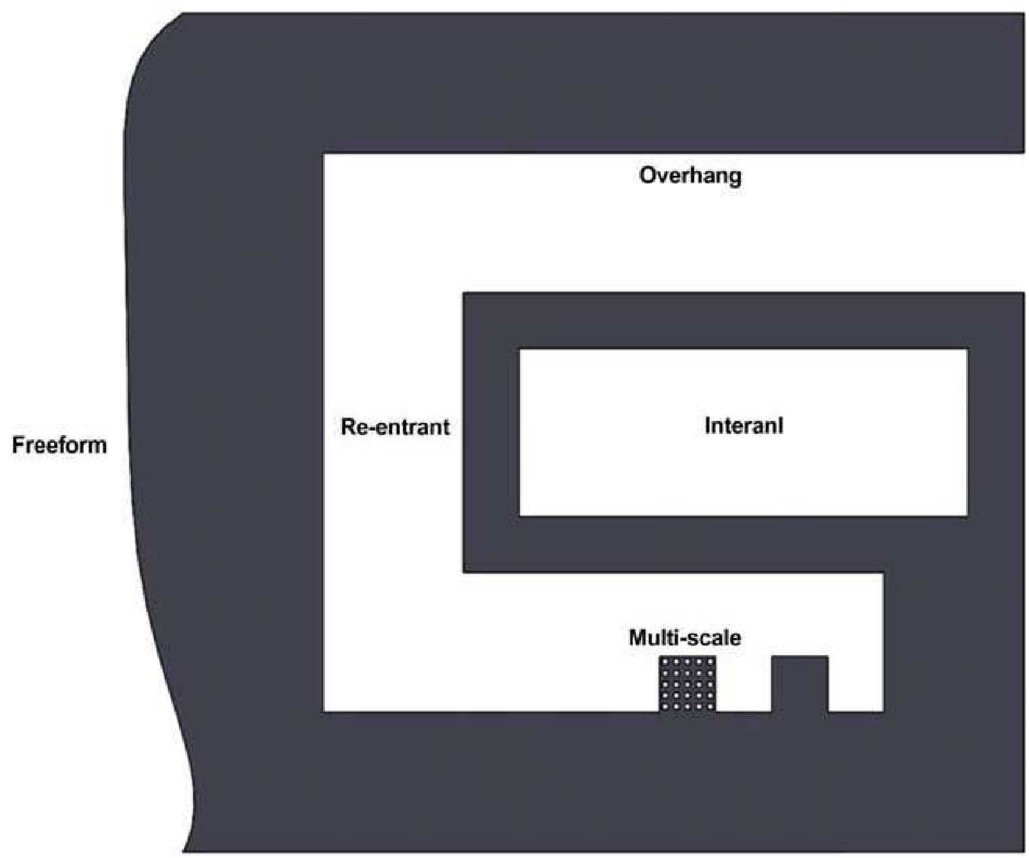

Figure 7.2 Simple schematic showing features available through metal additive manufacturing.

of the features desired in additive components, for example, internal geometries or architectured materials.

In practice, geometry constraints do remain from limits in printing and postprocessing. While complexity does come at a cost for inspection, metrology, and qualification (see Chapter 8, Qualification for metal additive manufacturing), complexity can be preferred from a process perspective. As an example, consider a bar designed using topology optimization (see Fig. 7.3) for a prescribed outside diameter and torsional load. The optimized design not only minimizes material use and part weight but prints faster than a simpler solid shaft with equivalent outside diameter and length. It also resembles a structure observed in nature, the skeleton of a cholla cactus.

Geometric complexity is available in every metal additive technique. Powder bed techniques, that is, powder bed fusion (PBF) and binder jetting, are most commonly used to fabricate complex metal part geometries, and provide the highest degrees of complexity relative to feature size, internal geometries, and overhang structures [6,7]. A range of metal alloys are available through powder bed as feature resolution is sub-1 mm, overhang slopes are limited to roughly 45°, form accuracy is competitive with castings, and surface finish is on the order of the feedstock powder size. Directed energy deposition (DED), whether powder- or wire-based, processes a similar range of metal alloys, but provides higher deposition rates for larger parts. The resulting courser features and rougher surfaces restrict its use for complex structures [6]. Overhang geometries are also limited based on the process and machine configuration. Sheet lamination in the form of ultrasonic additive manufacturing (UAM) is available for ultrasonically weldable materials where layer thickness and in-process machining capabilities limit part geometry [8]. Material jetting represents an exciting,

Figure 7.3 Topology optimized bar for a torsion load case (left) [4] that closely resembles the skeletal structure of a cholla cactus (right) [5]. *Photo Courtesy: David Gill, Sandia National Laboratories (left); Cholla cactus skeleton image used with permission by Scott Brill at Seekraz.wordpress.com (right).*

alternative technology with great promise for geometric complexity. It is traditionally associated with low melting temperature metals such as solder [9], but represents an active research area for a larger alloy range with recent promises for commercial equipment [10–12].

7.1.1.1 Design performance

The geometrical complexity enabled through metal AM affords designers the freedom to envision and realize parts, components, and systems with performance gains that range from the subtle to the transformative. Such gains routinely attract the attention of engineers, companies, and even entire industries. Arguably, it is these gains that have carried the community out from the shadow of rapid prototyping (RP) for development into the promising future of additive manufacturing for production.

The advantages of additive manufacturing include the ease of fabricating designs that incorporate a lack of symmetry, arbitrary freeform surfaces, features at varying length scales, and/or complex internal geometries. Such freedom presents numerous avenues for designers to improve design performance with revolutionary design features. Design optimization has become an incredibly powerful, and subsequently popular, approach whereby parts can be light-weighted and strengthened (Fig. 7.4). Optimization design software has become extremely popular and will be discussed in more detail in Section 7.4.6. Significant gains can also be realized in designs by integrating multiple assembly parts into a single monolithic structure to eliminate piece-parts and joint interfaces. The reduction in part count can simplify assembly processes to save time,

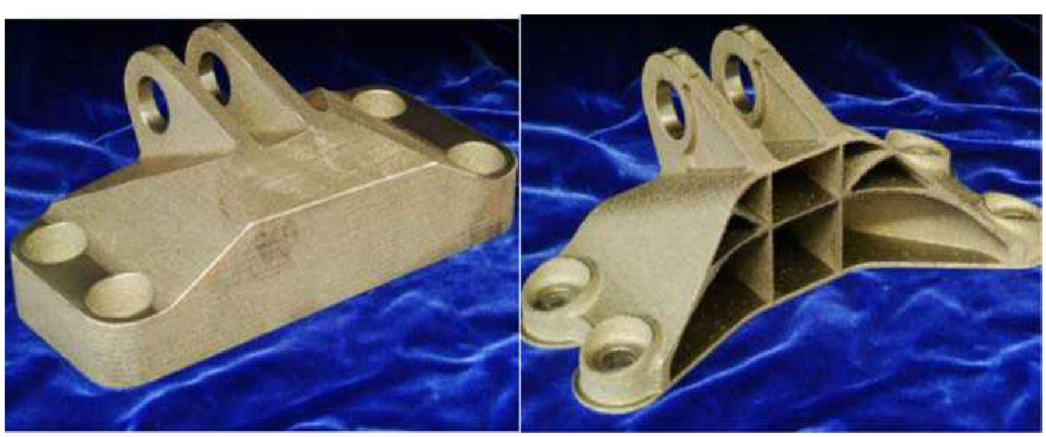

Figure 7.4 Winning design for a General Electric additive manufacturing design competition with a 84% weight reduction that performed well in load tests. *Photo Courtesy: General Electric (GE) Additive.*

Figure 7.5 General Electric's additively manufactured LEAP® fuel nozzle. *Photo courtesy: General Electric (GE) Additive.*

reduce costs, and/or improve process throughput. It can also eliminate joints, welds, fasteners and interfaces which commonly degrade component strength and stiffness. The aerospace industry is exploring applications for the use of AM to simplify complex assemblies. Fig. 7.5 shows General Electric's (GE) fuel nozzle for the LEAP® ("Leading Edge Aviation Propulsion") engine, a popular demonstration of the capabilities of metal AM. It replaces 20 parts with one part that is 25% lighter and five times more durable [13].

7.1.1.2 Challenges

While the geometrical complexity afforded by metal AM is enticing and exciting, challenges exist that must be considered during the design and product development cycle. Historically design definitions have relied on two-dimensional (2D) drawing representations to communicate part geometries and requirements. While most designers now generate parts as solid models using three-dimensional (3D) computer-aided design (CAD) tools, 2D drawings are still extremely common for defining, communicating, and archiving design intent. This is particularly true for tolerances, as many GD&T nomenclatures and conventions retain their origination and implementation from a 2D context. Even 3D CAD models are based on surface definitions rather than completely volumetric representations. Therefore many topographies that can be realized through AM, for example, lattices or topology optimized geometries, are difficult to specify in current design tools. They are also inaccurately and inefficiently represented by some existing file formats, for example, STL (Standard Tessellation Language). As a result, designers can have difficulty generating desired part geometries. Further, design files for truly complex topographies can be very large and difficult to translate, transmit, store, analyze, and eventually print.

While geometrical complexity is relatively free or even preferred from a process view point, inspection, validation, and verification of complex part geometries can be much more challenging. Analogous to CAD tools, most traditional metrology techniques only measure surfaces. They are predominantly line-of-sight techniques, making the measurement of internal features and architectured materials difficult, if not impossible. As a result, the metrology of complex geometries is commonly more difficult than fabrication. While the addition of geometrical complexity by additive can provide benefits, every feature incurs a cost for metrology and inspection. The sooner such costs are considered in the design cycle, the better.

7.1.2 Material complexity

Geometric freedom has provided a classic motivation for additively manufactured components. Access to discrete locations within each additive layer, however, introduces the revolutionary capability to also control material at the voxel level within a three-dimensional volume. This ability radically changes how parts can be designed, fabricated, and validated. It further paves the way to a new paradigm for developing, optimizing, and controlling engineered materials. New material structures and properties are becoming available that are impossible via traditional synthesis techniques. While relatively simple constructs are readily imagined and realized using existing design tools and experience, more powerful computational tools are desired and expected in the future to overcome the dependence on design intuition. Integrated computational materials engineering (ICME) [14] and the Materials Genome Initiative [15] are synergistic efforts found within the materials science community. Each fundamentally has visions of developing materials using computational tools and methodologies akin to mechanical design. The voxel level control of additive manufacturing provides one compelling path whereby these visions may be realized.

Emerging applications are increasingly driven by an unprecedented ability to access material complexity now available in three forms: architectured materials, microstructure control, and multimaterials.

7.1.2.1 Architectured materials

Architected materials, for example, metamaterials or lattices, leverage the geometrical complexity and scaling afforded by AM to create subpart scale structures (Fig. 7.6) that produce effective material properties distinct from fully dense monoliths. They expand the rather limited material palette with structures which possess a broader, multifunctional performance spectrum. They invoke topological complexity at meso- and microscales such that new effective properties can be realized, controlled, and varied across part volumes. This control provides designers the ability to tailor structural response behaviors with unprecedented specificity. Architected materials are primarily of single material constructions and have been used for negative stiffness [16], light-weighting [17], negative coefficient of thermal expansion, anisotropic thermal conductivity [18], and flexible electronics [19]. Their subscales may consist of periodic unit cells, like a lattice, or random structures, like a foam. Unit cell structures may be

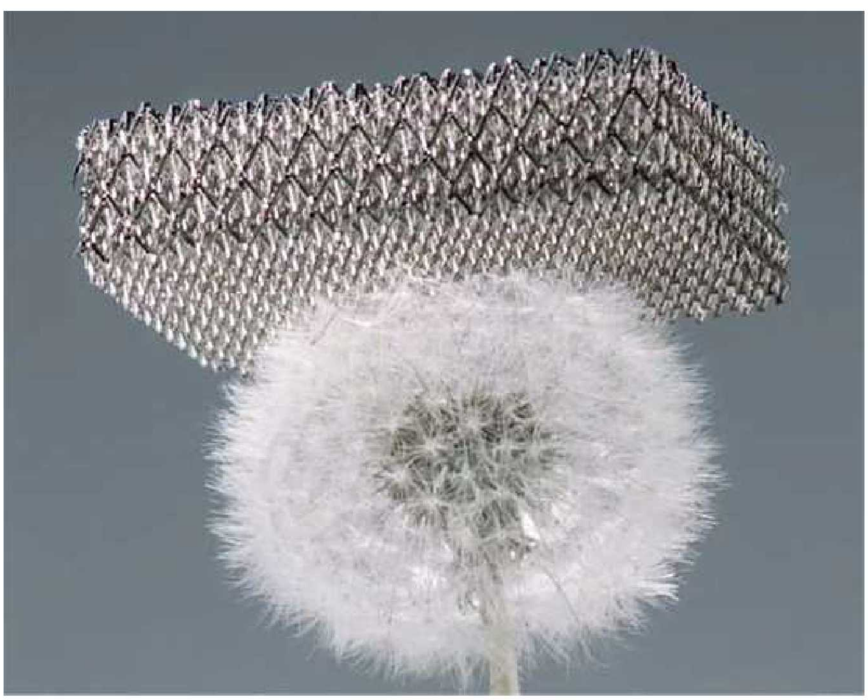

Figure 7.6 Metal microlattice balanced on the head of a dandelion. *Photo Courtesy: HRL Laboratories LLC.*

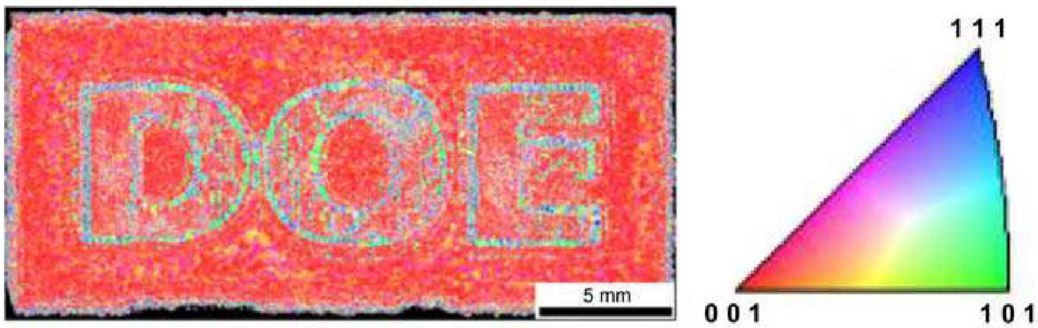

Figure 7.7 Control of grain texture in Inconel 718 via electron beam-powder bed fusion [23].

applied uniformly across a part geometry or varied as a gradient across the part in size, shape, or orientation.

7.1.2.2 Microstructure control

Microstructure control is common in any metal formation process [20], but only additive techniques enable control at discrete positions through a part volume. Process maps have quantified ranges for microstructure control in additive processes for over a decade [21,22] for powder DED. Researchers have also used electron beam-powder bed fusion (E-PBF) to change the crystallographic texture of grains in Inconel 718 to produce coarse columnar grains, epitaxial deposits, and fully equiaxed grains through precise control of process parameters [23] (Fig. 7.7). Such work highlights the ability to generate local microstructures and subsequently localized properties. This manipulation of process inputs introduces an innovative design approach whereby complex stress states can be managed and controlled through microstructure and not just geometry.

7.1.2.3 Multimaterials

Multimaterial parts contain diverse material compositions or alloys within a single geometry, often with multifunctional capability. While multimaterials are most commonly discussed in the context of polymer systems [11,24,25], capabilities exist for metals. Powder DED is the most popular method for producing metallic multimaterials as multi-hopper systems provide distinct powder streams that can be controlled discretely to alter alloy composition at any point within a part structure. This capability is available on OEM systems [26,27], and provides simple process control to print parts with distinct material regions or alloy gradients [28,30] (Fig. 7.8). Material changes can be performed layer-by-layer or within a

Figure 7.8 An Invar 36 to 304L stainless steel gradient alloy mirror mount. A metal-coated glass mirror is attached to the Invar side of the mount using epoxy. The mirror mount transitions into 304L stainless steel at its base [30,31,32]. *Photo Courtesy: NASA Tech Briefs.*

single layer. Gradient materials can also be generated in real-time using wire-feed DED machines with dual wire-feeders [26].

UAM provides access to material gradients as each layer in the build can be changed dependent on material bonding compatibilities. Its low temperature, solid-state bonding nature also affords the unique ability to integrate disparate materials, for example, embedded sensors, into metal structures [8,33] (Fig. 7.9). Laser-powder bed fusion (L-PBF) techniques have been demonstrated by research groups to produce multimaterial parts [34–36], although the process has not been commercialized. Binder jetting is another powder-based technique that uses liquid binding agents, filler infiltration, and sintering for part fabrication [7]. It provides similar capabilities for geometrical complexity as powder bed fusion. The use of an infiltrate does permit the potential for some bulk material complexity, but with limited local control.

Techniques for printing across material types (i.e., polymer, metal, ceramic) are limited, but extremely compelling and are poised to enable opportunities for an even wider design space. Direct write material

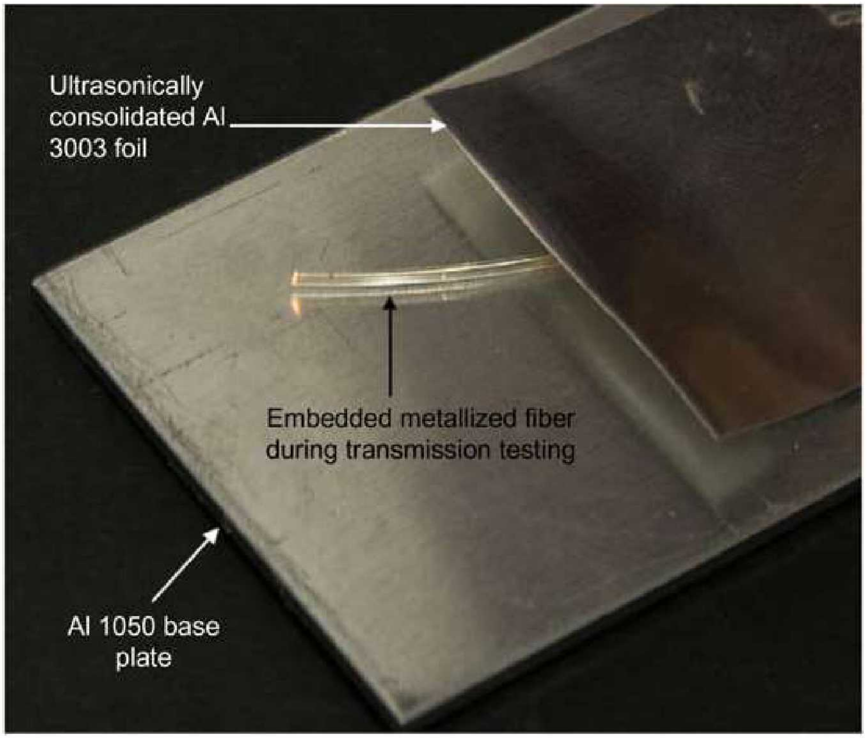

Figure 7.9 Transmission optical fiber embedded between aluminum that was bonded using ultrasonic additive manufacturing [33].

extrusion has generated parts with embedded electrical capabilities [37,38], while material jetting has produced opto-electronic devices with printed optics and drop-in electrical components [33,39]. Such integration and expanded functionality present designers and engineers the capability to print more than just the structural "box" for a component, but also "everything inside the box."

7.1.2.4 Challenges

As with geometrical complexity, designing material complexity also faces challenges. First, traditional design tools are not equipped to handle the information necessary to capture or specify material complexity. Surface-based solid models presume uniform, bulk properties and cannot manage the gradient compositions and microstructures desired for monolithic design models. As such, performance simulations and fabrication processes are restricted to simple structures that can be described by multipart assemblies and other contrived constructions. Likewise, standards are not established for communicating the design intent for inhomogeneous material structures within a monolithic part geometry.

Similarly, architectured materials rely on geometric complexity which can often be represented at unit cell levels. Such unit cells, however, must be applied to a larger part geometry which can result in prohibitively large file sizes for design management, performance simulations, and fabrication. Scaling and orienting unit cells nonuniformly across a part is also generally not available. OEMs are addressing some of these challenges as software is becoming available to specify lattice structures in a form prepared for direct printing [40–42].

Multimaterial design solutions have been demonstrated, but they have not propagated widely. Gradient materials, for example, have been available for over a decade [28,29], Fig. 7.10, but their use has been minimal [30] given that design tools are unavailable and intuition is limited in its ability to guide designers. Just as the emergence of geometrical complexity via AM has motivated the wider use of optimization tools, introducing material complexity into design tools will introduce unique and compelling design solutions that motivate further use and advancement of multimaterial processes and next-generation engineered materials.

A final consideration for the specification of material complexity is the limited methodologies available for inspection and verification. Metallography is an accurate means for characterizing material structures, but it is very restrictive because it is destructive, time consuming, and

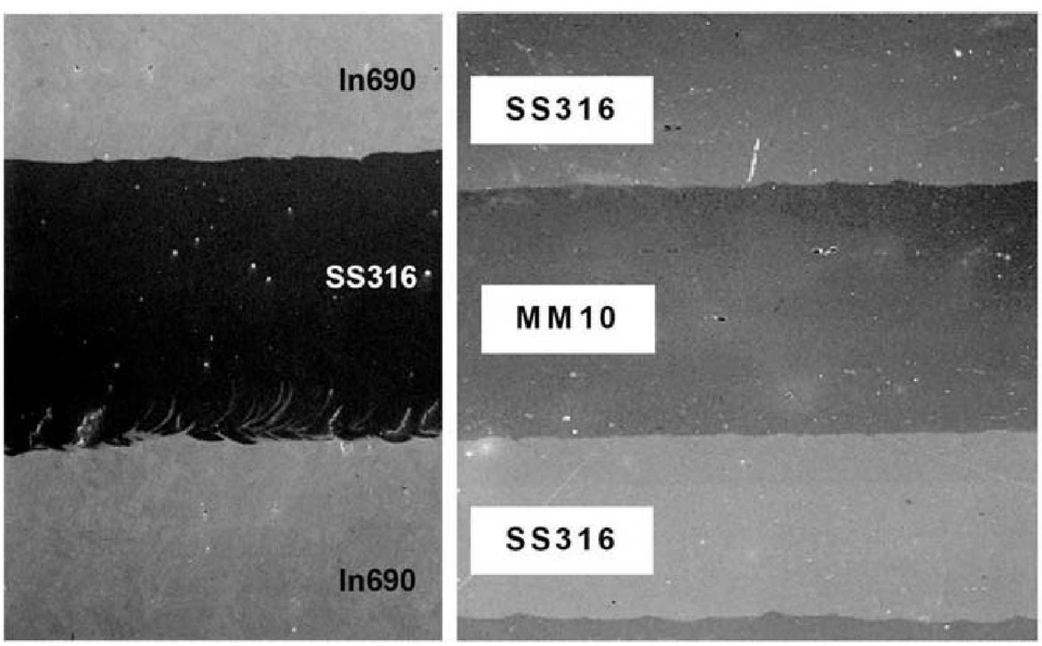

Figure 7.10 Directed energy deposition multimaterial structures of 316L stainless steel with Inconel 690 (left) and MM10 tool steel (right) [29].

typically only captures representative image planes within a part. Different forms of radiography, for example, computed tomography (CT), are utilized for characterizing internal geometrical complexity in AM metal parts [43–45], and each of these is also available for quantifying some material structures. Spatial resolution, accuracy, and density contrast, however, are critical constraints that must be considered.

7.1.3 Risk reduction

The ability of metal AM to rapidly generate complex part geometries directly from a computer model provides agility and flexibility that is invaluable in product development and in low-volume production. The digital nature of AM reduces multiple fixed engineering costs such as molds, tooling, fixturing, and machine programming. Metal AM also reduces material use which can be important for high-value feedstocks. Such material efficiencies are common drivers for the aerospace industry where reducing "buy-to-fly" ratio is an important business consideration and combining postmachining with net shape part printing can bring cost and schedule advantages. Therefore small lot quantities, prototypes, and test hardware can often be fabricated more quickly and less expensively via metal AM than through traditional routes such as machining, metal injection molding, or casting.

Reducing costs and schedules subsequently diminishes development risks. It can also accelerate cycles of learning as concepts and designs can be proposed, optimized, realized, and evaluated more quickly and cost effectively. Accelerating development cycles has motivated the use of rapid prototyping since its inception [46]. Further gains can be realized through a transition to additive manufacturing as the time and effort between development and product hardware can be reduced and even potentially eliminated. Metal AM is generally most advantageous when part designs are difficult and expensive to produce in desired quantities through conventional means. Additive manufacturing can also be fastest and cheapest for complex, low-quantity parts. As fabrication complexity decreases and part volumes increase, however, conventional manufacturing processes become preferable. Therefore pursuing metal AM for its own sake is rarely beneficial and should be avoided.

7.1.4 Mass customization

The Industrial Revolution introduced the world to mass production, whereby manufacturing processes fabricated a vast array of products at scales, throughputs, and costs hitherto never observed. The Digital Revolution produced a similar shift as mass customization transformed the production and distribution of digital products. The digital nature of AM has introduced one potential path for a digital manufacturing revolution, whereby mass customization of durable goods and products can be realized. AM enables rapid customization and production as digital part models can be modified quickly and then subsequently printed. Customization remains challenging, however, because processes are not always robust or consistent. However, elements of mass customization are already implemented today in the medical field for implants [1] (Fig. 7.11).

Metal AM is typically discussed in the context of the industrial manufacturing enterprise. Mass customization, however, also contains the maker movement; a social network for creative, technically savvy, and often entrepreneurial individuals. Makers are generally interested in designing and generating a wide range of items using tools owned by an individual or a small job shop [47]. They represent a democratization of design and manufacturing of sorts and have been empowered by low-cost, cloud-based design platforms, internet file-sharing networks, open source hardware and software platforms, and the freedom generally enabled through 3D printing. Makers most commonly utilize inexpensive, consumer-grade polymer 3D printers which can now be used to print filaments loaded with various metal alloys [48]. Printed metal parts exist in a green state that must then be postfired and sintered in a furnace. Makers

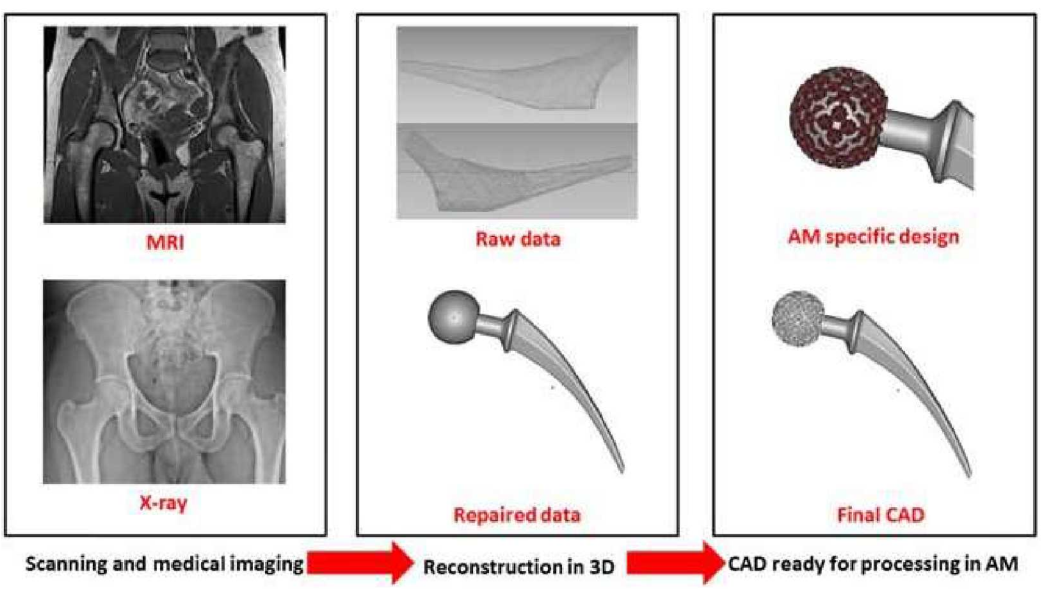

Figure 7.11 Process flow for custom orthopedic implants [1].

blur traditional roles by combining the functions of designers and fabricators, a trend that is easily sustained by individuals. The potential impact of a similar blurring between design and manufacturing within the industrial sector remains to be seen.

7.2 Process constraints

Metal additive manufacturing processes provide numerous advantages over conventional fabrication techniques. Yet, process constraints persist and must be considered during the design cycle. The concurrent nature of metal AM, whereby material and geometry are formed simultaneously, also demands coupling of part design with process knowledge, particularly for high-consequence applications where margins are aggressive and part performance is critical.

7.2.1 Printing

Process performance in metal AM is influenced by multiple factors which include the specific process, its process settings and conditions, the machine platform utilized, the metal alloy being printed, the metal feedstock form, and the desired part geometry. Given that process—structure—property—performance (PSPP) relationships in metal AM are highly coupled, work must be performed with each process, machine, and material feedstock to understand their impact on part performance. It is not uncommon for users unfamiliar with processes to make assumptions about the printability of parts based on another process or material, for example, printing a polymer part verses metal. Process constraints, however, do not necessarily translate across process types, materials, or even machines and must be verified, not assumed.

7.2.1.1 Geometry

Metal additive processes are commonly utilized to produce complex geometries that cannot be realized by traditional means. Process boundaries exist with any metal process such that complete geometrical freedom can never be truly realized. L-PBF, E-PBF, DED, binder jetting, and UAM have varying process strengths and weaknesses. While limits vary across processes, materials, and machines, a general class of process restrictions can be identified.

It is easily recognized that maximum part size depends on the machine build envelope. Part size, or more precisely part volume, however, is also

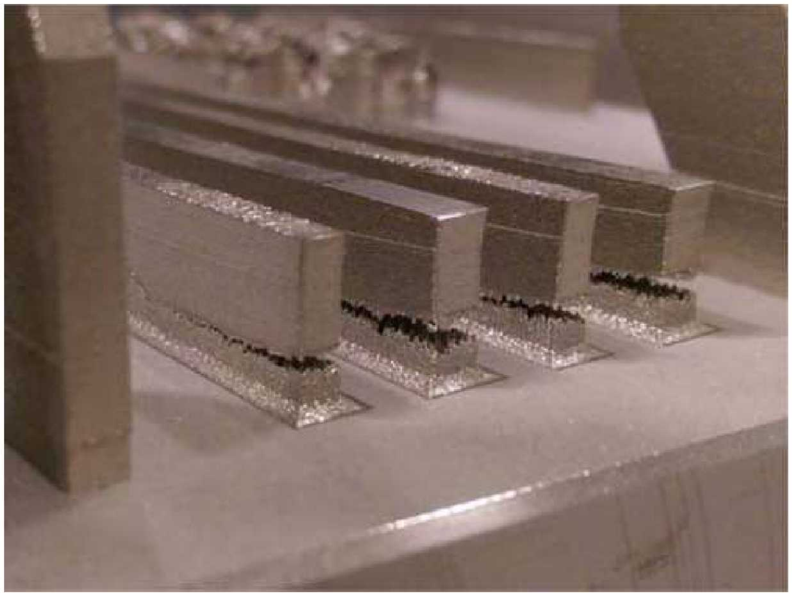

Figure 7.12 Part failure during printing due to excessive curling forces generated by material stresses. *Photo Courtesy: Albert To, University of Pittsburgh.*

influenced by the process build rate. As an example, using a laser-powder bed machine to print a 250-mm solid block of metal would require over 10 weeks of continuous printing using reasonable machine settings, i.e., a single laser with a 50-μm powder layer thickness, a 50-μm cross-feed, and a 1 m/s laser scan velocity. Such an approach, while possible, is unreasonable and impractical. Maximum part size can also be limited by residual stresses. Here internal material stresses during printing generate distortions to the point that part features fail or break (Fig. 7.12). Limits are based on the internal stresses generated, part material properties, and part strength. Large parts with thin features, thin walls or lattices are particularly problematic, as are more brittle alloys such as Ti–6Al–4V.

At the opposite size scale, minimum feature resolution is commonly of interest, particularly when extreme geometrical complexity is desired, for example, in a lattice. To first order, the material interaction zone provides the minimum limit at which a positive feature (e.g., a wall or strut) can be realized within the build plane (*XY*). For a PBF or DED process, this limit is close to the melt pool size, for binder jetting it is binder droplet size, and for UAM it is the material area across which ultrasonic bonding can occur. Out of the build plane (*Z*) feature resolution, that is, step size, is limited by the layer thickness and the resulting surface finish of the layer. In practice, the minimum printable feature size is larger to ensure that geometries can withstand process forces and complete a successful build cycle. Such process loads include powder spreading, part deformation, and residual stresses. Thus feature material strength, aspect ratio, build angle, overhang length, and surrounding build geometry are all contributing factors.

The minimum size and resolution of negative features, that is, holes or channels, are also dependent on feature material properties, aspect ratio, and build angle. Vertical features generally print well and are limited by the stability of the material interaction zone. In the orthogonal orientation, the printability of horizontal holes and channels is determined largely by their overhang geometries. Minimum features are restricted by the quality of the overhang surface whereby surface melting and slag do not collapse the hole (Fig. 7.13). The limit for the maximum horizontal feature size is also restricted by the quality of the overhang surface. Feature collapse is not the challenge, but rather the surface finish and dimensional accuracy of the downfacing surface. For this reason, designers commonly rely either on tear drop or diamond geometries (Fig. 7.13), or postmachining for large horizontal holes or channels.

Dimensional accuracy is an important requirement in any manufacturing process, and metal AM is no exception. Accurately predicting part geometry is a challenge, however, seeing as it is the result of multiple, coupled interactions. These interactions include the placement of material feedstock, deposition process physics, machine motion accuracy (e.g., laser galvanometer tracking or build plate motion), and part deformation due to shrinkage and material residual stresses (Fig. 7.14). As a result, geometrical accuracy changes with material feedstock quality, deposition process

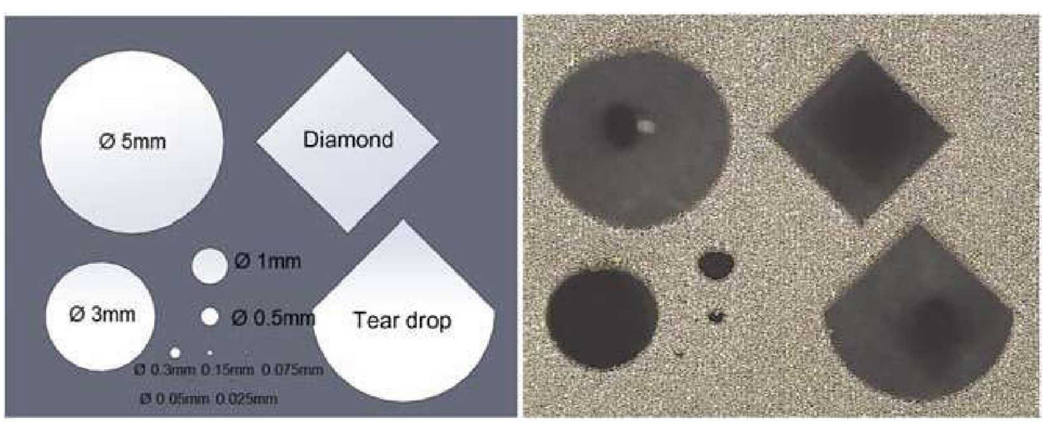

Figure 7.13 Design (left) and printed part (right) for horizontal features in 316L stainless steel by laser-powder bed fusion showing feature size limits and alternative geometries.

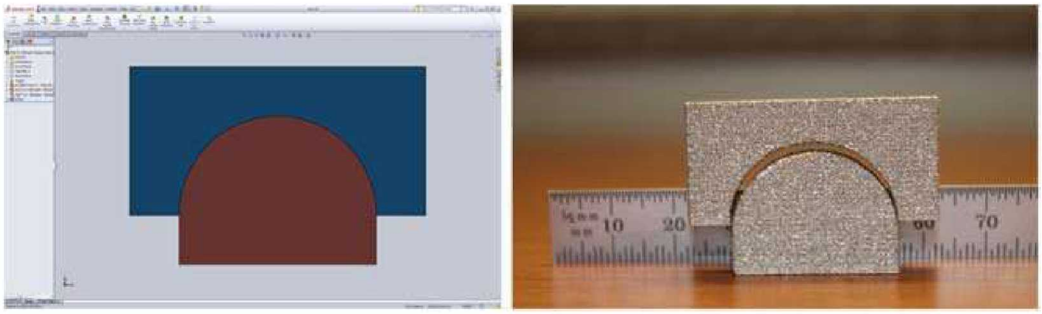

Figure 7.14 The design (left) of an arch and semicircle intended for assembly. The Ti–6Al–4V electron beam-powder bed fusion part (right) had minimal postprocessing and demonstrates large form errors [52].

conditions, and machine operation. Accuracy is also influenced by the part geometry, its orientation, and location within the build volume, and the surrounding structures and parts included in the build volume. In general, PBF processes provide the best part accuracy, typically on the order of castings, as they utilize material interaction zones on the order of 100–200 μm [49]. Binder jetting accuracy is similar, although distortions can become large and unpredictable due to the thermal cycles involved in sintering, infiltration, and annealing [7,50]. DED processes are generally much less accurate as they utilize laser beam and/or wire diameters of 1 mm and larger. Accuracy in metal sheet lamination is driven by machining tolerances, layer material overlaps, and feature strength [51]. The complexity of material interactions generally precludes a precise prediction of part geometry a priori. Experimentally based heuristics and design rules, however, are commonly developed to aid designers. Part scale models (see Section 7.4.3) are increasingly available to provide predictive capabilities of part deformations and final geometry. In some cases, the speed and agility of metal AM warrants simply printing parts to understand part form errors and then iterating modified part geometries to achieve a desired end geometry. Regardless of the approach, design rules, heuristics, and part models are material and process specific, and they require development investments to produce high-quality hardware.

7.2.1.2 Part distortion and residual stress

An important aspect of part geometry in metal AM is the distortion that occurs as metal cools from a molten or sintered state into solidified material. In binder jetting, part shrinkage during material consolidation and thermal gradients are the primary concerns as residual stresses are not generated during sintering and annealing [53]. The elevated operating temperatures of E-PBF produce a similar scenario as part solidification occurs at elevated temperatures before the entire part cools to room temperature at the end of the print cycle.

In both L-PBF and DED, the localized rapid heating and cooling of material generates part distortions and residual stresses throughout the part geometry. These stresses and distortions are influenced by the material system, the process conditions, and the part geometry. Failure commonly involves the severe deformation and damage of thin features, for example, buckling of thin walls or missing struts in a lattice. Severe deformation, cracking, and separation from the base plate, supports, or some other part region are also possible for larger parts, particularly for materials with low ductility. Deformation and failure of parts during printing indicates that residual stresses can exceed material yield and even ultimate strengths; a fact measured directly by researchers [13,54] (Fig. 7.15). Stress relaxation occurs during part removal from build plates, but its extent depends on part geometry and postprocessing. Excessive stresses may produce unacceptable part distortions or remain in the material bulk and degrade part performance. Therefore residual stresses must be recognized and considered in the intended end use of any part. For high-consequence applications, these stresses may be unacceptable and require postprocess thermal treatment. Experimental quantification of part stresses requires techniques such as X-ray diffraction (XRD) [55], neutron diffraction [54], or the contour method [56] which can each be difficult, expensive, and inaccurate in their implementation. As a result, part scale models are particularly compelling to the design engineer for predicting and addressing problems with residual stress and part distortion.

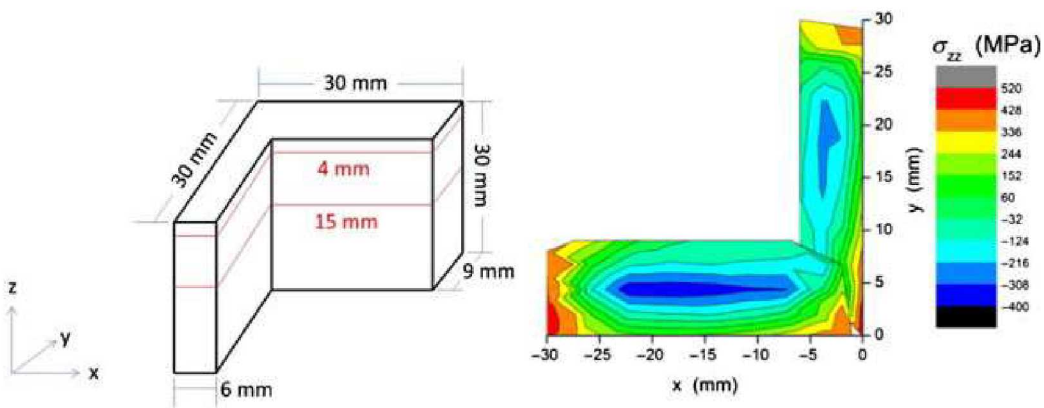

Figure 7.15 L-shaped specimen printed in 316L stainless steel by laser-powder bed fusion (left) and its axial residual stress 15 mm from its base measured by neutron diffraction [54].

7.2.1.3 Overhang surfaces

A consistent challenge across metal AM processes is the production of downfacing surfaces, that is, overhangs. These overhangs can be realized as freestanding features, for example, a simply supported cantilever; as spans over features, for example, a "bridge"; or some complex topography combining both elements. UAM sheet lamination faces the fewest challenges with overhangs because its layers can be placed into the process. Layer deflections under gravity and bonding forces, however, drive resultant geometries based on material strength, layer thickness, and layer support conditions. Longer spans, therefore, are possible than free-hanging cantilevers. Printing overhangs in DED is much more constrained as the melt pool from wire or powder cannot be placed into thin air but must be deposited onto underlying solid material. Surfaces are generally not produced beyond 15–30 degrees from vertical [57]. While this limit constrains powder- and wire-based DED systems relying solely on *XYZ* Cartesian motion, machine platforms are available with four and four axes [58,59]. Such machines allow parts and/or the printhead to be rotated relative to one another to insure that material deposition occurs parallel to gravity, reducing limitations for overhang features.

Powder bed processes are capable of more complicated downfacing topographies given that powder provides support underneath any material layer. As already discussed, the powder is inadequate to fully support a large horizontal build layer, but its presence does provide greater process freedom, particularly over relatively short spans. Just as with part accuracy, the material, the process type, the machine system, and the surrounding structures in the part and/or build plate all impact the quality and printability of downfacing surfaces. In practice, considering all these influences in design is difficult and impractical. As with material distortion predictions, process software is becoming available to provide process predictions. Many designers, however, simply rely on experimentally derived design guides that specify feature constraints such as overhang lengths, cantilever lengths, or maximum diameter for a horizontal hole based on limitations observed from simplified artifacts (Fig. 7.16).

7.2.1.4 Support structures

As mentioned previously, downfacing surfaces remain a significant process constraint. An important approach in powder bed fusion is to add material structures to downfacing surfaces. This material can be described as support material, support structures, or simply supports. At the first laser or electron beam pass for any downfacing surface, the supports provide a

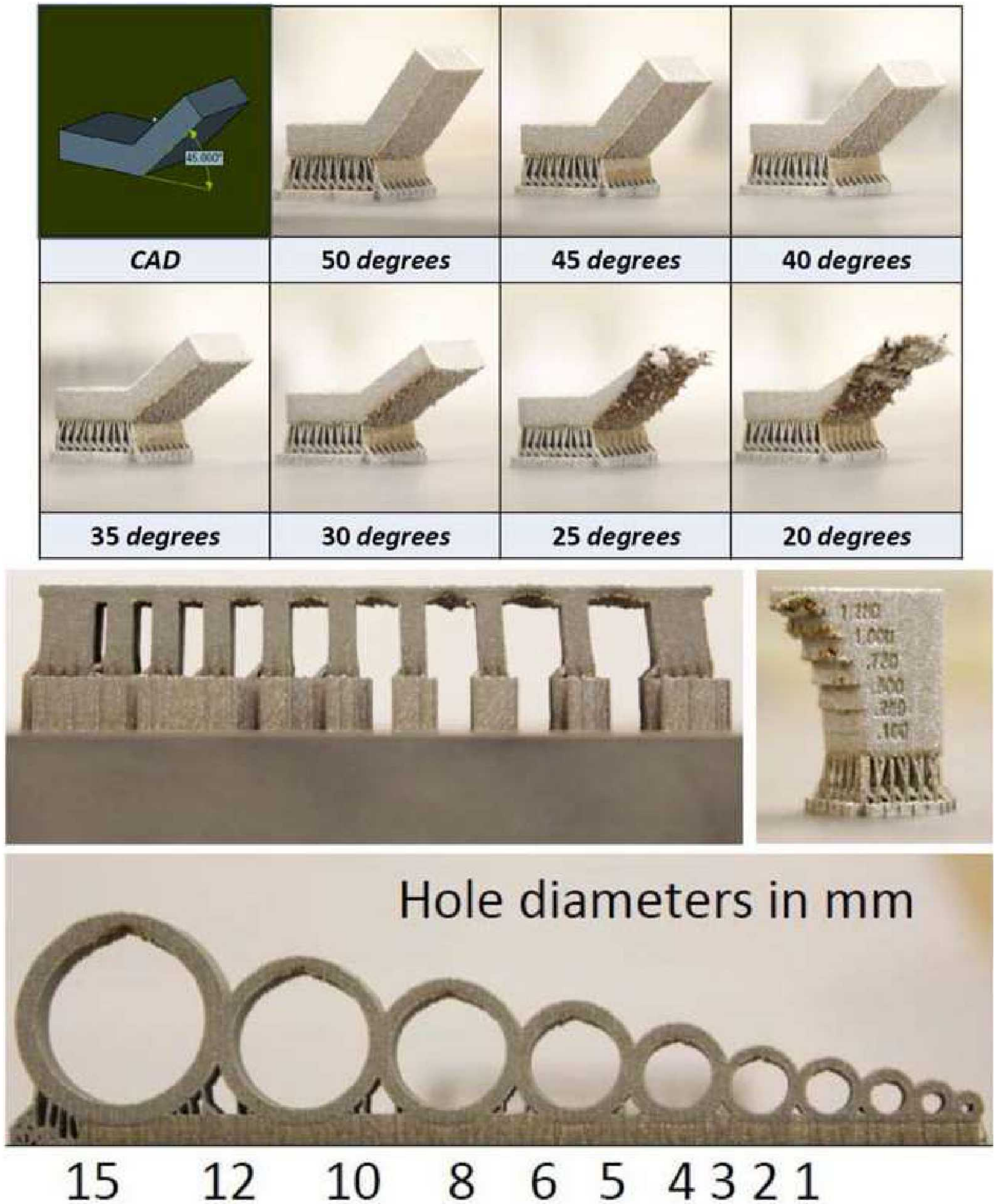

Figure 7.16 Artifacts for determining downfacing slope limits (top), spans (center left), cantilever overhangs (center right), and horizontal holes (bottom) [60]. *Photo Courtesy: David Bentley, Protolabs.*

better "interface" for the melt pool to generate good material than just powder. In subsequent passes, however, the role of supports changes. In E-PBF, supports primarily provide a thermal path for removing heat away from the part to maintain process stability [61]. In L-PBF, supports do provide thermal pathways, but also provide mechanical anchoring of part structures to resist part distortion from internal residual stresses [62]. Binder jetting remains unique among the metal processes in that no supports are necessary, and parts can be stacked throughout a build volume to maximum part production with each fabrication cycle.

While there has been research to optimize supports [62–65], process software commonly relies on simple surface slope and span length limits, for example, 45 degrees and 3 mm, to guide the placement of support materials. Process owners ultimately decide where and how to apply supports. Numerous types of support structures (Fig. 7.17) are provided across machine systems, and many users learn from experience what supports work best for their material and applications [66]. Simulation tools are now also commercially available which provide predictions of support performance during processing [41,67,68].

7.2.1.5 Surface finish

Part surface finish is crucial across a variety of products and applications. Metal AM produces surfaces that are distinct from traditionally machined

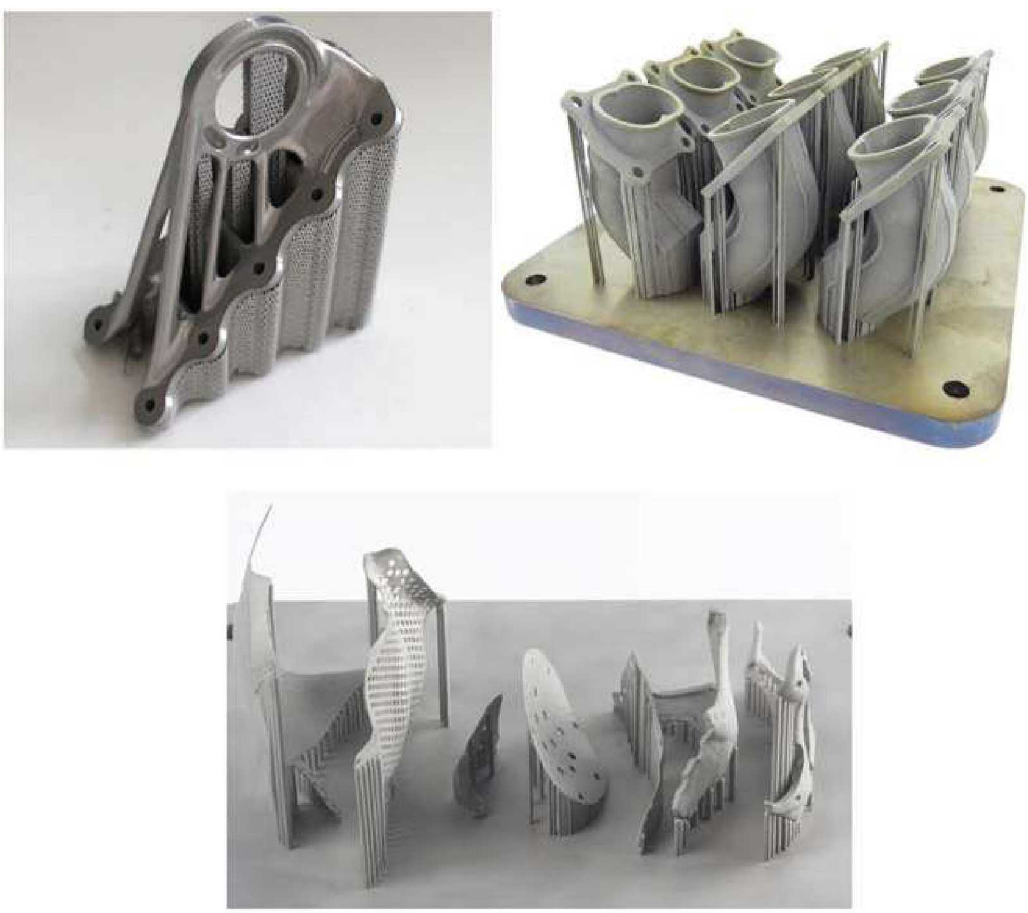

Figure 7.17 Metal parts using a variety of different support structures. *Photo Courtesy: General Electric (GE) Additive (top left); Renishaw plc (top right, bottom).*

surfaces; an important design consideration. The printing process, the material feedstock, and the part surface orientation are all principal factors determining printed surface topology. In general, powder bed processes provide surfaces comparable to castings. Top and side surface roughness are on the order of the average powder particle size (Fig. 7.18), although remelting steps can be taken to improve surface finish at the cost of increased fabrication times [69–72]. Up-facing angled surfaces are some combination of powder size and layer thickness, while downfacing surface finish is dependent on the surface geometry and orientation angle. Surfaces approaching a vertical orientation exhibit a finish like the side wall. As the surface moves toward an overhanging horizontal plane, its finish degrades as dross and slag form due to the melt pool moving over a bed of unmelted powder rather than solid metal.

Like PBF processes, surface finish in binder jetting is closely coupled to the feedstock powder size. Binder jetting can rely on finer powder sizes due to relaxed restrictions on powder flow, so in principle smoother surfaces can be generated [53], potentially by as much as 50%. In DED

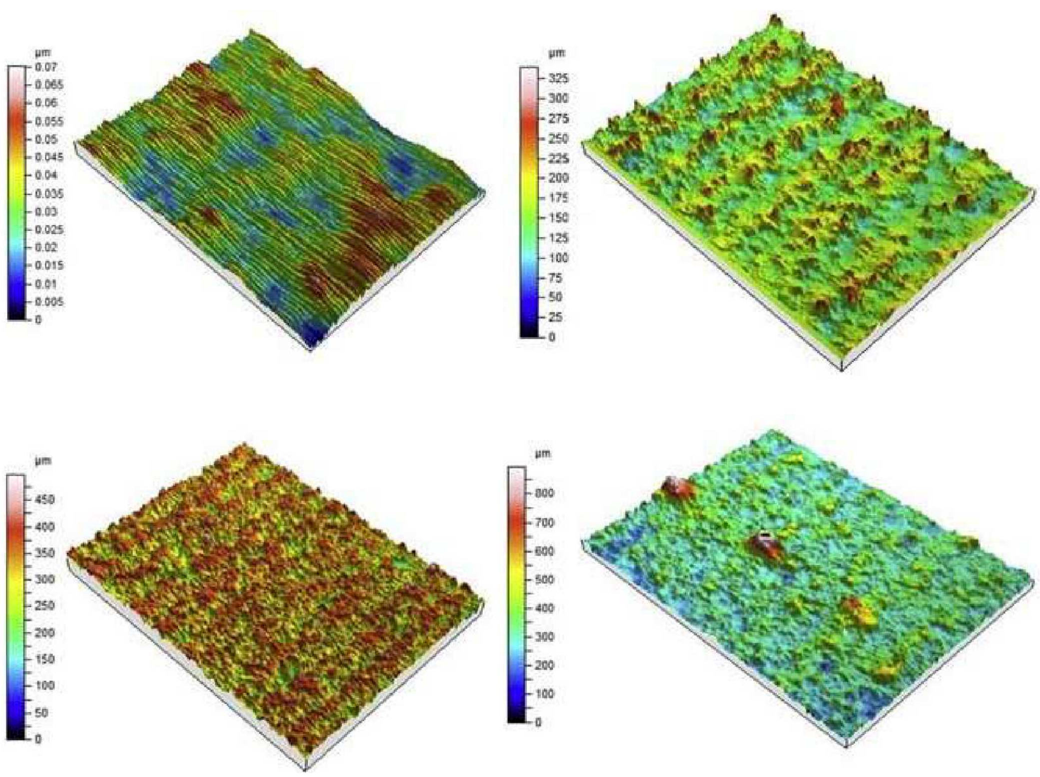

Figure 7.18 Representative Ti–6Al–4V surfaces from electron beam-powder bed fusion with top (top left, S_a = 2.13 µm), 45 degrees up-facing (top right, S_a = 13.01 µm), side (bottom left, S_a = 20.83 µm) and 45 degrees downfacing (bottom right, S_a = 21.79 µm) surfaces [73].

processes, the powder or wire size combined with the hatch spacing or cross-feed determines the surface finish on part faces. Surfaces are generally much courser than in powder bed processes, and postprocess machining is commonly anticipated. This is particularly true for large parts where DED can deposit material rapidly, but very coarsely. Finish on UAM parts is less influenced by printing process parameters but is driven by the machining parameters used to cut and finish part layers. While such machining is inherent to UAM, hybrid machines are also now available for L-PBF [74] and DED [58,75], which introduce a machining step into the process for improving part dimensional accuracy and surface finish.

7.2.1.6 Design artifacts

Throughout the history of AM and RP, researchers and engineers have explored, developed, and used artifacts to characterize numerous aspects of printing [76]. They vary from the relatively simplistic (Fig. 7.19) to the extremely complex (Fig. 7.20), and have been used to quantify a range of metrics associated with process performance, equipment state of health, and material performance. While process models are becoming increasingly capable, additive processes remain extremely flexible and agile. Thus the fastest means for gathering process information to

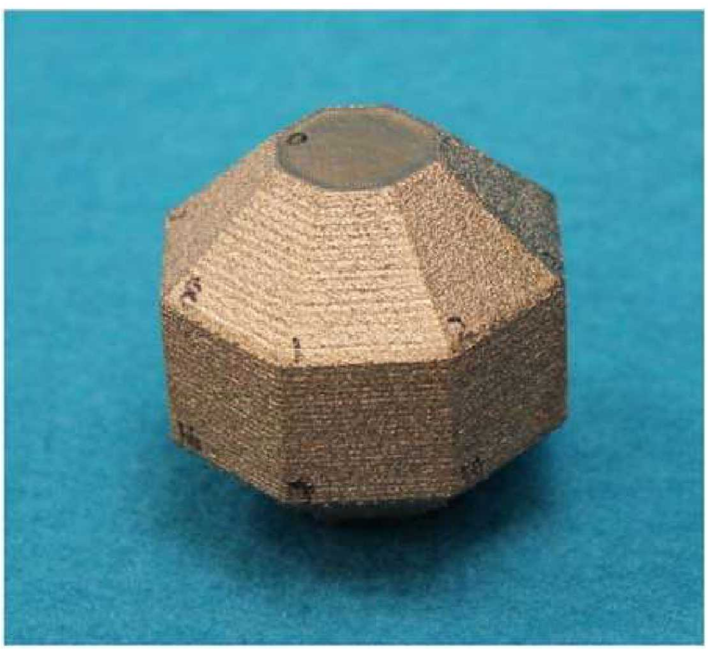

Figure 7.19 Simple 26-sided, 43 mm wide polyhedron produced in Ti–6Al–4V by electron beam-powder bed fusion to characterize orientation anisotropies in part dimensional accuracy, surface form accuracy, and surface finish [73].

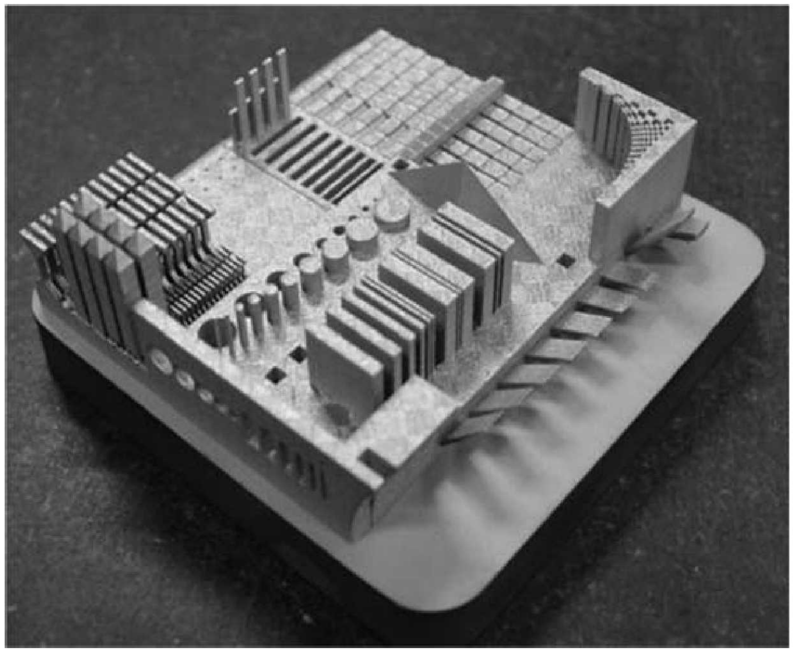

Figure 7.20 Complex design artifact produced in 17-4PH stainless steel using laser-powder bed fusion to characterize process capabilities and material properties. Build plate dimensions for scale are 100×100 mm. *Photo Courtesy: Brad Boyce, Sandia National Laboratories.*

inform design decisions can still be to print test artifacts that explore variations across the desired design space. This is particularly true when the process space is relatively small. Potential variations cover a wide range and can be process related, such as laser settings or feedstock changes, or geometry related, such as feature size or orientation. Metrics also range widely and include material properties or geometrical attributes such as finish or form accuracy. Thus design artifacts are a practical method, even if sometimes overly simplistic, for capturing the information necessary to develop design guides used to direct design decisions.

7.2.2 Postprocessing

Although geometric and material complexity are compelling drivers for metal AM parts, it is rare that metal additive parts are utilized as-printed without postprocessing. Instead, parts typically represent near-net shapes which require additional processing to address problems with dimensional accuracy, surface finish, residual stress, porosity, and material microstructures. Postprocessing often represents "hidden costs" that are not anticipated in the design cycle. It is imperative, therefore, that designers include attention to postprocessing as it can be time consuming and expensive, potentially eliminating anticipated cost or schedule gains.

7.2.2.1 Powder and part removal

The first step after printing for any powder-based process is to remove parts from the machine and then clean out unconsolidated powder (Fig. 7.21). While these are relatively simple steps, there are design aspects to be considered. Before parts are even removed from a machine, powder is removed from around them. While design requirements may demand features restricting powder access, geometries allowing easy powder removal are desired where possible. This facilitates maximum powder reuse, reduces powder exposure risks for operators, and reduces powder transfer into the surrounding environment. Powder can also be problematic for machining operations, particularly wire-electrical discharge machining (EDM), required to liberate parts from their build plates.

PBF and DED each involve building parts onto a base substrate or material. Except for applications involving part repairs, a required process step is to separate parts from this base substrate commonly by machining using a wire-EDM or bandsaw. These can be simple operations for simple parts, although challenges can occur and must be recognized. Part geometries must add sacrificial material to their height to account for removal processes, either in the form of solid material or support structures. If machining is undesired or unavailable, parts can be printed entirely onto

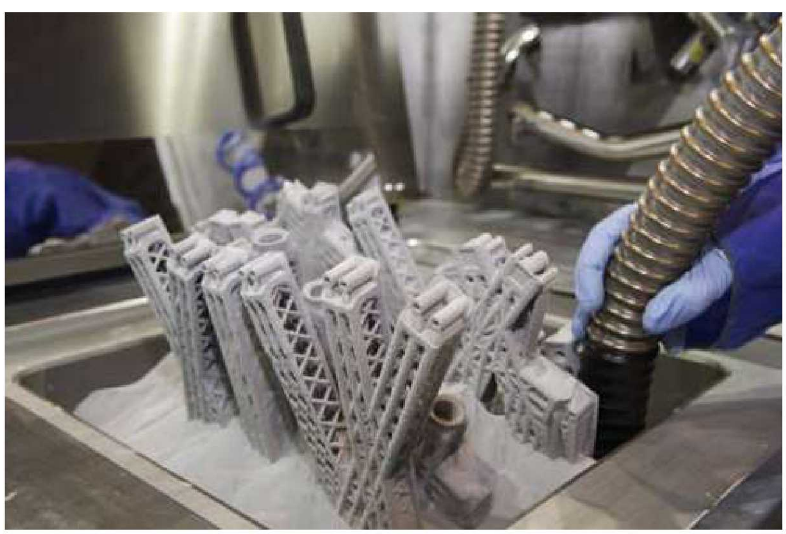

Figure 7.21 Removing the powder surrounding printed parts. *Photo Courtesy: APWORKS.*

support structures. Parts and supports can then be separated with simple hand tools, but they must be designed such that damage does not occur during removal.

7.2.2.2 Cleaning

Cleaning commonly occurs once parts are released from their build plate. It is straightforward for simple parts, and often merits minimal design consideration as parts can be vacuumed and then washed and/or rinsed manually or by ultrasonication. For applications where the potential presence of residual or stray powder is unacceptable, cleaning requires design consideration to ensure that access to part features is unrestricted. For powder processes, cleaning internal geometries can quickly present problems, unless the retention of powder within the part is an acceptable or even desired design feature. Exit pathways must be present and large enough to allow the extraction of powder and cleaning fluids from within the part. These can be in the form of internal channels for solid parts, or adequate spacings for architectured material geometries. Powder size and its flow characteristics must be accommodated in designing these features, and minimum feature sizes for printing may be more constrained by powder cleaning than printing capabilities. This is particularly true for E-PBF as loose powder is sintered during printing to produce a "cake" that can be difficult to remove post printing. Similar access constraints also exist for lamination based processes as machining chips must be managed and removed either in-process or postprocess.

7.2.2.3 Microstructure

It is well known that metal AM produces parts with material properties that are distinct from those observed in traditional metal-forming methods. There are applications where such properties are not desired and additional material modifications are necessary. These modifications are predominantly performed in the form of heat treatments to relieve internal residual stresses, to transform undesired material phases, to modify grain structures, Fig. 7.22, and to either anneal or strengthen the final material. Hot isostatic pressing (HIP) is also applied, dependent on the material system, to eliminate closed-cell internal porosity and/or to modify grain structures. These processes can have a significant impact on material and part performance and must therefore be included in design decisions. They also provide an additional degree of freedom in the design

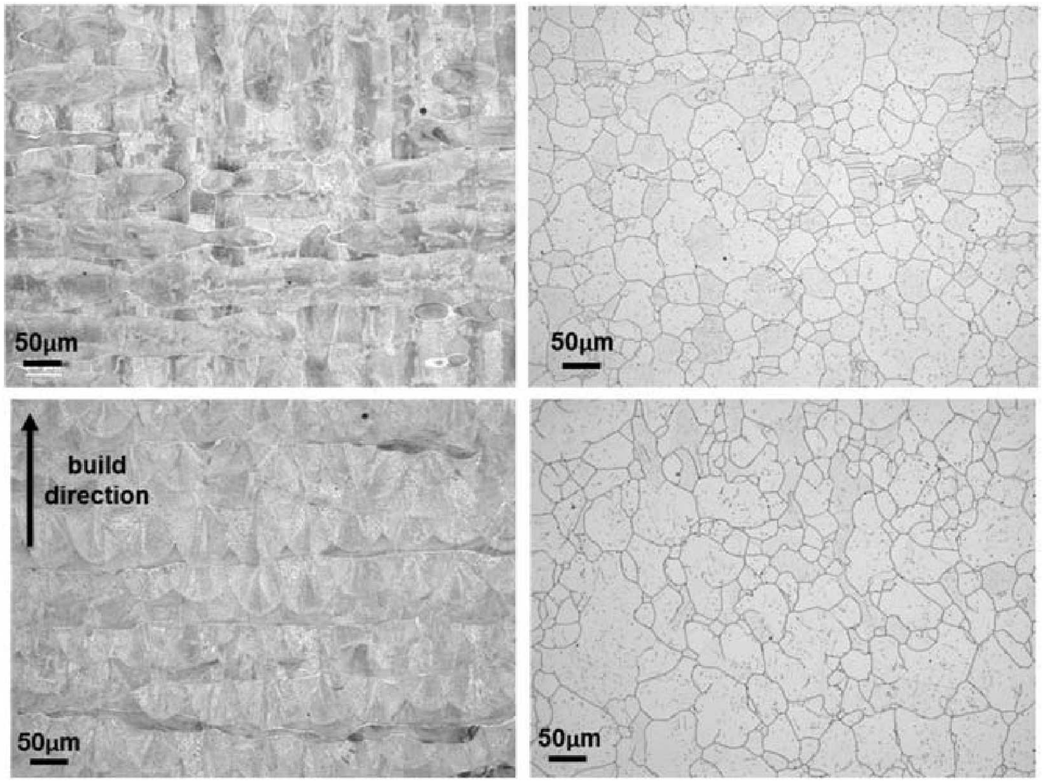

Figure 7.22 Microstructure change for laser-powder bed fusion 316L stainless steel. As-printed top-down view (top left) and side view (bottom left). After 2 hours in argon at 1200°C top-down view (top right) and side view (bottom right). *Photo Courtesy: Don Susan, Sandia National Laboratories.*

cycle for optimizing the part geometry, the part material, and the fabrication process for the intended application.

7.2.2.4 Finishing

Dimensional accuracy and surface finish are commonly cited as challenges for parts produced by metal AM [77]. As a result, postprocess finishing is commonly required for parts to satisfy these requirements. PBF, powder DED, and metal binder jetting can each be considered near-net shape processes, so finish machining operations are typically reduced to specific zones, not an entire part surface. Wire-feed DED generally produces much coarser geometries and surfaces that are machined in their entirety. Postmachining is typically unnecessary in UAM as machine operations occur during the process.

Machining has been discussed in the context of part removal, but additional operations are commonly performed to remove support structures and to establish precise surfaces for mating interfaces or measurement datums. Machining constraints are like those found in traditional operations, and to first order are defined by cutter geometries and their ability to access surfaces requiring machining. Adequate material must also be present in the part geometry to ensure that machining can achieve the desired surface finish and final geometry. Internal and re-entrant features introduce significant barriers to machining. AM metals may also have unique solidification microstructures that can impact machinability, not just mechanical properties. It has been observed, for example, that EDM process settings must be refined for AM metals relative to similar wrought alloys. It has been surmised that inhomogeneities in the AM microstructure, specifically the presence of nonconductive oxide particles, disrupt material—electrode interaction, resulting in shorts and process inefficiencies.

Metal additive parts are relatively rough compared to machined parts. Therefore postfinishing is typically applied, both to improve the surface finish to meet design requirements and to remove parasitic powder particles, that is, cling-ons, that could fall off once the part is placed into its intended service environment. For general service, sand and bead blasting are commonly first choices because they are fast, easy, and relatively inexpensive. Both are line-of-sight processes and are therefore restricted predominantly to easily accessible external surfaces. Tumble polishing is another inexpensive process common to shop floors (Fig. 7.23). It can provide a superior surface finish than blasting and is gentler with small parts and fragile surfaces. Like blasting, however, it is most effective on external surfaces as polishing media are restricted in their ability to enter re-entrant and internal features. A range of other polishing techniques are also available which span electropolishing, chemical polishing, vibratory polishing, and abrasive flow machining. Process constraints apply to AM parts, just as with conventional parts, and must be considered in the context of the desired part material and geometry. External surfaces are generally accessible for these techniques, while internal geometries present challenges for polishing media and chemicals.

7.2.2.5 Metrology

While "complexity is preferred" may be an accurate assessment of part formation in additives, the cost of metrology and/or inspection increases dramatically with complexity and can become impractical, cost-prohibitive, or impossible. Such costs and capabilities must be considered in the design cycle to ensure that metal AM provides sustainable benefits

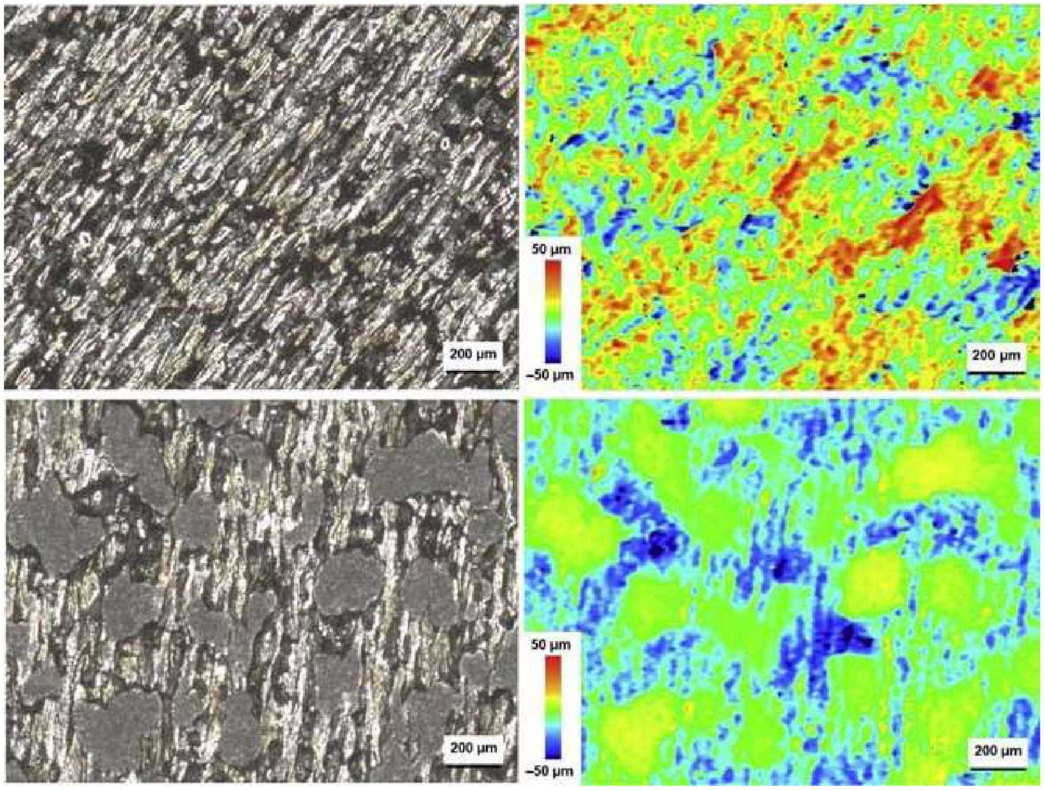

Figure 7.23 As-printed 316L stainless steel surface produced by laser-powder bed fusion (top left) with 13.4 μm S_a surface finish (top right). Surface after tumble polishing (bottom left) with 9.46 μm S_a surface finish (bottom right).

and value for products, companies, and customers. Traditional industrial metrology techniques are classically surface-based for a majority of the metal parts produced worldwide. AM is changing this paradigm, however, as volume measurements are becoming increasingly commonplace and necessary for capturing part details relevant to final performance.

Freeform surfaces cannot be measured as or represented by relatively simple shapes such as planes or cylinders. Fig. 7.24 shows a complex variant of the polyhedron geometry discussed in Section 7.2.1.6 that was printed in PH17-4 using L-PBF. While part fabrication was relatively simple, metrology proved challenging. Measurement of the entire surface in a single setup remains elusive with surface-based metrology techniques. Extending this geometrical complexity internally creates even more challenges for metrology and inspection. Such structures, regardless of scale, can only be characterized in a commercial setting destructively or through radiometric-based techniques such as radiography or CT. Such techniques tend to be cost and/or time prohibitive, less precise, and introduce large datasets that must be managed efficiently and effectively during the entire

Figure 7.24 A 26-sided, 43 mm wide polyhedron with design features on each face that is relatively easy to print, but much more difficult to measure [78].

lifecycle. If only traditional surface-based metrology techniques are available, for example, profilometer or hard gaging, then instrument access to part features becomes an important design constraint for products.

7.3 Materials

At a fundamental level, additive processes represent a truly digital manufacturing paradigm as they can produce material at discrete, localized positions throughout a part volume using a digital definition. This introduces design freedom to generate geometrical and material complexity at levels inaccessible in the past. Unfortunately, such access also generates design risk as process variations and disturbances introduce the potential to introduce undesirable material defects and property variations at any location within a part volume. Thus design for metal AM must be aware of and account for these spatial property variations within a part volume. It must also understand and quantify the potential distributions of material and part performance across multiple parts, multiple machines, multiple builds, and varying process inputs.

Existing material options are limited compared to the larger material palette available across traditional metal-forming techniques. Extensive work has been performed in material alloys with broad interest across applications and industries. These alloys include stainless steel (316L, 15-5PH, 17-4PH), nickel (Inconel 625, 718), chromium (CoCr), titanium (Ti−6Al−4V), and aluminum (Al-Si-10Mg) [79]. Researchers have also explored other material systems such as maraging and tool steels, copper alloys, refractories [79], high-entropy alloys [80], and shape memory alloys [81]. DED and PBF processes are limited to materials that are robust in the presence of extremely rapid melting and solidification rates. 6061-T6, for example, is ubiquitous across machine shops and tool rooms, but is susceptible to cracking and is largely ignored as a metal AM feedstock [82]. Binder jetting is capable of processing aluminum, cobalt, copper, iron, nickel, and tungsten alloys [50]. Metal UAM is extremely flexible relative to materials as it can bond numerous metal alloys (e.g., aluminum, copper, titanium, iron) and multiple dissimilar metal pairs (e.g., aluminum/copper, aluminum/iron, nickel/titanium). While the process cannot bond metals to nonmetals, nonmetal components can be incorporated within metal structures.

7.3.1 Spatial variations

PBF and DED each melt and subsequently solidify material feedstocks using melt pools that are much smaller than the desired part geometry. The thermal profiles of these melt pools directly impact local material microstructures and properties. While they are influenced by process inputs and the surrounding process environment, thermal time histories are also impacted by local and global part geometries. As a result, material microstructures can vary across build volumes producing part anisotropies that change across the part itself [83], with feature size scales [84], and with part location and orientation within the build process [85] (Fig. 7.25). Whether intended or not, these spatial variations must be recognized and accounted for during design. Ideally, future computational design tools will catalog, specify, and predict property variations within an AM metal design. No such capability exists currently, although it is an active topic of research (Chapter 6, Metal additive manufacturing process modeling and simulation). Instead, designers typically base design criteria on conservative estimates of material property minimums with large design margins and safety factors.

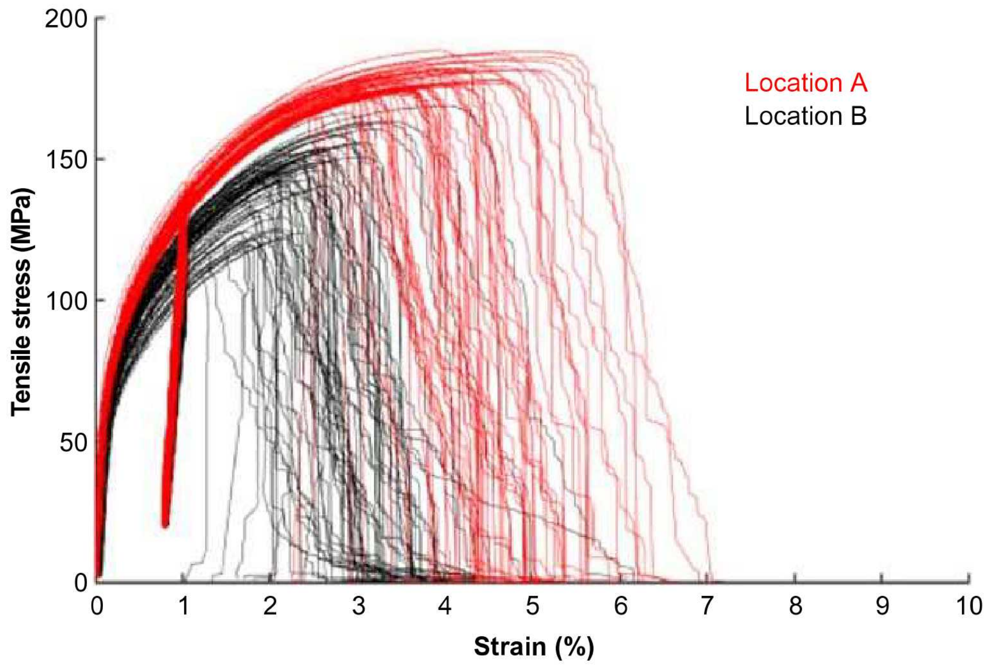

Figure 7.25 Engineering stress—strain curves for Al-Si-10Mg tensile bars generated using laser-powder bed fusion. Location A is in the corner of the build plate where the argon flow and the powder spreading began, while location B is the opposite build plate corner [85].

7.3.2 Material distributions

A consistent challenge identified in metal AM, particularly in the context of qualification and certification, is the variation observed in materials and part performance. This variation can occur within a single build, across multiple builds, across multiple material feedstock uses, and with varying process inputs. Variations are also observed across common machine systems with different serial numbers, across different platforms by a common OEM, and across platforms by different OEMs. Designers and engineers commonly address these process variations for products by restricting part fabrication to a dedicated machine system with a dedicated material feedstock.

Given that metal AM applications are dominated by structural mechanical requirements, bulk mechanical properties and behaviors have been research and characterized extensively. Mechanical strength, modulus, ductility, and toughness are dominated by material microstructure and are therefore influenced by the material feedstock, machine operation, process parameters, and part geometry. Defects can be associated with material phases, feedstock porosity, contamination, and alloy segregation. Process-induced porosity and inadequate material fusion commonly represent dominant defect forms for structural properties and are influenced by process parameters, feedstock quality, process spatter (for PBF and DED), and powder dynamics (for PBF and DED). Metal additive surfaces are also rougher than typical machine surfaces and thereby introduce additional failure modes associated with surface stress concentrations, microcracks, and unmelted powder [83,86]. Mechanical properties for binder jetting tend to be lower than those for PBF and DED as sintering creates larger grains and internal porosity, while reliance on infiltration prohibits material homogeneity [50]. Metal sheet lamination or UAM is a solid-state process that essentially cold rolls material as it is joined and printed. Thus material properties are relatively consistent with those of the feedstock material [51], although microstructural changes and layer defects can be present [87].

Structural properties of additive metals can exhibit significant variability when sampled across statistically relevant datasets. Fig. 7.26 shows a 17-4PH material test array with six rows of 20 dogbone tensile specimens each with a 1 mm × 1 mm gage cross-section that are mounted onto a single base, roughly 50 mm square and fabricated using L-PBF [88]. Fig. 7.26 also compares Weibull cumulative probability distributions for strain at failure of wrought 17-4PH with two 17-4PH arrays fabricated by separate vendors. The additive material clearly underperforms, a trend repeated for yield and ultimate strength, which has been attributed to the presence of lack-of-fusion voids, excessive surface roughness, and a microstructure distinctive from wrought material [88]. Such variation is similar to that observed in ceramics and metal castings. Thus three-parameter

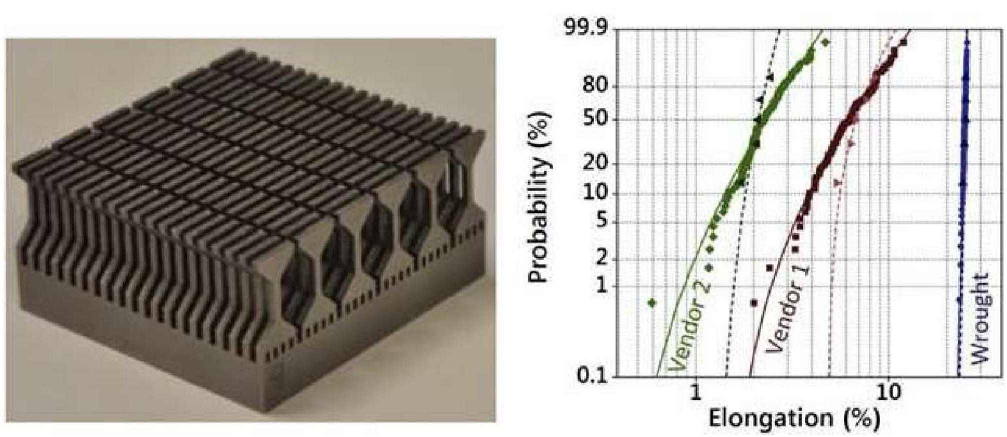

Figure 7.26 A 50 mm × 50 mm 17-4PH stainless steel high-throughput tensile array produced by laser-powder bed fusion (left) and resulting cumulative probability distributions for strain at failure compared to wrought 17-4PH (right) [88].

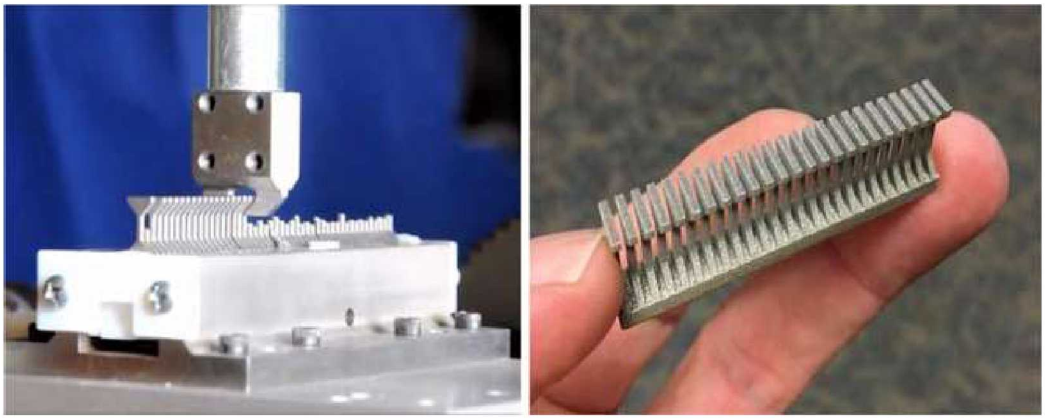

Figure 7.27 A test platform for automated high-throughput tensile testing of AM materials (left) and its test sample printed in 316L stainless steel by laser-powder bed fusion (right) [90].

Weibull fits are valuable in determining design margins and thresholds. While defects cannot be presumed for every additive material, it is important to properly capture and evaluate stochastic material distributions to establish accurate design thresholds.

Metal AM's ability to rapidly generate parts and materials is a benefit for development engineers, but it presents a new challenge to material scientists because material characterization techniques are time consuming and struggle to keep pace. One approach to addressing this challenge is using high-throughput techniques for material characterization [89]. Fig. 7.27 shows an automated, tensile tester and corresponding sample geometry that quantifies tensile strength for structural materials in 1–2 minutes compared to 1–2 hours for traditional techniques. As a result, the statistical variations in additive materials can be captured efficiently to insure process optimization, to establish margins, to estimate outlier probabilities, and to track process trends.

7.4 Design tools

Product design is an extremely active and dynamic field that has changed dramatically over the years as draftsmen, drafting tables, templates, and pencils have been replaced with CAD software, laser printers, high performance computing (HPC), and virtual reality. These tools have already held a crucial role in the advance of metal AM, and it is expected that these roles will only expand as computational and process capabilities increase. While AM provides the ability to generate complex geometries and materials that cannot be realized using traditional manufacturing techniques, existing design tools are incapable of fully exploiting this potential. Therefore work is developing analysis-driven design tools that capture and leverage the full potential of AM to increase its future impact and benefits across a range of applications and industries.

7.4.1 Computer-aided design

CAD tools today were developed in a manufacturing paradigm predominantly dependent on the machining of extruded or forged bulk feedstocks. As such, geometries are generated using analogous steps of extruding and cutting away part volumes [91–93]. These tools are extremely powerful and capable for a wide range of applications, part geometries, and design needs. It is likely that a majority of metal additive parts produced to date have relied on these existing, commercial tools. These tools are also based on surface definitions, not true volume representations. As a result, they face significant challenges and limits for the geometrical and material complexity desired through metal AM. Simple architectured material unit cells, for example, an octet truss, can be generated relatively easily in conventional CAD software. Complex gyroid unit cells, however, become much more challenging. Scaling and repeating either of these geometries into a much larger, desirable structure becomes problematic relatively quickly as file sizes become prohibitive and volume representations can be inaccurately represented by available file formats. Further, reliance on surface design definitions presents fundamental barriers in representing material complexity at any scale as it is incapable of specifying variations within the material volume. Solutions to some of these problems are becoming available for architectured materials, however, as design software is now capable of defining lattice and surface structures using beam-based and nonmanifold representations, respectively [42], or through implicit modeling [40] (Fig. 7.28). Such representations require smaller file sizes, enable definition of more complex structures, and can even improve printing throughput.

7.4.2 Design rules

Design rules are important to any technical community as they guide designers and engineers in making decisions using validated information based on application experience, laboratory experimentation, and

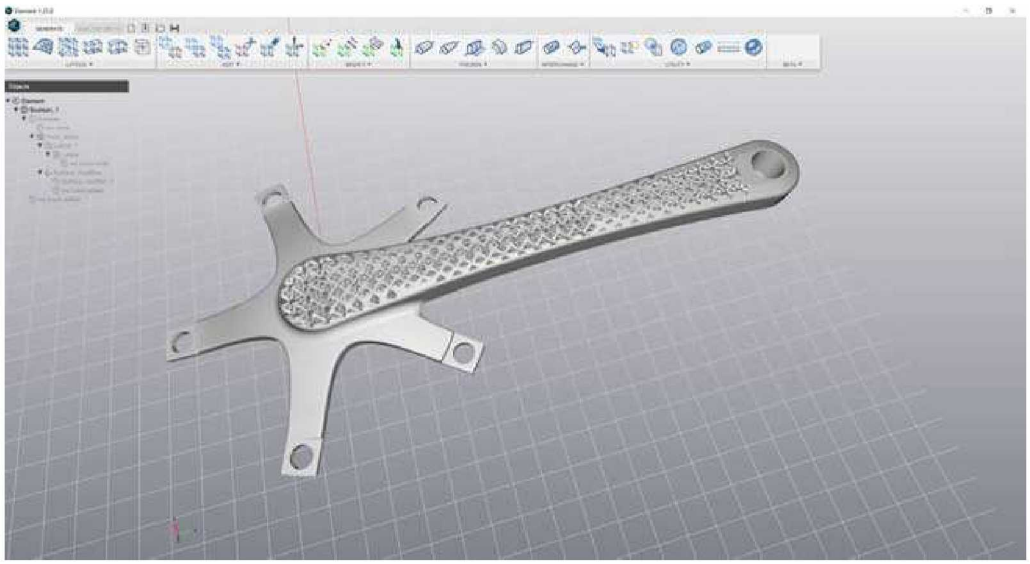

Figure 7.28 CAD interface for a bicycle crank arm incorporating a cube vertex centroid lattice structure [40]. *Photo Courtesy: nTopology.*

computational simulations. Over time design rules can even lead to standards and codes. When a disruption like metal AM occurs, design rules quickly change, become obsolete, or are abandoned. Design rules in metal AM are most commonly tied to process and material constraints and are therefore specific to the material, process, and machine applied. They are commonly developed by individuals or organizations using artifacts (see Section 7.2.1.6), and are considered proprietary or trade secret to maintain competitive advantages. Guidelines can be found in the open literature [60,94,95], although these should be utilized conservatively until validated as necessary. The close coupling of metal AM processes, materials, and geometries makes the generation of accurate and universally applicable design rules very difficult. Therefore design rules may be developed and implemented that are closely coupled to a specific application, machine, material, or process. While design rules are most commonly discussed relative to part geometry, aspects may also address material properties and process conditions.

7.4.3 Performance models

Part scale performance models have become indispensable for engineers as they can provide high-fidelity predictions of part and/or material behavior in relevant environments to improve design confidence, reduce design—test—build cycles, and eliminate costly experiments. The necessary fidelity and complexity of part predictions is driven by the load environment, the part complexity, its material response, design margins, and the consequences of part failure. Performance predictions are routine for conventionally manufactured parts, and are available to a wide audience through a range of simulation software packages. The primary distinction for metal AM parts, however, is the identification and representation of material properties within the part model. Using isotropic, homogeneous bulk material properties is clearly the simplest available material model, but it is one that could be either overly conservative or risky, depending on how values are determined relative to material data. Introducing material anisotropy, spatial property variations, and stochastic distributions each improve material models, but with subsequent increases in model complexity, files sizes, and computational costs. Capturing material heterogeneities in the form of grain structures, textures, and porosity defects in material models is an active topic within the research community [96–98] (Fig. 7.29), particularly for high-consequence applications in the aerospace and defense sectors. Such models are generally performed in HPC environments and are not available for widespread use.

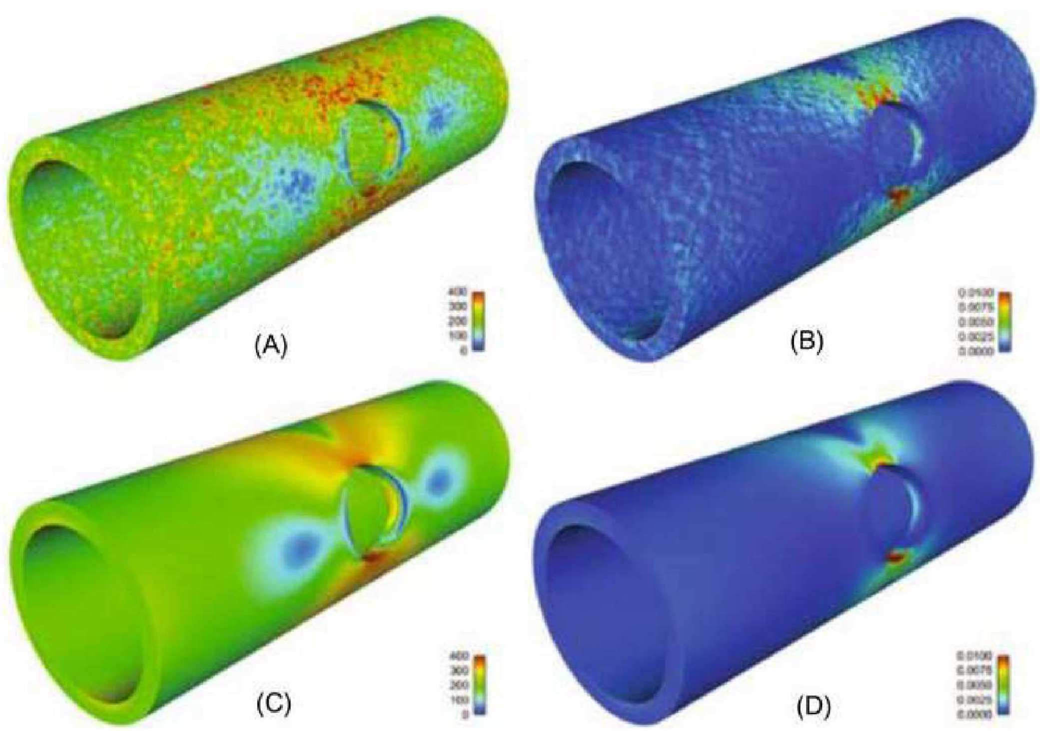

Figure 7.29 (A) von Mises stress field and (B) equivalent logarithmic strain field resulting from the direct numerical simulation of a tube containing microstructure and loaded in uniaxial tension. (C) von Mises stress field and (D) equivalent logarithmic strain field resulting from using the homogeneous macroscale von Mises plasticity model. (Stress units are MPa.) [98].

7.4.4 Computer-aided manufacturing

Computer-aided manufacturing (CAM) tools are used widely in machining operations, although they are not required for manual machining. The complexity and digital nature of metal AM tool paths, however, has made CAM software ubiquitous across machine platforms and processes, even for consumer grade machines. Computer numerically controlled (CNC) machining centers typically operate using G-code, a standardized programming structure that can be easily learned, programmed, and translated across different machining platforms. Most metal AM machines, however, do not rely on a standard programming code but utilize proprietary file formats and program structures that are generated by dedicated CAM packages developed and implemented by OEMs specifically for their machine platforms [41,99,100] (Fig. 7.30). Third-party vendor CAM software is available [67,101], however, and is commonly utilized across the industry. Open source codes are also available [102], although these are generally restricted to open source consumer-grade polymer machines or research metal machine platforms.

Historically, AM processes have required that part models be converted from their native format into STL before being imported into CAM software. STL files can be ASCII or binary, and they represent geometries with unstructured, triangulated surfaces that do not contain scale or unit definition [103]. STL files have been used for decades in the rapid prototyping

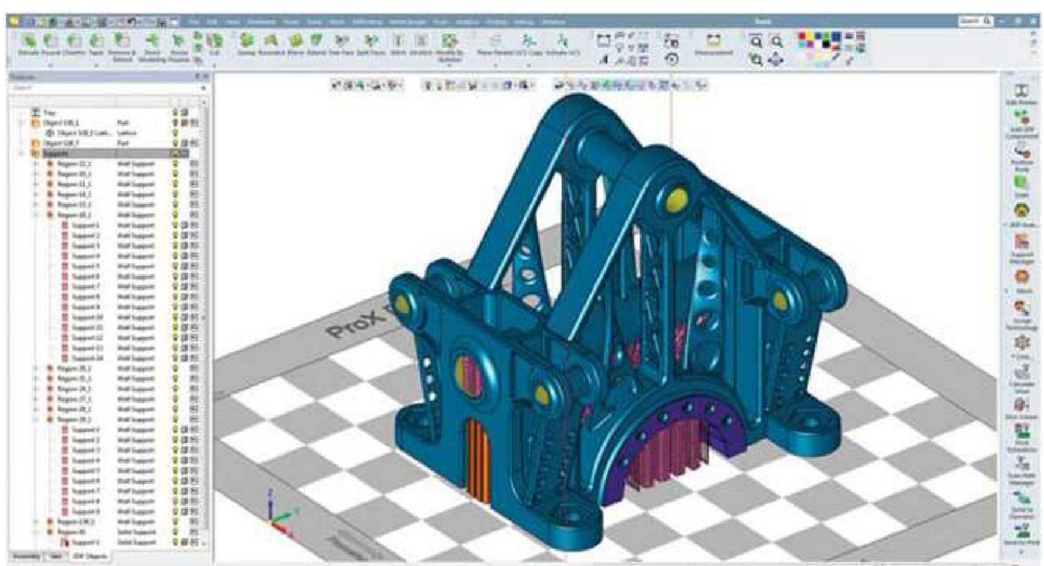

Figure 7.30 CAM software with a build layout and build supports [41]. *Photo Courtesy: 3D Systems.*

field, but they present limitations and challenges in terms of accuracy and efficiency [104]. Yet, STL has had remarkable staying power as new formats, for example, 3MF [105], have been proposed as replacements but have experienced slow adoption rates. AMF (Additive Manufacturing File format) is a popular attempt to overcome multiple STL shortcomings. It is XML (eXtensible Markup Language) based, contains unit information, and is defined by ASTM standard 52915-16 [106]. Like STLs, however, it describes part geometry using triangular meshes and can be resolution limited. The intermediary file format, however, may become a relic as recent CAM packages are beginning to allow the use of some native CAD models [41]. Many DED platforms are also capable of processing solid models directly in the form of STEP (Standard for the Exchange of Product data), Parasolid and IGES (Initial Graphics Exchange Specification) files.

Until recently, CAM software has been relatively inflexible as OEMs have maintained strict control of machines and processes. Proprietary file formats, programming languages, and encrypted process files have all limited a user's ability to modify machine capabilities and processes. Most OEMs have also maintained extremely tight control of machine process settings as changes have required additional license purchases, have been limited in their scope, or have been unavailable completely. Proprietary OEM material databases are also commonly utilized to establish process conditions for materials used in a machine. Newer software packages, however, have become more powerful and capable as control of process settings is becoming much more common. More advanced design capabilities are also being introduced into CAM software, for example, lattices [41], streamlining the development process and potentially paving a pathway by which design and process optimization will one day be performed in concert, not in isolation. Further, the advent of multimaterial printing extends CAM software capability needs as users will increasingly require control of material type across a part volume. This could occur within a single layer or across multiple layers but must provide the ability to manage the specification and customization of both material and process parameters.

7.4.5 Process simulations

Process—structure—property—performance relationships are critical to predict and ensure product performance throughout metal AM development and production cycles. Such relationships, however, are extremely complex and rely on physics at multiple length and time scales. Chapter 6, Metal additive manufacturing process modeling and simulation, covers process models in better detail, but it is sufficient to state that process simulations can, do and will play a prominent role in design for metal AM parts. Empirically based heuristics are necessary and invaluable to establish design and process guidance, but they are often simplistic and therefore insufficient; particularly as complexity increases for geometry, processes and materials. Again, the close coupling of material, process, and geometry in metal AM requires the availability of computational models to predict, control, and optimize part performance. Thus development cycles will only be accelerated when the design—build—test paradigm that dominates the preliminary stages of technology adoption and implementation is supplanted by agile and affordable design cycles that reliably meet requirements and margins.

Multiscale computational models that link atomic-scale unit processes through mesoscale phenomena up to macroscale behavior represent an important and powerful component of metal AM [107] (Fig. 7.31). Researchers across the additive community are developing these models at length and times scales ranging from feedstocks [108] to parts [96] with the intention of quantifying and exploring multiphysics interactions,

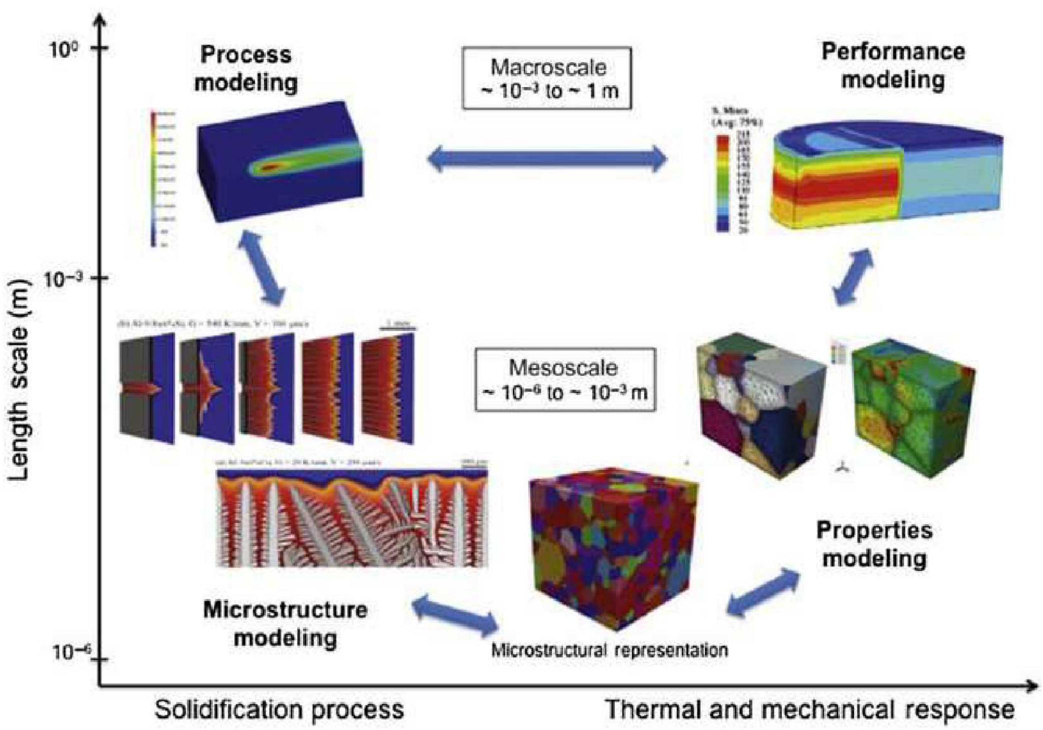

Figure 7.31 Illustration of an integrated process—structure—properties—performance modeling and simulation approach with associated length scales [109].

optimizing process parameters and predicting material heterogeneities [97], part deformation, and residual stress [96,109]. Commercial software is now available that provides predictive capabilities for residual stress and part distortion [67,68]. Such information can then be used to inform support structure design and to perform process optimization without expensive, iterative part builds. While the complexity of the underlying physics driving additive processes varies, phenomenological models must capture the relevant physics at time and length scales appropriate for accurate prediction of material performance. The complexity of such full-scale models precludes their use in design tools for the foreseeable future due to their extensive computational costs. Instead, reduced-order material and process model surrogates informed by full-scale models and empirical datasets will be adopted for use during design calculations.

7.4.6 Design optimization

Performance modeling is often referred to as solving the forward problem given that the response from a candidate design is computed. This contrasts with solving the inverse problem, which amounts to finding the design for a desired response, that is, design optimization. Additive manufacturing has prompted a resurgence in optimization methods such as topological optimization (TO) and shape optimization (SO) where design and analysis are performed concurrently to generate geometries based predominantly on functional requirements, not manufacturing constraints. As a result, simulation is not performed outside the design process as a validation step, but rather is integrated directly within design.

Generally, the optimization problem involves finding the spatial distribution of material attributes that optimizes a performance objective for a design domain and set of requirements. In its simplest form, it is an iterative procedure. First, the response to a candidate design is computed as fields satisfying the state equations are determined for the current design and then used as the basis for evaluating performance objectives, and their sensitivity to change. Field solutions can be found using well-established analysis codes such as Abaqus [110], Nastran [111], or Sierra Mechanics [112]. Design changes are then determined as the objective, sensitivity, and other information from the calculation are passed to an optimization engine that updates the design while enforcing constraints. Basic iteration continues until convergence to an optimal design with respect to functional requirements is met or iteration limits are exceeded.

While TO has existed for 25 years in the literature [113], additive techniques are necessary to realize many of its resulting design solutions which are often nonintuitive and mimic biological constructs. Optimization codes have, until recently, resided predominantly in the domain of highly advanced users, that is, computer scientists, mathematicians, and academics. Access to engineers has only occurred in the past few years with the release of commercial software packages [114–117]. Fig. 7.32 demonstrates a housing designed where stiffness was optimized to minimize the amplitude response in a vibration environment. This design could have never been conceptualized or fabricated without the marriage of TO and metal AM. Such capabilities have captured the imagination of engineers, designers, inventors, and entrepreneurs sparking a revolution in product design and development (Fig. 7.33).

Optimization-based design has become an increasingly active and diverse field of research as multiple techniques and tools are now available [118–120]. Research codes are readily accessible, but provide limited capabilities and are not properly supported to address user needs [121,122]. Commercial software is more user-friendly and can deliver size, shape, bead, topography, topometry, and freeform optimization methodologies to complement topology-based calculations. Minimization of compliance is a common structural problem given a fixed mass budget, but tools exist to minimize weight, stress, or strain, to achieve a desired

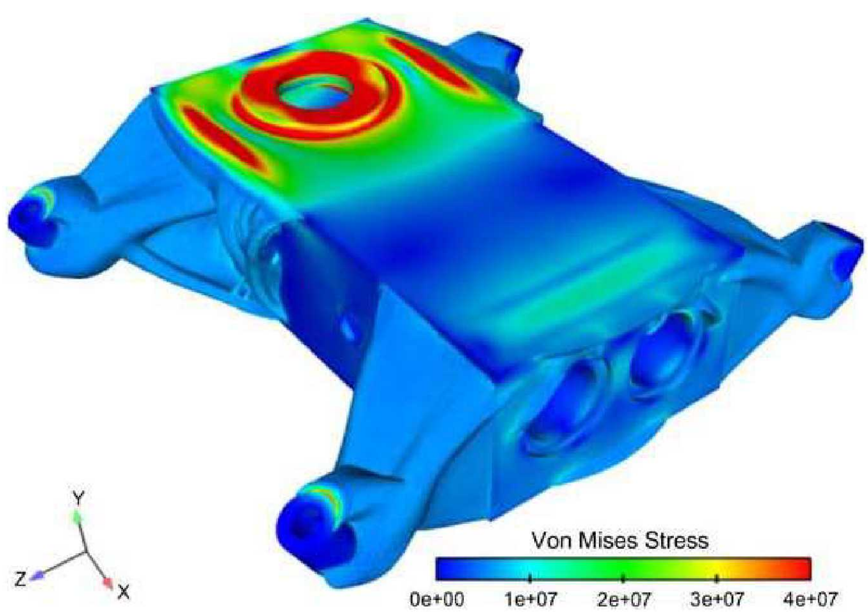

Figure 7.32 Housing designed using topology optimization with optimized stiffness to minimize vibration modes and amplitudes [78].

Figure 7.33 Topology optimization is being utilized to explore a wide range of parts and applications for metal AM including brackets and high-performance consumer products. *Photo Courtesy: SLM Solutions (top left); Airbus (top right); Siemens (bottom left); APWORKS (bottom right).*

frequency response, or to optimize fluid channel flow. Available boundary constraints include displacements, velocities, accelerations, forces, moments, body loads, contact pressure, center of gravity, temperature, heat flux, and transient thermal loads [114–117].

An essential element in any design methodology is its consideration of process constraints. Current commercial optimization software includes some additive process constraints such as minimum feature size [123–125] and surface roughness [126]. Overhang constraints have been implemented by researchers for 2D topologies [65] (Fig. 7.34), and self-supporting 3D structures have been designed which perform similarly to those designed without manufacturing constraints [127]. Methods are also being developed to account for manufacturing variability [128,129], build orientation material anisotropies [130] and design for AM principles [131]. While no commercial software includes a multimaterial capability, research in multimaterials has been active for over two decades [132,133]. Architected materials, that is, lattices, have been recently incorporated into tools [134,135], motivated by widespread interest in light-weighting. Significant work remains, however, to couple design for AM into

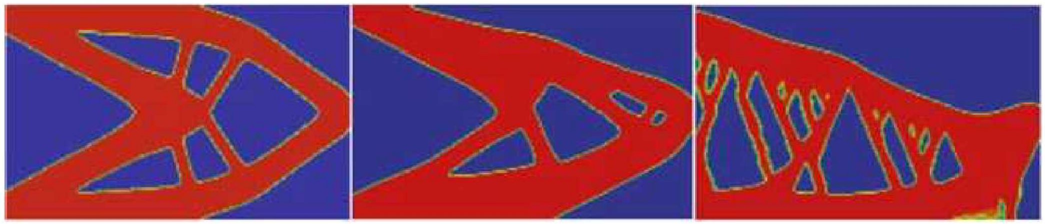

Figure 7.34 Topology optimized cantilever beam solution with no overhang constraints (left), a self-supporting angle constraint of 26.6 degrees (center), and a self-supporting angle constraint of 63.4 degrees (right) [65].

optimization platforms. It is common, for example, that TO geometries require excessive support materials, to be difficult to postprocess, to be impossible to print, or to have features with excessive residual stress and deformation. Incorporation of even heuristically based process constraints within optimization codes will alleviate many of these issues, guiding part orientations and setup, and reducing fabrication and design iterations.

Commercially available design solutions most commonly utilize linear isotropic material properties, but orthotropic and anisotropic materials can be specified [117,136]. Accommodating the property variations inherent to and the material complexity available through metal AM, however, is unavailable with existing toolsets. The inherent coupling of material, processes, and structures further demands the introduction of constitutive PSPP relationships into optimization codes. While process-aware optimization with full-scale process models clearly represents a grand vision for future capabilities, the computational expense of such models is prohibitive, even in isolation. While full integration into optimization algorithms is unclear in even the long term, the definition of reduced-order surrogates that reasonably capture important process physics is clearly necessary and will shape near-term research efforts.

Incorporating material distributions, uncertainty quantifications, process constraints, and process physics are desired to improve design accuracy and to truly optimize design for metal additive manufacturing. The introduction of these design objectives, however, quickly increases the computational expense required to perform them, whether in model complexity and fidelity, in file size and memory allocation, or in computer clock cycles. Therefore work must be performed, and is on-going in the research community [137,138], to enable the execution of massively parallel calculations, to improve optimization algorithm performance and to implement reduced-order models.

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CHAPTER 8

Qualification for metal additive manufacturing

Abbreviations

2D	two-dimensional
3D	three-dimensional
AMS-AM	SAE Aerospace Material Specifications—Additive Manufacturing committee
ASME	American Society of Mechanical Engineers
AWS	American Welding Society
CT	computed tomography
DED	directed energy deposition
EBF^3	electron beam freeform fabrication
EDS	energy-dispersive spectroscopy
ELI	extra low interstitial
E-PBF	electron beam-powder bed fusion
FAA	Federal Aviation Administration
FDA	Food and Drug Administration
GD&T	geometric dimensioning and tolerancing
HIP	hot isostatic pressing
ICME	Integrated Computational Materials Engineering
ISO	International Organization for Standardization
L-PBF	laser-powder bed fusion
MPIF	Metal Powder Industries Federation
NDE	nondestructive evaluation
NDT	nondestructive testing
NNMI	National Network for Manufacturing Innovation
OCT	optical coherence tomography
PSD	particle size distribution
PBF	powder bed fusion
PM	powder metallurgy
PSPP	process–structure–property–performance
RP	rapid prototyping
RVE	representative volume element
SAE	SAE International
SDO	standards development organizations
SEM	scanning electron microscopy
TEM	tunneling electron microscopy
TO	topology optimization
UAM	ultrasonic additive manufacturing

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XRD	X-ray diffraction
WLAM	Wire and laser AM
WAAM	Wire-arc AM

8.1 Qualification and product acceptance

Metal additive manufacturing's roots are planted firmly in rapid prototyping (RP), which began in the 1980s and 1990s [1,2]. Rapid prototyping provided a means for representing three-dimensional (3D) design forms in a rapid and inexpensive manner, thus finding widespread adoption across a range of design and development activities. The dependence on polymeric materials [1,2], however, restricted part functions and prevented their use for manufacture of products for most service environments. As such, qualification, certification, and product acceptance were not primary concerns for early users of additive manufacturing processes who were printing parts to explore and communicate designs at various stages in the development cycle.

Early researchers did recognize the potential for polymer-based RP techniques in manufacturing and sought to use it in the fabrication of molds capable of casting metal parts [3]. Researchers also quickly worked to develop techniques for the direct fabrication of metal parts [4] (Fig. 8.1), clearly focused on providing a process route for the fabrication of parts meeting broader functional requirements. Quality became an important focus for early researchers and users interested in production, not development [5–7]. Product function, not just form, drove numerous requirements for product and process qualification, certification, and production acceptance that heralded the eventual shift from "rapid prototyping" to "additive manufacturing."

The claim that "complexity is free" [8] is a common refrain promoting the utility and opportunity of additive manufacturing for designers and inventors. Its agility and flexibility are also commonly cited as means by which a responsive and cost-effective manufacturing infrastructure can be leveraged to reduce production cost and schedule risks. The cost of assuring and validating product quality, however, is a critical consideration for metal additive manufacturing as traditional acceptance protocols and methodologies can be inadequate. Depending on design requirements, margins, and the consequence of product failure, the qualification and production acceptance of additively manufacturing metal parts can require investments, resources, and schedules that exceed those of traditional manufacturing processes. Thus designers and engineers must accurately evaluate and account for these costs during the product development cycle.

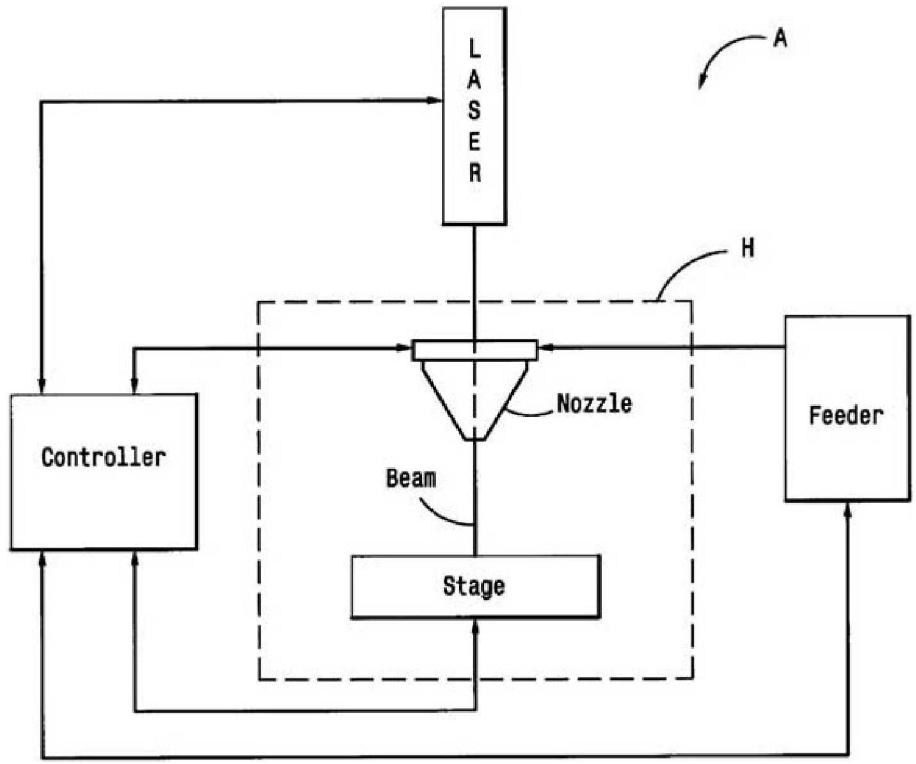

Figure 8.1 Schematic from one early patent on powder deposition based metal additive manufacturing [4].

The "cost of complexity" is increasingly critical as the impact of product failure becomes more severe and unacceptable. As a result, qualification is a fundamental barrier preventing the widespread adoption of metal AM processes for a range of high-consequence applications in the aerospace, automotive, medical, and defense sectors. To facilitate adoption in these important industries, fundamental questions regarding the intrinsic reliability of additively manufactured metals must be answered.

Because terminology can vary across industries, organizations, and corporations, definitions are important for clear communication. Some use qualification and certification almost interchangeably, while other organizations rely predominantly on the use of a single term, most commonly qualification. Context can often provide insights and clarification. Qualification here represents a demonstration and evidence that a *product design* meets requirements in the presence of operational environments. It can refer to a process, a machine, a material, a part, or even a supplier [9]. Certification predominantly refers to parts, components, or systems and is established to the satisfaction of a *certifying authority*. The US's Federal Aviation Administration (FAA) and the Food and Drug Administration

(FDA) are examples of regulatory agencies responsible for certifying products for the aerospace and medical sectors, respectively. Both qualification and certification occur within the context of development. Product acceptance is a term not as widely utilized but refers specifically to the process by which *production parts* are asserted to meet product requirements [10]. Product acceptance methodologies and demonstrations are generated during development and qualification, but their implementation occurs during production. Qualification and/or certification are used here about *development* activities; product acceptance for *production* activities.

8.1.1 Challenges

Because part geometry and material are produced concurrently during metal additive processes, they are inherently coupled and must be developed, controlled, and validated together. This is distinct from traditional subtractive-based manufacturing processes such as machining, forging, stamping, and other metal forming processes where certificates can be provided for material feedstocks to insure material quality *a priori* to the generation of a part's geometry. Casting, metal injection molding, and powder metallurgy form part material and geometry in the same process. Material solidification, however, occurs in a bulk form with these processes as material solidification volumes are much larger and solidification rates are much slower. The process physics of laser welding are similar to those experienced in directed energy deposition (DED) and powder bed additive processes. Welding, however, does not produce part geometries explicitly and usually occurs over much shorter process durations, that is, multiple seconds or minutes compared to multiple hours or days. Thus metal AM processes and parts are unique in how they must be monitored, controlled, qualified, and inspected.

Monitoring and controlling metal additive processes has been a focus of researchers for more than a decade [11−13] to both improve and insure part quality and reliability. Such efforts, however, have proven difficult due to the complexity of additive process physics (Fig. 8.2). The melting and solidification of material at local scales provide exquisite material control. The associated physics, however, are both extreme and dynamic as they range across multiple temporal and spatial scales. Localized material interaction temperatures exceed melting and can exceed vaporization [14], resulting in multiphase material behavior. Material interaction zones and deposition speeds vary across processes but can approach multiple

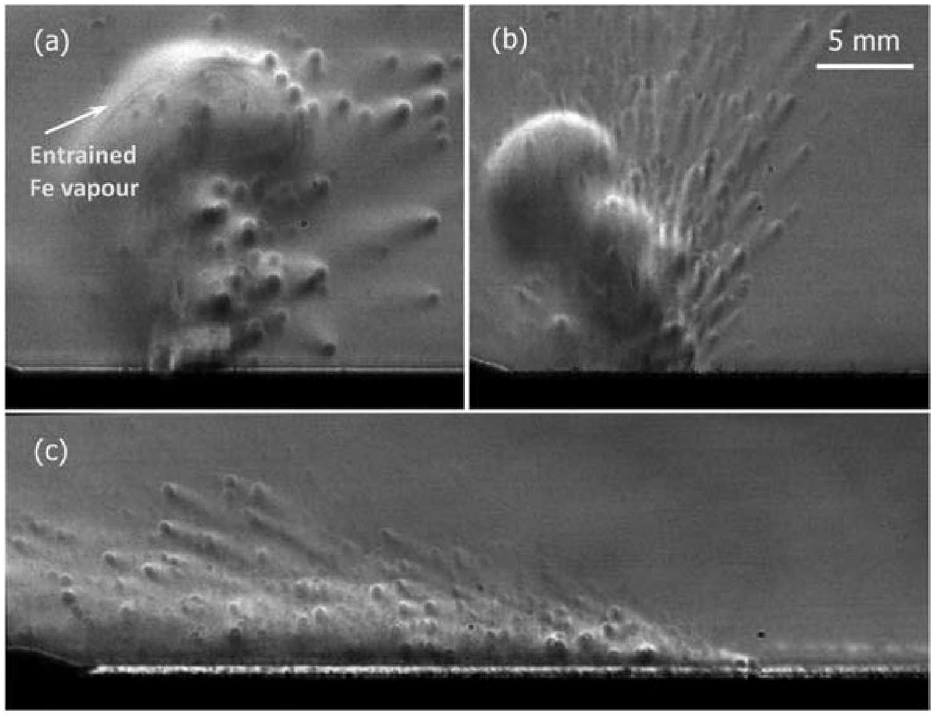

Figure 8.2 Schlieren images of laser-powder bed fusion of 316L stainless steel. Entrained iron vapor, spatter and laser plume are observable and demonstrate highly dynamic phenomena during printing [17].

millimeters and millimeter/minute for wire-based DED processes and a few hundred microns and multiple meters/seconds for powder bed fusion (PBF). Resulting heating and cooling rates, therefore, span 10^4-10^6°C/s [15,16]. Local process conditions also impact part scale phenomena such as residual stress and distortion, which occur over several hundred millimeters. Further, local conditions couple to and influence the surrounding build environment based not just on part geometry but also that of surrounding parts in the build volume. Resulting material structures and properties are influenced by factors including changes in spatter, plume dynamics, local and global thermal histories, and boundary conditions. Observing and capturing all these process inputs is difficult at any instant in the build process. Capturing them throughout a complete build cycle is even more daunting and requires continued development and research efforts. As a result, process monitoring and control are limited in existing metal machines. Research to date has predominantly focused on detecting process anomalies to identify parts with outlier behavior.

The complexity and dynamic physics of metal AM processes is one contributor to the variation and uncertainties observed in materials and parts [18,19]. Fluctuations in the build environment, input energy levels, and feedstock quality and placement all impact part quality. Microstructure variations result in the formation of porosity, phase gradients, and alloy segregations. Other part characteristics inherent to metal processes such as poor surface finish, residual stress, and geometrical distortions also impact part and material performance. These variations and uncertainties fundamentally drive the hesitance to more broadly accept and utilize metal additive manufacturing, particularly for higher consequence applications. Instead, designers, engineers, companies, and government agencies leverage metal AM for applications with redundancy, large design margins, conservative specifications, and relatively benign operating environments.

8.1.2 Defect formation

The geometrical complexity afforded by additive manufacturing is rooted in its layerwise nature. Through it, every volume element, that is, voxel, is printed and therefore accessible within a part geometry. Such access provides the potential for unparalleled control of material at local scales and opportunities for unique product designs. It also introduces multiple pathways to introduce compromising local defects at any position within a part volume. These pathways and mechanisms must be understood and addressed during development as they provide a basis for addressing uncertainties and variability during qualification and certification.

Feedstock-induced defects occur whenever powder composition, size, and/or morphology reside outside specifications constrained by process and material requirements. Foreign particle contamination represents a gross composition defect that can occur from a range of sources. Proper powder handling, shipping, storage, and exposure environments; machine maintenance and cleaning; and vendor controls are necessary to mitigate this defect source. Experience has demonstrated that bulk particle contamination is most likely discovered through particle analysis and postprocess metallurgical techniques (Fig. 8.3). It is difficult to identify otherwise, unless material densities contrast enough to facilitate detection by radiographic methods.

Powder contamination also occurs when the alloy composition is in error, either in the bulk or on the external surface. Surface oxide layers are inherent to almost any metal powder particle [21], so they must be understood and mitigated through proper storage and handling. Excessive oxides can be identified through particle analysis techniques such as energy-dispersive spectroscopy (EDS). Precise layer quantification requires sectioning and high-magnification scanning electron microscopy (SEM) or

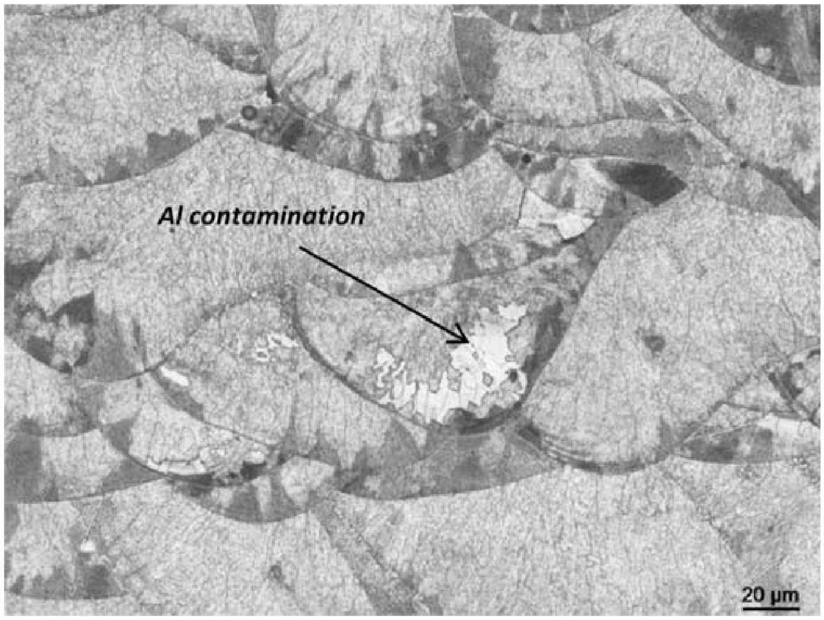

Figure 8.3 Aluminum in 17-4PH stainless steel due to powder feedstock contamination [20].

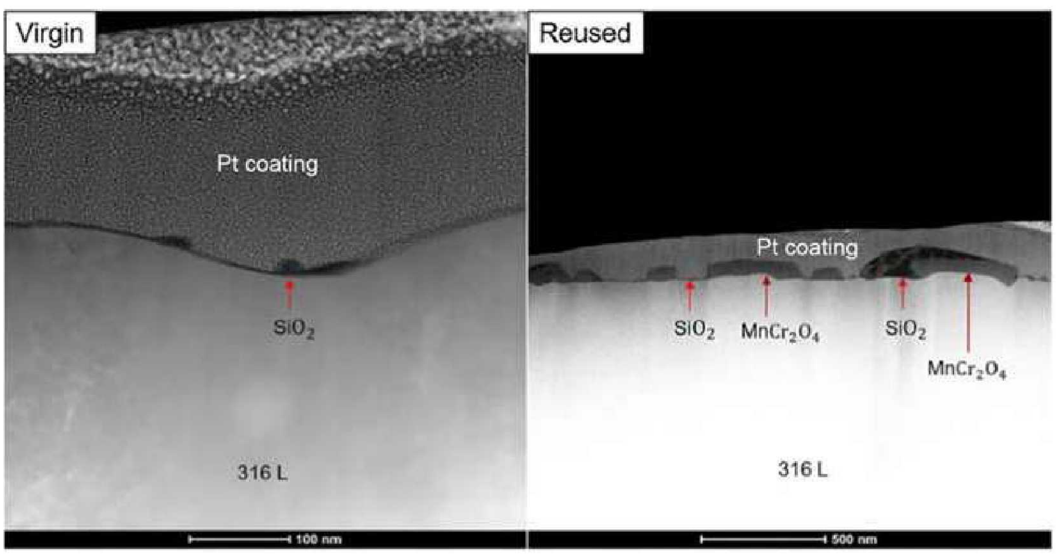

Figure 8.4 Tunneling electron microscopy images of virgin and reused 316L stainless steel particles in cross-section. The top platinum coating was used for imaging purposes [22].

tunneling electron microscopy (TEM) (Fig. 8.4). Powder atomization by the supplier is critical to powder quality as it can provide a pathway for undesired elemental diffusion into powder [23]. Nitrogen is a commonly observed species detectable through LEICO combustion analyses which can degrade the properties of some steel alloys [24] (Fig. 8.5). Spherical entrapped gas porosity (Fig. 8.6) is also commonly observed in additive

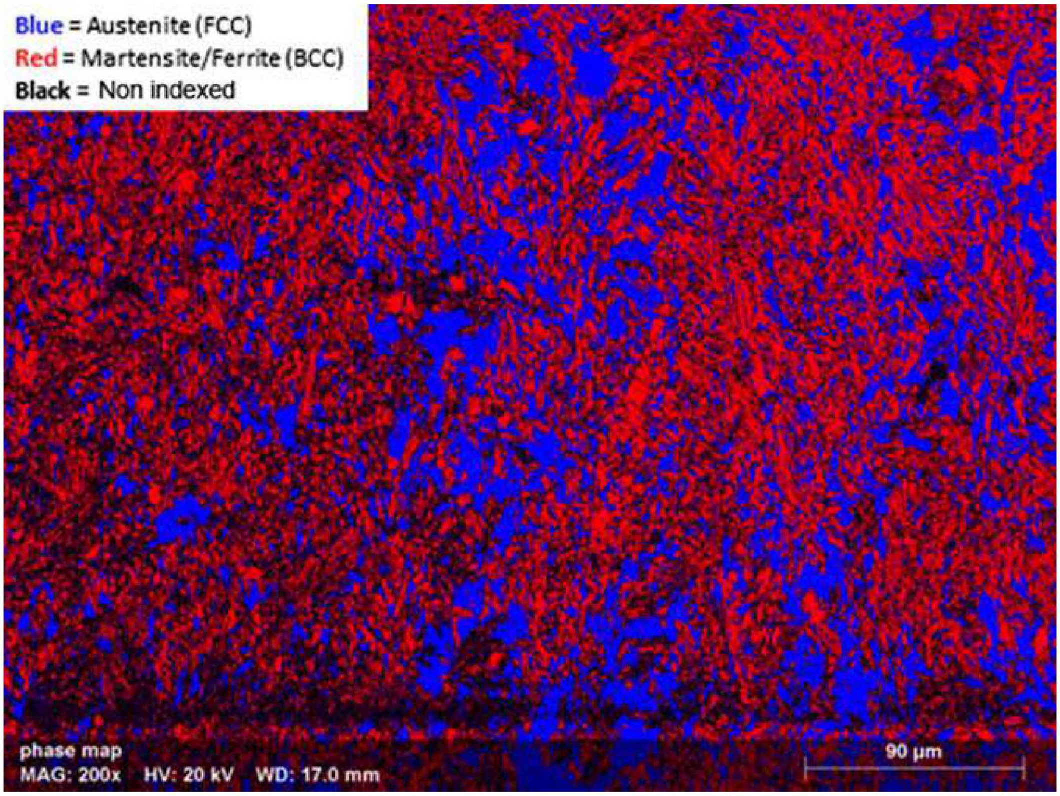

Figure 8.5 Electron backscatter detection image of 17-4PH stainless steel from laser-powder bed fusion after solution heat treatment and H900 aging. Forty-three percent retained austenite is observed due to excessive nitrogen content that increased the strength but reduced the as-printed material ductility [20].

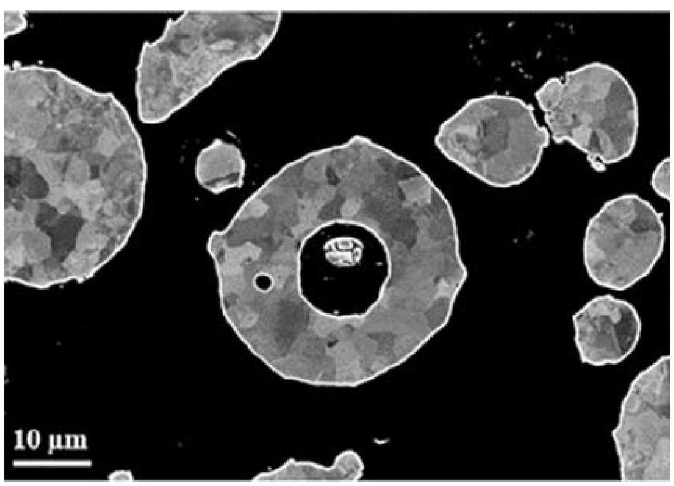

Figure 8.6 Porosity in gas atomized 316L stainless steel powder via scanning electron microscopy [22].

metals with sizes typically ranging below 10 µm [25–28]. Such porosity is formed within the powder during atomization [29] and rarely escapes the melt pool during printing. Gas porosity requires time-consuming metallography and sectioning or high-resolution computed tomography (CT) to detect in the raw powder feedstock. While its impact on printed material can be more easily identified, for example through density measurements, users remain dependent on it being controlled and minimized by the powder supplier.

Process-related defects degrade the quality of printed parts and manifest themselves in the form of cracks, part deformation, residual stress, surface roughness, and void porosity. Void porosity (Fig. 8.7) and surface roughness (Fig. 8.8) occur at submillimeter scales, while part distortion and residual stress are observed at the part scale. Extensive work exists within the literature tying void porosity and surface roughness to process parameters [30–35]. Lack-of-fusion voids represent regions containing unmelted powder which generally occur when process energy levels are

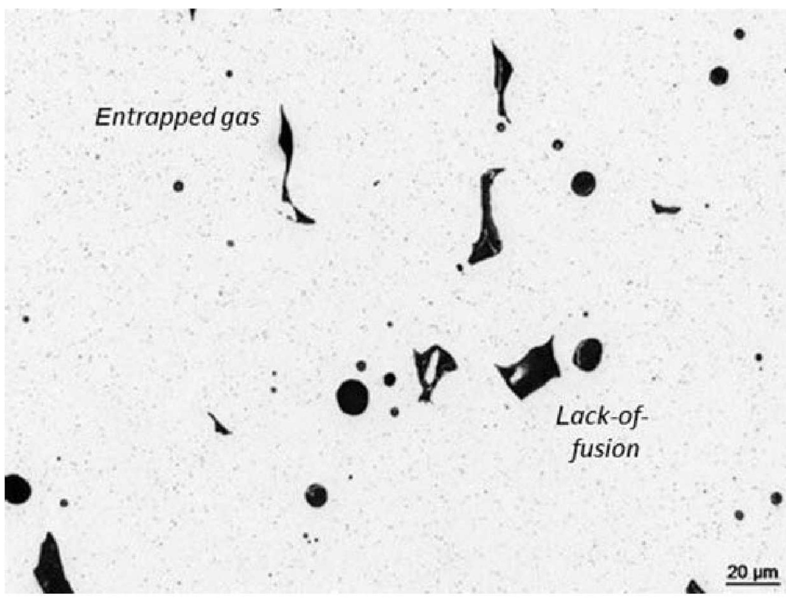

Figure 8.7 Representative lack-of-fusion and entrapped gas porosity in laser-powder bed fusion 17-4PH stainless steel [37].

Figure 8.8 As-printed 8 μm S_a rough surface of a 17-4PH stainless steel dogbone with 1 mm gauge width and 4 mm length [20].

too low, scan velocities are too fast, and/or overlapping scan paths are too far apart. Gas inclusions and key-holing are formed when excessive energy is applied to the material interaction zone due to power levels being too high or scan velocity being too slow. Studies have shown that these systematic sources of porosity can be minimized through parametric process optimization tailored to a specific printer and feedstock [26,36]. Surface roughness of as-printed parts is driven by similar phenomena as internal voids. Because the boundary conditions at the surface are different, however, process conditions optimized for minimal internal porosity differ from those necessary for minimal surface roughness. Internal material stresses can produce part distortions which exceed geometrical tolerances and/or require extensive postmachining. The presence of residual stresses can also limit part performance by reducing the external load at which failure occurs.

Another challenge for metal AM is that dynamic process disturbances can move process inputs away from an optimal regime resulting in localized defects. Examples of these disturbances include spatter [38], powder feed errors (e.g., short feeds) [25], layer thickness variations, powder variations, and machine drift (i.e., changes in the operating environment or energy source). Part geometry, feature size, build orientation, and the presence of surrounding parts are also influences that must be considered. Variation of these sources within a single build, within multiple builds, across similar machine models, and across different OEM machine platforms leads to the lack of consistency commonly observed in additive materials and highlights the challenges that must be addressed to insure material quality.

A final source for defects in additive metals is postprocessing. Steps such as postmachining, surface finishing (e.g., bead blasting or tumble polishing), cleaning and heat treatment generally improve part and material properties. Care must be taken, however, to ensure that contamination residues (e.g., machining oils) do not remain on part surfaces. Polishing media (e.g., grit blasting) have also been discovered on part surfaces, embedded due to excessive impact energies. While each of these processes is widely utilized in the context of traditional fabrication processes, work must be performed to insure compatibility with additively manufactured materials and processes.

While defects are commonly found in metal additive parts, an important question to be answered is which defects are critical, that is, which defects control or limit material performance? Follow-on questions then must be answered in the context of qualification and product acceptance for the desired application. How do defects impact the product performance? How can defects be detected, whether in-situ or ex-situ? How can defects be controlled or eliminated during printing? The behavior, formation mechanisms, and "signatures" of critical defects must also be quantified to facilitate efficient identification and characterization. In the future, a detailed understanding of defects will motivate and facilitate advanced process controls to identify, correct, and reliably prevent their formation in real-time.

8.1.3 Development organizations

Multiple organizations throughout the United States and the world are working to develop methodologies, guidelines, and standards for the qualification of parts using metal AM. A majority of the leading work has been concentrated in the medical, aerospace, and defense sectors. Large global corporations [7,39–41] have invested extensive resources to understand process, materials, and part performance to reap the benefits of AM for their advanced products. Small to medium-sized companies, however, also exist to provide capabilities critical to qualification such as modeling and simulation [42–45], material testing and characterization [46,47] and contract manufacturing [48,49]. Equipment OEMs have been extensively involved in developing process and equipment capabilities, for example, in-situ process monitoring, necessary to accelerate and improve qualification activities [50–52]. A range of organizations spanning academia [53–57], government laboratories [58–64], and research institutes [65,66] are also performing research to develop the methodologies and the scientific basis necessary for qualifying metal AM products.

Companies typically hold technical capabilities and advancements internally, particularly when they provide business advantages critical to maintaining profit margins and corporate health. However, the recent, rapid progress toward the qualification of additively manufactured metal parts has occurred in part due to extensive collaborations across industry, academia, and government research labs. Many of these collaborations have occurred through mechanisms typically utilized in industrial development and academic research. In the United States, however, America Makes has served as an additional catalyst for multiparty collaborations advancing metal AM qualification and certification. America Makes was the first National Network for Manufacturing Innovation (NNMI) institute established by the US government in 2012 to increase US global competitiveness. It is a public–private partnership for innovating and accelerating additive manufacturing and 3D printing nationally, with member organizations from industry, academia, government, and nongovernment agencies [67].

An important effort for AM qualification has been the work by standards development organizations (SDO) across the globe. While many of these efforts are relatively new and incomplete, progress exists. ASTM and the International Organization for Standardization (ISO) are the most widely recognized efforts, as they have established joint standards under the activities of ASTM F42 [68] and ISO TC 261 [69]. Work is also ongoing within the American Society of Mechanical Engineers (ASME) [70], SAE International (SAE) [71], and the American Welding Society (AWS) [72]. Table 8.1 provides a summary of existing standards relevant to metal AM and their scope. SDO websites can be visited to find updates on standards in various phases of development.

Table 8.1 General standards relevant for metal additive manufacturing.

Reference number	Title
ASTM Committee F42 on Additive Manufacturing Technologies [68]	
F3187-16	Standard Guide for Directed Energy Deposition of Metals
F2971-13	Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
F3301-18a	Standard for Additive Manufacturing—Post-Processing Methods—Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion
F3303-18	Standard for Additive Manufacturing—Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications
International Standards Organization (ISO) Technical Committee 261 Additive Manufacturing [69]	
ISO 17296-2:2015	Additive manufacturing—General principles—Part 2: Overview of process categories and feedstock
ISO 17296-3:2014	Additive manufacturing—General principles—Part 3: Main characteristics and corresponding test methods
ISO 17296-4:2014	Additive manufacturing—General principles—Part 4: Overview of data processing
Joint Group ASTM F42/Joint ISO TC 261	
ISO/ASTM 52900:2015	Additive manufacturing—General principles—Terminology
ISO/ASTM 52901:2017	Additive manufacturing—General principles—Requirements for purchased AM parts

(*Continued*)

Table 8.1 (Continued)

Reference number	Title
ISO/ASTM 52910:2018	Additive manufacturing—Design—Requirements, guidelines and recommendations
ISO/ASTM 52915:2016	Specification for additive manufacturing file format (AMF) Version 1.2
ISO/ASTM 52921:2013	Standard terminology for additive manufacturing—Coordinate systems and test methodologies
SAE Aerospace Material Specifications—Additive Manufacturing Committee (AMS-AM) *[71]*	
AMS7003	Laser Powder Bed Fusion Process
AMS7005	Wire Fed Plasma Arc Directed Energy Deposition Additive Manufacturing Process
American Society of Mechanical Engineers (ASME) *[70]*	
ASME Y14.46-2017	Product Definition for Additive Manufacturing [Draft Standard for Trial Use]
American Welding Society (AWS) *[72]*	
AWS D20.1	Standard for Fabrication of Metal Components using Additive Manufacturing

8.2 Approaches

Fundamentally, qualification, certification, and product acceptance are focused on providing the body of evidence necessary to demonstrate that a product meets its specified requirements. Additive manufacturing does not change this basic premise, and therefore is unlikely to modify the phase-gate steps utilized by many organizations in their development processes. Because metal parts often cannot be tested in fully operational environments during production, a predictive capability must be established. This predictive capability is the challenge for metal AM qualification and product acceptance. It is also the motivation whereby extensive resources have been invested within the community. The rigor and acceptable margins vary with the application and the consequences of product failure. The desired end-state for qualification, however, is invariant; product margins must be quantified relative to requirements, and methods must be defined and implemented to monitor and control quality metrics during production.

Early in the development cycle, an important question to be addressed is whether a metal additive process, material, or part can be developed, qualified and produced with the available resources and timelines in a cost-effective manner. The answer to this question may be relatively easy or extremely difficult to discern and quantify. It may also not be answered completely until extensive development activity occurs. Design requirements must first be established, including tolerances and margins, for parts, materials, and processes. These can then be compared against quantified process, material and part metrics, uncertainties, and sensitivities. Subsequent methodologies for part inspection, material verification, and process control can then be identified. While multiple factors influence the viable use of metal AM for a particular product, to first order it will be based on the technical maturity of materials and processes, the level to which they have been characterized and controlled, and the subsequent uncertainties in their properties and performance.

Multiple elements must be considered during the development cycle of any metal additive product to satisfy the needs of qualification, certification, and product acceptance. Fig. 8.9 provides a schematic of these

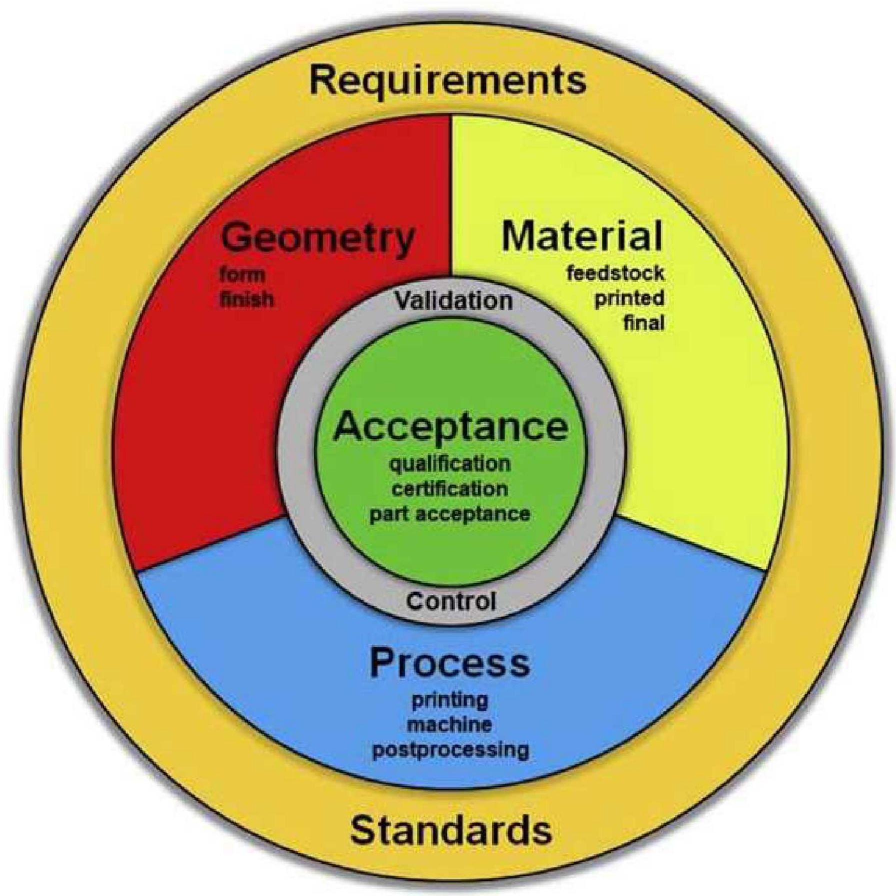

Figure 8.9 Foundational elements in qualifying and accepting additively manufactured metal parts. *Photo Courtesy: Lisa Deibler and Bradley Jared, Sandia National Laboratories.*

necessary elements which are discussed through the remainder of the chapter. Functional design requirements, associated margins and appropriate standards provide the foundation upon which the entire development cycle must be based. These requirements provide the basis for subsequent specifications of the part geometry, the part material, and the printing process which are intimately related and inextricably coupled. Geometry considers part form and surface finish. Material considerations account for feedstock requirements, printed material quality, and postprocessed properties. Process specifications encompass elements of printing, machines, and postprocessing. Validation and control methodologies must be developed to insure product quality using inspection, metrology, testing, and process controls. In most manufacturing processes, these steps are performed separately for part geometry, material, and process. This is also currently the case for most metal processes. In principle, however, this validation and control could be performed in tandem through in-situ process monitoring and control. Combining each of these elements provides the path necessary to reach the desired target, product acceptance.

8.2.1 Traditional manufacturing

The schematic in Fig. 8.9 is presented for metal additive manufacturing but also captures critical elements required in any development effort. Distinctive elements for AM are obviously those related to printing. Validation and control methodologies can also differ for more traditional process routes. Subtractive manufacturing techniques, that is, machining, stamping, and forming, decouple part geometry and material as the source feedstock can be certified prior to the formation of part geometry. Thus part performance is typically established based on feedstock quality and dimensional metrology of the part surface. Applications and industries reliant on parts produced via subtractive techniques generally face the steepest learning curves and largest barriers in transitioning to metal additive manufacturing processes.

Laser welding involves process physics similar to metal AM processes and therefore can share common elements such as process control through machine calibrations, in-situ monitoring, and process artifacts. Laser welders are familiar with the impact of both source feedstocks and process inputs on final part material. They are also accustomed to the material characterization required using destructive and nondestructive evaluation (NDE), or nondestructive testing (NDT), techniques such as snap plates and CT, respectively. Welding is distinct from metal additive manufacturing in that it does not explicitly produce part geometries, although attention is commonly necessary to limit joint distortions to satisfy assembled geometry requirements.

Casting, forging, metal injection molding, and powder metallurgy mimic metal AM in that they all form part material and geometry simultaneously. Thus they incorporate all the elements in Fig. 8.9 and provide a precedence for qualification. Structural castings, in fact, have been successfully implemented into aviation despite similar challenges with manufacturing variability, material anomalies, and the lack of predictive process and material models [73]. As a result, infrastructure does exist in some industries to develop pathways for metal AM qualification [9]. Zoning, that is, dividing parts into discrete regions with varying requirements, is one notable approach from the casting community that merits attention by metal AM designers and engineers. It eases qualification and inspection burdens by reducing tolerances on noncritical part features and subsections [73] which reduces resource allocations for less critical part zones.

8.2.2 Point design

Process complexities, the presence of defects, and the subsequent material uncertainties produced therein have motivated relatively conservative approaches for qualification to date. Efforts have relied on traditional point design or point source qualification approaches. Here development is performed to demonstrate that a single part design fabricated using a narrowly defined material and process specification meets requirements for a specific product application. The resulting qualification evidence generally has limited transferability to a new application, requirements, part, material, and/or process. Such an approach works for large-volume production runs, but it becomes prohibitive for small to medium lot quantities and applications requiring frequent product modifications, for example, repair or mass customization.

Point approaches require extensive development investment as data generated during testing and characterization must be generated with each unique product design or process change. Due to the stochastic performance observed for AM metals [19], distributions must be quantified to

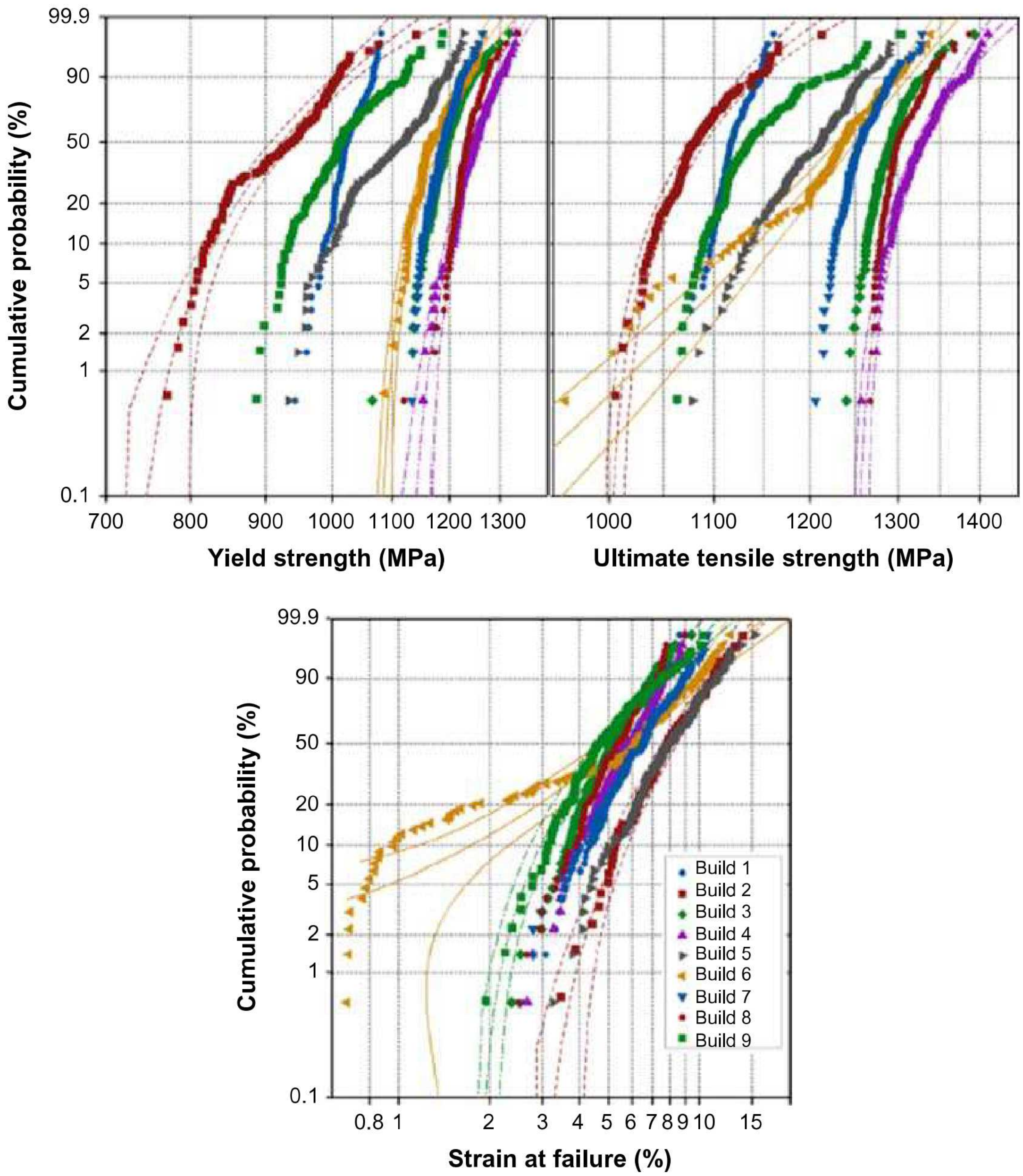

Figure 8.10 Property variations for 17-4PH stainless steel across nine different builds. Properties are plotted as Weibull probability distributions and can be fit to appropriate parameters [19].

establish design margins with uncertainties (Fig. 8.10). Current approaches require extensive testing during development which can be cost prohibitive, even when recently demonstrated high-throughput testing methods can be utilized [18]. Restrictive margins and specifications are typically applied to material feedstocks, final material, process steps, equipment settings, build layouts, and product design files as deviations are prohibited and require requalification activities within some defined quality framework. Rigorous postprocess inspection during production is generally slower, more expensive, and in some situations less precise than desired but remains common in a point design framework. The importance of process—structure—property—performance relationships (PSPP) is commonly explored by AM researchers to understand process physics and material behavior at fundamental levels [74]. While such knowledge is clearly beneficial and desirable in a point design framework, a broad, comprehensive understanding is not required for a product to be qualified.

8.2.3 Part families

Point design approaches are expected during early adoption of metal AM as companies and industries build process and material knowledge. A natural evolution is the adoption of part family qualification. Here, parts with similar functionality, material, geometrical form, inspection protocol, and process pedigree can leverage a common qualification evidence base to accelerate the development cycle [9]. While gradations can occur between point design and part family qualification approaches, a fully mature part family approach qualifies a baseline part that is representative of all other parts within the family. Full transferability of qualification evidence is then available such that any new design within the part family does not require a separate qualification effort.

8.2.4 Advanced qualification

For many applications, the full potential of metal AM is hindered by the challenges, schedules, and cost of qualification, certification, and product acceptance. To this end, researchers across the globe are working to accelerate the rate at which metal parts can be developed and deployed for a wide range of applications and industries. Varied terms are used to describe these advanced approaches such as rapid qualification [75], accelerated certification [58], Born Qualified [76], Quality Made [77], model-based qualification [9] and science-based qualification [78]. Regardless of the nomenclature, these advanced approaches strive to generate a predictive capability whereby qualification evidence, process definition, material properties, and part performance can be generated, validated, and qualified accurately, rapidly, and cost-effectively.

The foundational elements of Fig. 8.9 are unchanged in any advanced qualification methodology. The paths by which these elements are developed and validated, however, are different. The underlying foundation for advanced qualification is an enhanced scientific understanding of metal additive process physics, material properties, and part performance, that is, PSPPs. These PSPPs are necessary to develop part processes, material, and geometry in an integrated manner consistent with the physical couplings that exist in metal additive processes. As a result, part and process optimization can be performed, process sensitivities can be characterized, and margins can be quantified. Therefore part design and process development can be realized quickly and reliably to meet product requirements without costly design-build-test iterations.

Process complexities prohibit a singular reliance on empirical methodologies for quantifying PSPPs due to cost, both in time and expense. Instead, modeling and simulation tools are required. A comprehensive Integrated Computational Materials Engineering (ICME) based approach has been proposed [82] that captures process and material physics across multiple spatial and time scales. Process models must capture the physics and process—structure relationships associated with feedstock delivery, material melting, melt pool interactions, and material solidification to provide a comprehensive capability for process optimization. Models at the material interaction scale, typically tens of microns to millimeters, are necessary to define process conditions that mitigate and minimize defect formation [14,83]. Part scale models are focused on predicting residual stresses, distortions, and potential build failures, but can also be coupled to thermal-mechanical models to predict material microstructures [84,85].

Part scale performance models can be implemented at three levels of maturity, sophistication, and accuracy. The first is a finite element analysis continuum model that utilizes experimentally derived bulk material properties. These properties can be implemented as discrete values, for example, modulus or yield strength, or as response curves, for example, an engineering stress—strain curve. A second level of model complexity is to incorporate material defects, predominantly porosity voids, into part models (Fig. 8.11). The impact of defect distributions can then be explored during development to define margins, product defect tolerances and/or inspection criteria. Determining these quantities experimentally can be both expensive and difficult, so computational tools are extremely

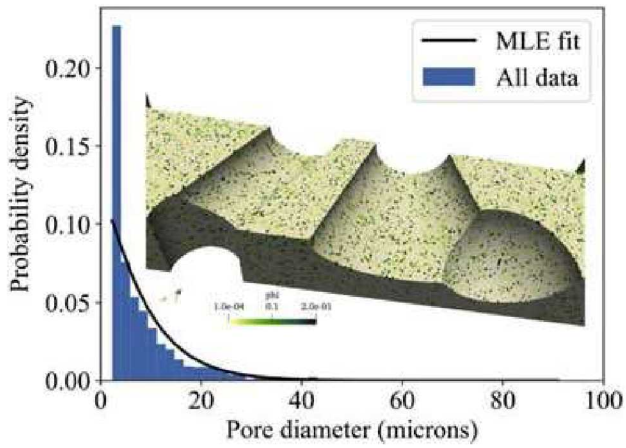

Figure 8.11 Integration of a pore probability function onto part geometry for a performance load simulation [86].

valuable and desirable. Material models, if executed quickly and efficiently, could also be useful in production if part pore structures from CT could inform a part model to predict expected product performance. A final level of model fidelity captures material microstructure at relevance scales. Such models more accurately predict material and part performance by incorporating porosity, grain structure, inclusions, phases, and other contributions to material behavior [87]. This capability would be enabling for a grand vision of material and alloy design that would push materials and parts into regimes inaccessible through conventional means. Further, a more holistic design and fabricating paradigm would couple these advanced material models with process models and computationally based design optimization tools [79] (Fig. 8.12). These model elements are all relatively expensive computationally, so combining them requires research to dramatically increase computational efficiency [88].

Regardless of the design and development approach, product validation and acceptance remain critical for metal additive processes, particularly for high-consequence applications. Nondestructive techniques, both in-situ and ex-situ must be advanced to facilitate rapid, accurate, and reliable screening, metrology, in-process monitoring, and process control. Standards must be developed to ensure that material and process specifications are trusted and relevant for qualification activities. Data management and analytics are also important topics. The ability to rapidly fabricate parts with varying pedigrees, and the wide range of inputs associated with these variants highlight a need for databases and product management. Solutions may be internally [89] or commercially based [90], but they are crucial to a robust

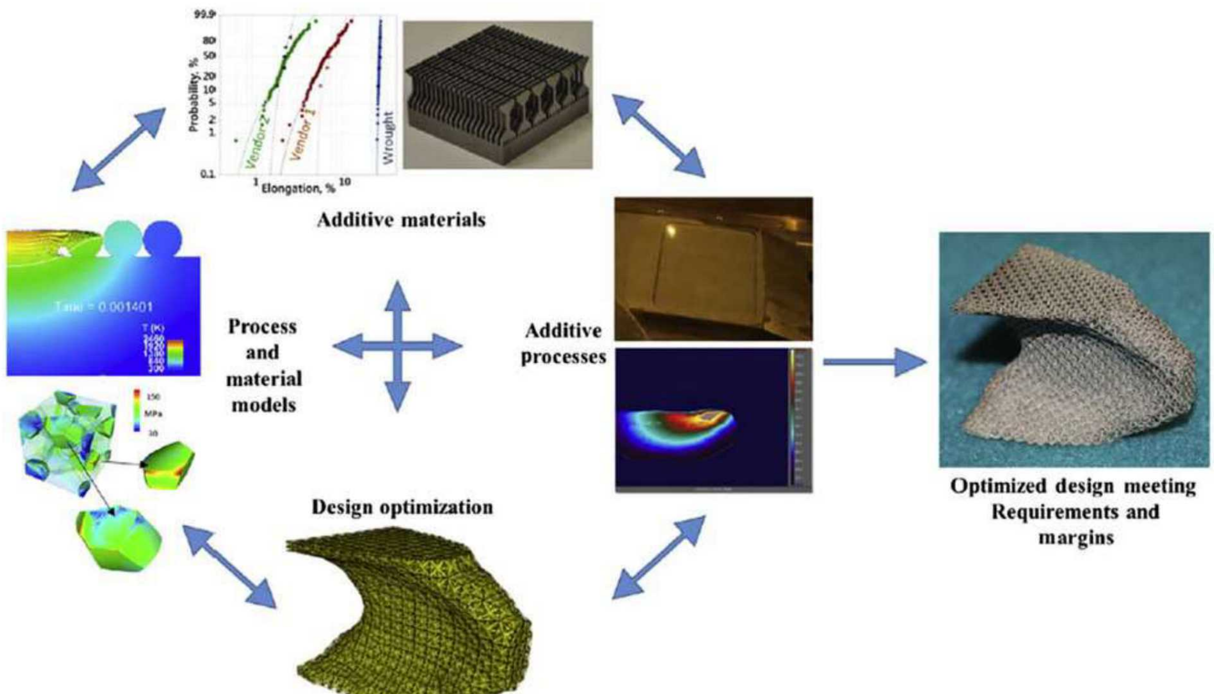

Figure 8.12 Schematic for advanced qualification incorporating elements of computational models, design optimization, process optimization, and material awareness [79].

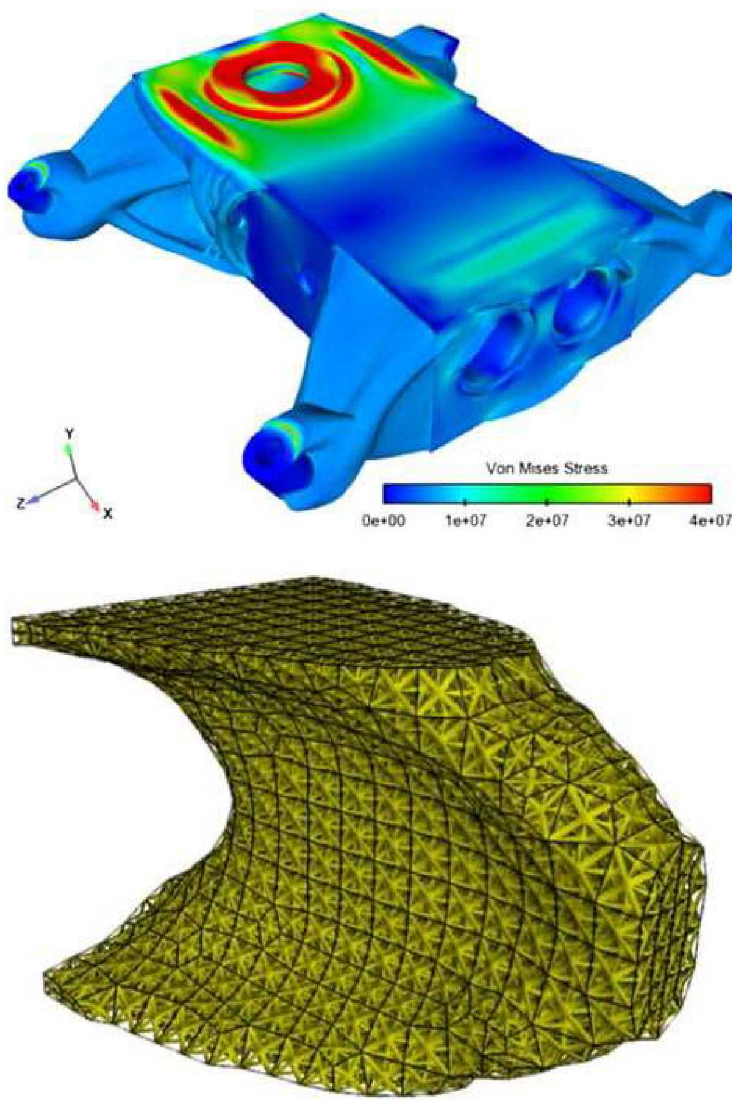

Figure 8.13 Housing designed using topology optimization with optimized stiffness to minimize vibration modes and amplitudes (left) [81]. A three-dimensional Mitchell structure designed with tetrahedron lattices (right) [80].

development and production environment. The presence of large datasets whether for design files, computational models, in-process data streams, or postfabrication inspection further taxes existing data infrastructures. Any advanced qualification methodology must advance the techniques and tools necessary to address each of these challenges.

8.2.5 Design for qualification

The complexity and freedom afforded by metal AM is a strength frequently cited and applied within the context of design function and design for manufacturing. Designing in light of qualification and acceptance criteria, that is, design for qualification [91], however, is an additional consideration for the development cycle. Requirements at system, component, and part levels must all be considered and managed with attention to uncertainties and margins. Engineers, particularly those in the aerospace sector, are familiar with managing the impacts of randomly distributed material defects and other stochastic performance phenomena. Knockdown factors [92], probabilistic damage tolerance analyses [73,93], risk-based frameworks [75] and uncertainty quantifications [94] represent common approaches. While necessary and important, these steps are typically viewed as reactionary and suggest barriers to qualification, particularly in the context of traditional design methodologies.

One qualification advantage for additive manufacturing is its ability to combine multiple parts into an integrated single part. If done properly, this can trade system complexity for material complexity and reduce the overall qualification burden. Another positive and proactive approach is to couple design requirements and uncertainties with process and design optimization tools, for example, topology optimization (TO), to generate a holistic design framework whereby parts are essentially qualified during design [79] (Fig. 8.12). While a future, forward-reaching objective for the research community, such a capability would radically reduce development time and cost, transform the design space, and provide product designs known to meet requirements with margins in the presence of uncertainties.

8.3 Function

8.3.1 Design requirements

Design function is the highest requirement level applied to a system, component, or part and it establishes the basis for all other specifications guiding geometry, material, process, and validation. While functional requirements drive other specifications, the structures and materials available through metal AM can provide a path to functionalities that cannot be achieved through traditional means. Thus requirements and AM process outputs can constrain one another consistent with the general activity of design, that is, to *define a component, system, or process that will optimally perform a specialized task subject to constraints* [95]. Operational functions typically dominate product requirements, but cost, reliability, manufacturability and reusability are additional factors that must also be considered during design.

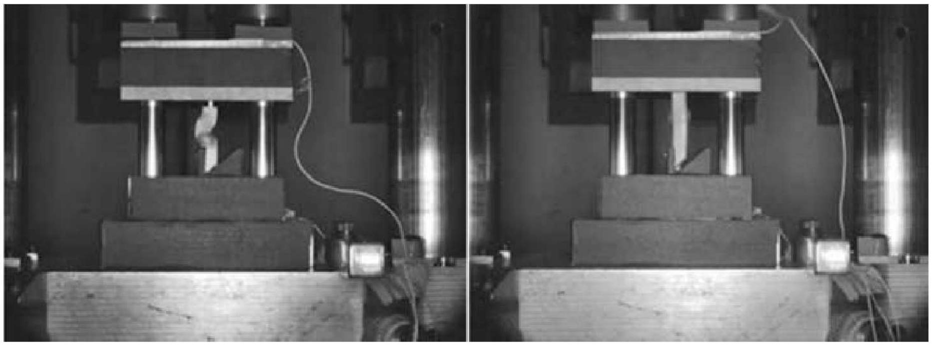

Figure 8.14 Impact testing of a hollow metal housing. The one-piece additive design (right) is both lighter and stronger than the conventional two-piece machined and welded design (left). *Photo Courtesy: Sandia National Laboratories.*

8.3.2 Performance evaluation

Functional requirements are commonly provided in an initial, sometimes notional, form during the early conceptual design phases of product development. An important aspect of development, therefore, is to refine and define these requirements based on operating environments, life cycles, margins, and uncertainties. Depending on the criticality and understanding of part performance, establishing and verifying design performance can span a range of difficulty and cost. Regardless of the scale, evaluations typically involve experimental testing, material and part characterization, and/or simulations. Coupling testing and characterization with simulations can be particularly beneficial as results can be used to validate and/or improve model outputs. Subsequently, simulations can then be performed more quickly, more efficiently, and less expensively to provide faster design iterations and quantification of margins.

Performance testing can span a wide spectrum of activities, but is intended to examine system, component, part, or material behavior under relevant environments. These environments impart loads that can be mechanical (e.g., shock, vibe) (Fig. 8.14), thermal (e.g., high temperature), electrical (e.g., voltage, current), magnetic (e.g., magnetic fields), chemical, or biological in nature. Environments can also be cyclic, for example, fatigue, or time-dependent, for example, corrosion. Ultimately, operational tests are performed to validate product performance and/or to quantify margins.

8.3.3 Product acceptance

Qualification challenges in development are a commonly cited barrier to the wider adoption of metal AM processes. Insuring product quality in production, however, is no simpler or easier a task. Because production part counts can greatly exceed that of development, it is not unreasonable to claim that product acceptance may be the more daunting challenge. This is particularly true for high-consequence applications where it is necessary to positively prohibit the acceptance of parts that do not meet requirements.

Ideally, functional tests in representative operating environments would be exercised to insure the performance of every part in production and eventual use. Such testing, however, is rarely reasonable due to cost, schedule, test, and measurement capabilities, or the potential to damage product prior to delivery. Therefore alternate, orthogonal tests and characterization steps are performed during production to provide a rigorous and comprehensive evaluation of part quality [96]. Acceptance criteria are critical as production tests must provide a predictive evaluation of material and part performance. Part acceptance criteria and the consequences of parts failing to meet these criteria are generally established during development; hence the burden of proof occurs during qualification. This explains, in part, the pervasive focus on qualification across metal AM applications.

Tests on production parts are a common and important approach for metal AM parts. If design loads are below damage thresholds, for example, yield strength, then nondestructive proof tests can be performed on every part. Capturing a load curve during testing can identify defective parts due to the presence of gross defects. Destructive lot sampling can also be performed on a limited number of sacrificial parts. Such testing is presumed to capture global process failures where shifts in material feedstock or process inputs have moved outside acceptable process boundaries. Important questions to be resolved during development include the number, frequency and selection criteria of parts to test, for example, one part per build plate at a random build location. Inherent to these criteria is an understanding of part similitude, that is, how well a sacrificial part represents or predicts the behavior of other parts in the build cycle.

8.4 Geometry

8.4.1 Requirements

Geometrical complexity is a hallmark for any AM process, and metal AM is no exception. Tolerances for AM parts are analogous to those for conventional geometries and represent essentially two length scales; dimensional form or geometric accuracy, and surface finish. Achievable form and finish tolerances vary with the process and the material, but they more closely meet the net shape and finish of casting than the precise geometries and finishes of subtractive machining. Design tolerances for metal AM are commonly captured and communicated similar to conventional designs, within the 3D CAD model itself or on a representative two-dimensional (2D) drawing. Distinctive to AM, however, are internal and re-entrant features, computationally optimized topologies and architected materials (Fig. 8.13). The freeform nature of these topographies can rarely be represented by relatively simple shapes such as planes or cylinders; and their inherent complexity prohibits their representation in 2D drawing forms. Form callouts do exist within the standard geometric dimensioning and tolerancing (GD&T) system, so a new dimensioning and tolerancing framework is not necessary. The design of dimensional tolerances on freeform topology and architectured surfaces, however, is poorly understood and much less intuitive than conventional tolerance callouts such as flatness, cylindricity, or parallelism. Thus designers and process engineers must work together to ensure that design intent is accurately specified, communicated and achieved.

Commercially available metal machines utilize CAD models to represent part geometry and to establish process sequences. Thus a model-based manufacturing infrastructure must be implemented from development across to production to manage and control geometry specifications and datasets. Part geometry must be specified through the CAD model, most commonly in a format compatible with current CAD software packages. Topology optimized geometries and architectured materials, however, can rely on different formats, most notably level sets [97] and beam-based representations [98], respectively. File sizes can also become large for these advanced topologies, presenting challenges for file storage, transfer, manipulation, and translation across networks and software platforms.

8.4.2 Dimensional metrology

Inspecting and verifying part geometry is a well-known art. Dimensional metrology, however, has historically focused on quantifying the accuracy and finish of external part surfaces (Fig. 8.15). Hard gauges, calipers, micrometers, height gauges, measuring microscopes, structured light scanning, form interferometers, and coordinate measuring machines are all used in production environments to inspect part shapes and to ensure that they meet dimensional tolerances. Similarly,

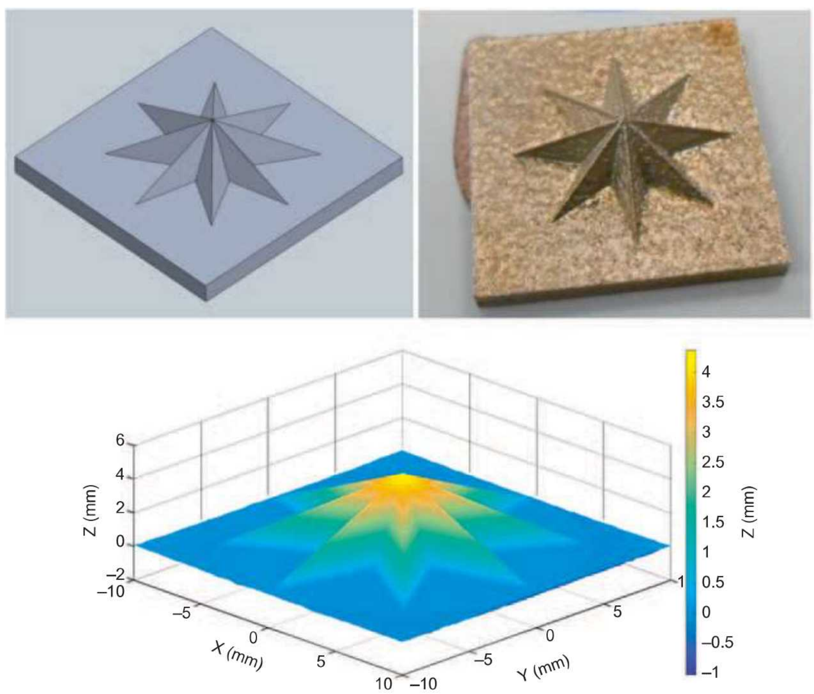

Figure 8.15 Three-dimensional Siemens star design (top left) printed in 17-4PH stainless steel by laser-powder bed fusion (top right) whose surface topography is measured by fringe projection microscopy (bottom) [99].

stylus profilometers, optical profilometers, structured light scanners, and interferometers are commonly used to measure part surface finish. Thus the geometry of metal AM parts with accessible surface features can be quantified by a variety of existing techniques. The availability of these measurement techniques, however, does not preclude the costs associated with their use. While the minimal cost of complexity in printing additive parts represents a radical paradigm shift for manufacturing processes [8], part complexity still increases the time, cost, and difficulty associated with inspection and metrology. This reality must be understood and addressed during qualification as it is critical to product acceptance, and in some situations may render development or production activities impractical or impossible.

Internal, re-entrant, and architectured structures provide compelling advantages for features associated with light-weighting or conformal channels. Such geometries, however, cannot be measured using traditional dimensional metrology methods. Instead they must rely on destructive characterization, that is, serial sectioning, or radiation-based techniques, that is, CT [100–104], radiography [82], or neutron diffraction [105]. Destructive sectioning can be useful during development, although it is typically utilized to understand material microstructure and not part geometry. Radiation techniques are much more suited to product acceptance because they do not destroy parts intended for product, and they can access internal volumes and features. Neutron diffraction is a valuable research tool for development, but remains impractical for product acceptance due to its long measurement times, low resolution, and excessive equipment costs.

Radiography and CT (Fig. 8.16) represent much more viable routes for characterizing internal part geometries, and they are being explored extensively throughout the metal AM community. They traditionally have focused on identifying part defects such as cracks, inclusions, and porosity. The recent growth in AM and the introduction of complex parts with internal features and architectured structures, however, has motivated the application of these techniques to dimensional metrology. As such, measurement techniques, hardware capabilities and analysis software are developing. Critical challenges include the management of large datasets, analysis algorithms for extracting dimensional quantities of interest, limited reference standards, and establishing a traceable path for quantifying measurement uncertainties.

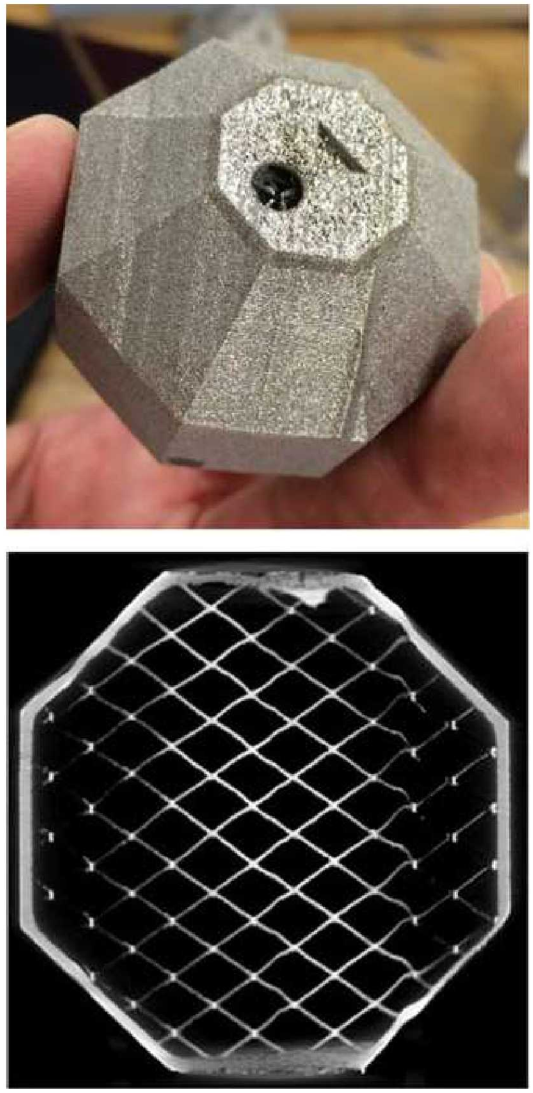

Figure 8.16 Hollow 26-sided, 43 mm wide polyhedron printed in Inconel 718 using laser-powder-bed fusion (left). Computed tomography of the part interior after powder removal (right) showing the internal support structure and wall thicknesses.

8.4.2.1 Standards

Dimensional metrology of part surfaces is a mature field [106] as numerous standards exist relative to measurement techniques, analysis methods, and uncertainty quantifications. ASME Committee B89 provides a host of standards for dimensional form metrology which covers topics including length, geometry, coordinate measurement technology, general principles, environment, and measurement uncertainty [107]. Similarly, ASME Committee B46 has developed standards for the designation and measurement of part surface finish [108], including AM topographies [109]. CT and structured light scanning are relatively new metrology techniques that are receiving great interest and attention from the technical community due to the growth of additive manufacturing. While standards are limited and immature for these toolsets, standards bodies are active and working to resolve gaps and issues [103,110].

8.5 Feedstock

8.5.1 Requirements

Feedstock quality is extremely important as it forms the foundation for printed material. Feedstock defects are rarely consumed during printing, but tend to manifest themselves as defects in the printed part. Thus quality parts require quality feedstock material. Metal AM feedstocks come in three primary forms; powder, wire, and sheet. Powder is used in PBF, DED, and binder jetting. Wire stock is used in multiple deposition-based processes which include wire and laser AM (WLAM), electron beam free-form fabrication (EBF^3), and wire-arc AM (WAAM) [111]. Sheet stock is used in metal sheet lamination or ultrasonic additive manufacturing (UAM). Challenges vary across feedstock forms and alloys, but requirements can broadly be classified around composition, geometry, and dynamic behavior. These requirements should be established during development and qualification. Further, they must be defined concurrent with process development and part performance validation activities due to the intimate coupling between the feedstock, the additive process and the final part properties.

Composition specifies alloy constituents, ratios, and phase fractions. Inhomogeneities are often generated during feedstock formation, requiring appropriate specifications and control for feedstock production. Feedstock contamination can be found on surfaces (e.g., oxides), inside the bulk (e.g., inclusions or gas-trapped porosity), or as individual foreign particles in the case of powders. They can form or be introduced during production (e.g., excessive nitrogen), storage (e.g., humidity or oxides), handling (e.g., foreign particles), or conditioning (e.g., sieving, riffling, or heat treatment). Contamination can also occur during printing through the introduction of spatter particles [22] or machine contaminates. Specifications must establish the acceptable types and levels of feedstock contamination, as well as mitigation procedures for their prevention during production, handling, storage, conditioning, and reuse. Composition can be specified based on standards (Table 8.2), commercially available

Table 8.2 Available standards for metal AM powder specification.

Reference number	Title
ASTM International Committee B09 on Metal Powders and Metal Powder Products [112]	
B243-19	Standard Terminology of Powder Metallurgy
SAE Aerospace Material Specifications—Additive Manufacturing Committee (AMS-AM) [71]	
AMS7001	Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 62Ni−21.5Cr−9.0Mo−3.65Nb
AMS7002	Process Requirements for Production of Metal Powder Feedstock for Use in Additive Manufacturing of Aerospace Parts
AMS7013	Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 60Ni−22Cr−2.0Mo−14W−0.35Al−0.03La

off-the-shelf products [113−115], or custom blends suited specifically for product application.

Metal wire and sheet are traditional material forms, so extensive standards exist for their characterization. ASTM Committee A05 on Metallic-Coated Iron and Steel Products [116] provides several examples. Material certifications are readily available from vendors as their size, that is, diameter or thickness, uniformity, and material homogeneity can be well controlled.

Feedstock geometry addresses its size and shape. For powder, this is particle diameter and sphericity; for wire it is diameter and cylindricity; and for sheet it is thickness, flatness, and parallelism. For wire diameter and sheet thickness, a single value with a tolerance is sufficient for specification due to their uniformity and consistency. Metal powder, however, is described by a distribution as it typically consists of billions of small particles, typically with diameters of tens to hundreds of microns, which are difficult to produce in a tightly controlled range. Potential distribution metrics included average particle diameter; particle size distribution (PSD) for 10% of the distribution, 50% of the distribution, and 90% of the distribution; aspect ratio and circularity. Actual size distributions can be communicated based on volume fraction or the cumulative frequency (Fig. 8.17).

The *dynamic properties* of metal AM feedstock are those associated with its motion into the material interaction zone where deposition occurs. For discrete powder, properties are related to powder rheology and are associated with spreadability (powder bed and binder jetting), flowability (DED), apparent density, and tap density [117]. For wire and sheet feedstocks, material motion is less stochastic than for powder and is influenced

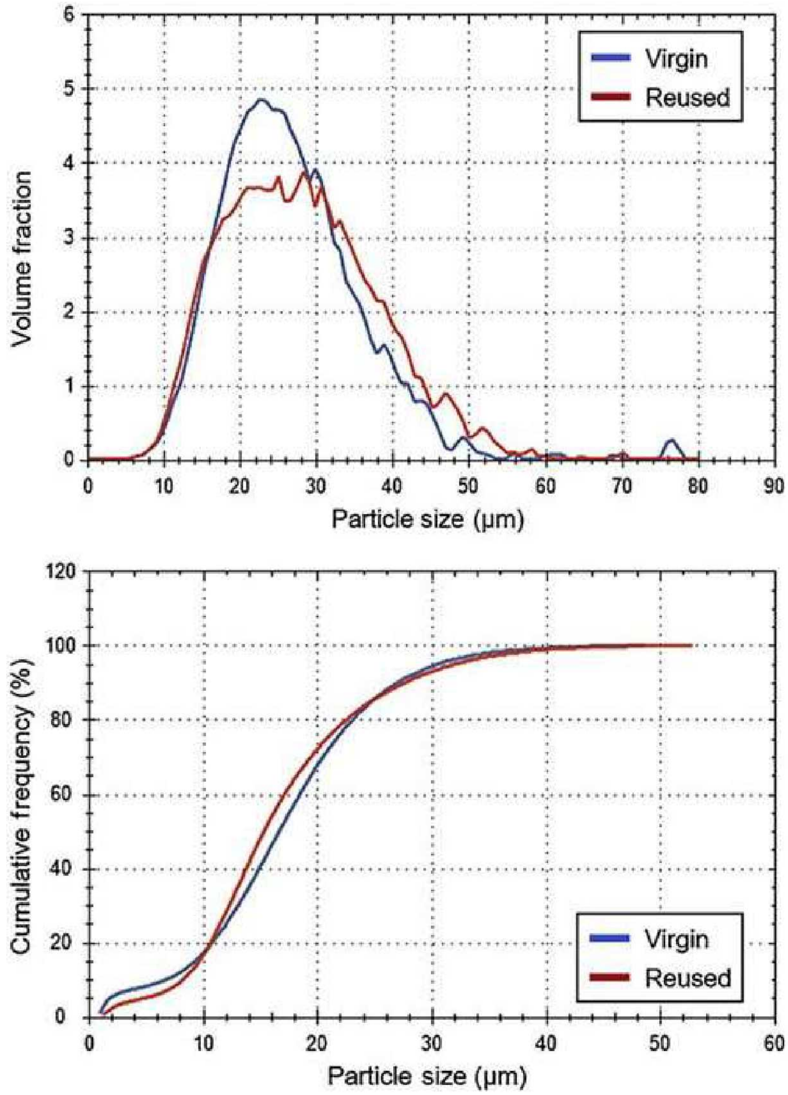

Figure 8.17 Differential size and cumulative size distributions for virgin and reused 316L stainless steel powders measured by scanning electron microscopy [22].

by feedstock stiffness and the friction conditions between sliding surfaces. Dynamic properties are ultimately determined by other properties, that is, size, shape, and composition; but are often characterized separately because correlations are difficult to establish.

An important consideration when dealing with powder feedstocks is the conditions for powder reuse, sometimes inaccurately described as recycling. Powder specifications are typically applied to incoming materials that are provided in a "virgin" or "unused" state (Fig. 8.18). An extremely conservative approach is to require the use of virgin powder from a single powder heat lot for all development and production

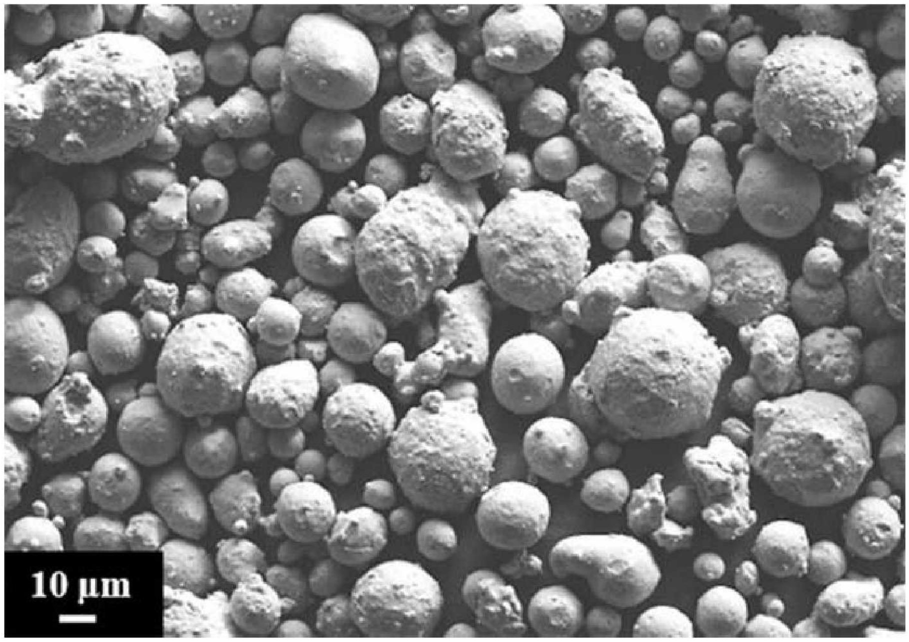

Figure 8.18 Unused 316L stainless steel powder [22].

activities. Thus the entire powder lot can be inspected, verified, and validated with a high degree of confidence that it will perform as specified. Such an approach can be extremely expensive unless the used powder can be reclaimed to build other parts with lower quality requirements. Powder can be truly recycled using spheroidization where powder shape and surface contaminants, mainly oxides, are reconditioned using inductively coupled plasmas [118]. While metal powder is known to change during printing, sieving, and handling processes [22], the rate of change and its impact on printed material and part is alloy and process specific [9]. 300 series stainless steel, CoCr and Inconel alloys, for example, have been observed to be relatively insensitive to handling and reuse cycles [9,22]. Reactive alloys such as Ti–6Al–4V [9] and Al–Si–10Mg [119] are much more sensitive to use and reuse conditions, and therefore must be handled and managed accordingly. Understanding these sensitivities and their subsequent impacts on material and part performance is critical for properly specifying powder requirements.

8.5.2 Inspection

Inspecting unused, reused, or reconditioned metal feedstocks is an important activity in development to establish specifications. It is equally important for production to ensure product quality. Sampling frequencies are driven by product margins and the rate of feedstock change during printing. At a minimum, it should be performed with each feedstock lot purchase and after reconditioning. Characterization with each reuse is recommended, although a limited inspection protocol may be implemented to reduce costs and increase throughput.

Inspection of wire and sheet feedstock is relatively straightforward since dimensions, for example wire diameter or sheet thickness, and composition can be obtained through multiple measurement technique common to conventional manufacturing processes. Powder inspection, however, requires different characterization techniques to provide complete information on composition, morphology (size, shape, distributions), rheology (flowability, spreadability, tap or apparent density), and porosity. Surface composition can be estimated using EDS [120], a technique best suited for production which is relatively quick but not highly accurate. More precise surface characterization requires TEM, Auger spectroscopy, or X-ray photoelectron spectroscopy. Techniques for bulk composition analysis include TEM, LECO furnace combustion, and mass spectrometry [22]. Powder particle sizes, shapes, and distributions can be quantified using SEM imaging [121] or laser diffraction [122,123]. Internal powder porosity can be quantified using helium pycnometry [124], Brunauer—Emmett—Teller theory [125], metallographic sampling, and CT. Powder flowability and spreadability are subjective metrics that are difficult to tie to process physics and that are widely discussed and debated within the community [126]. Regardless, the Hall flowmeter (ASTM213-17) [127], the Arnold meter (ASTM B855-17) [128], the Carney funnel (ASTM B964-16) [129], the Hausner ratio [130], and avalanche angle mesaurements [136] are each used to quantify the relative flowability of powders. There are no standard techniques for characterizing powder spreadability, although researchers are exploring potential methodologies [131—133]. Other techniques for characterizing powder dynamics focus on measuring different aspects and metrics of powder rheometry [134,135].

Multiple organizations provide specifications for powder characterization, most with roots in powder metallurgy (Table 8.3). While these specifications provide guidance, they are not necessarily adequate for metal additive processes [138]. Standards committees are developing new standards specific to the needs of metal AM powders. These include ASTM Committee B09 on Metal Powders and Metal Powder Products [112], ASTM Committee F42 on Additive Manufacturing

Table 8.3 Standards for characterizing powder feedstocks.

Reference number	Title
ASTM International Committee B09 on Metal Powders and Metal Powder Products [112]	
B212-17	Standard Test Method for Apparent Density of Free-Flowing Metal Powders Using the Hall Flowmeter Funnel
B213-17	Standard Test Methods for Flow Rate of Metal Powders Using the Hall Flowmeter Funnel
B214-16	Standard Test Method for Sieve Analysis of Metal Powders
B215-15	Standard Practices for Sampling Metal Powders
B329-18	Standard Test Method for Apparent Density of Metal Powders and Compounds Using the Scott Volumeter
B330-15	Standard Test Methods for Estimating Average Particle Size of Metal Powders and Related Compounds Using Air Permeability
B527-15	Standard Test Method for Tap Density of Metal Powders and Compounds
B703-17	Standard Test Method for Apparent Density of Metal Powders and Related Compounds Using the Arnold Meter
B821-10(2016)	Standard Guide for Liquid Dispersion of Metal Powders and Related Compounds for Particle Size Analysis
B822-17	Standard Test Method for Particle Size Distribution of Metal Powders and Related Compounds by Light Scattering
B855-17	Standard Test Method for Volumetric Flow Rate of Metal Powders Using the Arnold Meter and Hall Flowmeter Funnel
B873-17	Standard Test Method for Measuring Volume of Apparent Density Cup Used in Test Methods B212, B329, and B417
B922-17	Standard Test Method for Metal Powder Specific Surface Area by Physical Adsorption
B923-16	Standard Test Method for Metal Powder Skeletal Density by Helium or Nitrogen Pycnometry
B964-16	Standard Test Methods for Flow Rate of Metal Powders Using the Carney Funnel
ASTM Committee F42 on Additive Manufacturing Technologies [68]	
F3049 − 14	Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
Metal Powder Industries Federation (MPIF) [137]	
01	Sampling Metal Powders
03	Flow Rate of Free-Flowing Metal Powders Using the Hall Apparatus

(*Continued*)

Table 8.3 (Continued)

Reference number	Title
04	Apparent Density of Free-Flowing Metal Powders Using the Hall Apparatus
05	Sieve Analysis of Metal Powders
28	Apparent Density of NonFree Flowing Metal Powders Using the Carney Apparatus
32	Average Particle Size of Metal Powders Using Air Permeability
46	Tap Density of Metal Powders
48	Apparent Density of Metal Powders Using the Arnold Meter
53	Volume of the Apparent Density Cup—Hall/Carney Apparatus

Technologies [68], ISO Technical Committee 261 Additive Manufacturing [69], SAE Aerospace Material Specifications—Additive Manufacturing committee (AMS-AM) [71], and the Metal Powder Industries Federation (MPIF) [137].

8.6 Material

8.6.1 Requirements

Material requirements for any product are driven by design function. While metal AM does not alter this principle, it does change the way materials are produced and their resulting properties. AM metals differ from traditional forms with equivalent alloy or chemical composition as they possess unique microstructures and defects. AM metal properties are also sensitive to the input feedstock, printing conditions, part geometry, and postprocessing steps. Therefore a vital component in development and qualification is to quantify and optimize part properties, often through extensive material testing and characterization. This is particularly true for the use of new alloys and processes.

Property requirements for metal AM products parallel those for traditional metals. Structural mechanical properties include density, modulus of elasticity, yield strength, ultimate tension or compression strength, torsion strength, hardness, ductility, fracture toughness, fatigue strength, and creep. Surface properties may include wear resistance and coefficient of friction. Thermal properties for consideration are thermal conductivity, specific heat, coefficient of thermal expansion, emissivity, and the solidus or liquidus temperatures. Electrical properties may consider electrical conductivity, dielectric breakdown, and contact resistance. Potential reliability and aging needs include corrosion resistance and chemical compatibility. Property anisotropies cannot be ignored for AM metals, neither can variations with part geometry and feature size. Temperature and strain rate effects must also be quantified for the product application.

A fundamental challenge in the qualification and acceptance of metal AM parts is the uncertainty associated with structural mechanical material properties. AM metal deviations are influenced by multiple factors including process instabilities, feedstock variations, and defect structures. Because process boundary conditions and thermal histories vary throughout a part build, as-printed material properties can also vary within a part. Subsequently, material behavior can vary widely and appear stochastic in nature. Qualification activities must be aware of these uncertainties and attempt to quantify and account for them. The number of parts fabricated and tested during development is typically in the tens to a hundred. The number of parts produced and delivered as product can be much higher, hundreds to thousands or more. The probability of failure is therefore different in the two populations, a reality that must be understood and addressed during qualification and design. Mean or even minimum property values observed during testing may not be adequate, particularly if test lot sample sizes are small. Statistically relevant minimum thresholds, for example, the Weibull threshold, should be utilized based on test sample quantities adequate to define accurate distributions [18] (Fig. 8.19).

A major contributor to the variation of AM metals is the presence of defects in forms that include voids, cracks, inclusions, microstructure variations, and surface irregularities. The uncertainties involved in AM metal properties can be quantified and therefore reduced if defects critical to product performance can be identified, if their impact on properties can be quantified, and if detection methodologies can be implemented to quantify and characterize them during production. Analogous work has supported the casting industry [140,141]. Defect size, shape, orientation, location, and neighboring defects are all important to material and part quality. While gross defects intuitively degrade part performance, a large number of smaller defects can also have a large impact on material response [119]. Extensive work has been done in the aerospace industry where defects are known to degrade fatigue strength [142,143]. As with other aspects of metal AM, defect impacts on material behavior is complex and difficult to characterize in isolation. Valuable trends, however,

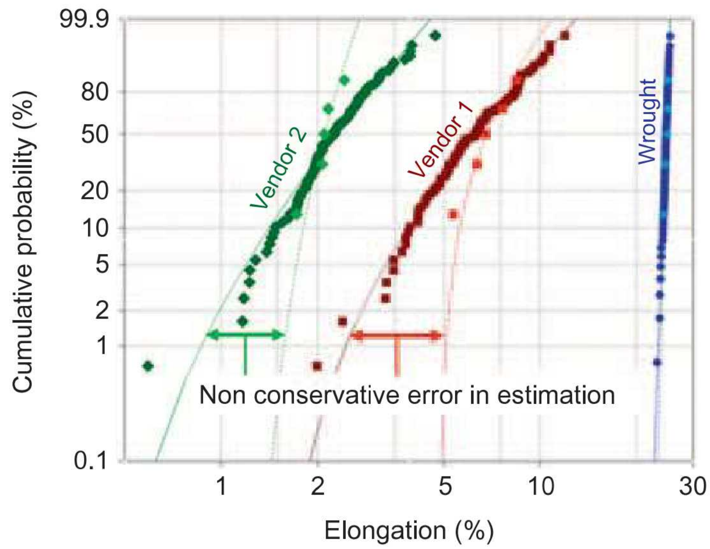

Figure 8.19 Comparison of the statistical inference from only five samples (*dashed line*) compared to 99 samples (*solid line*) for 17-4PH stainless steel from laser-powder bed fusion. Weibull fits from five samples produce nonconservative estimates of the lower tail of the distribution [139].

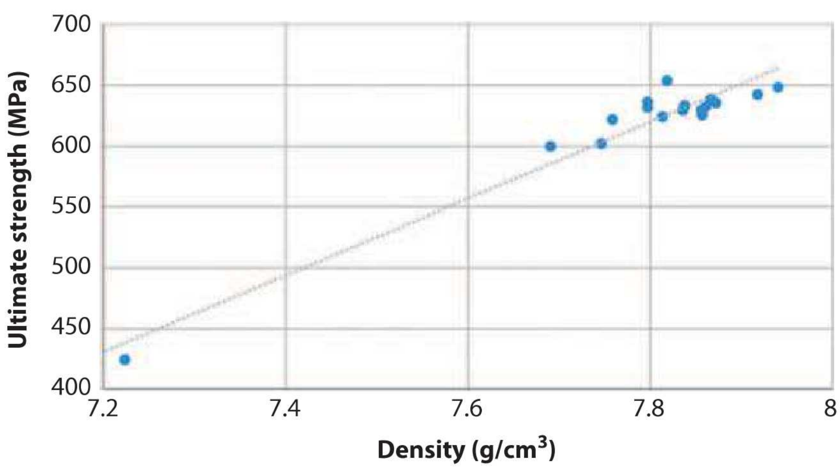

Figure 8.20 Impact of material density on ultimate tensile strength for 316L stainless steel from laser-powder bed fusion. Each data point represents the average of 25 samples.

can still be generated describing how material properties, for example, ultimate strength, vary with an average bulk defect measurement, for example, Archimedes density (Fig. 8.20). Using such information, defect requirements can be established for inspection, qualification, and product acceptance.

The introduction of engineered materials with unique material complexity, for example, gradients, represents an exciting advance in AM metals with potential that remains largely unexplored. Establishing, communicating, and verifying specifications for these constructs are also largely unexplored, and represent a paradigm change for material specification that must be addressed. Requirements will certainly be crafted based on the application, and could be defined spatially or based on some measurable functional output.

A widely acknowledged gap for AM metals has been the lack of standards within the community, both in the United States and internationally. While guidance and standards have been in place for feedstock materials from their use in powder metallurgy, this is not the case for printed materials. Organizations have been forced to generate and rely on internal specifications during development and qualification activities. While this is acceptable for large institutions with large research and development budgets, the lack of standards is a significant barrier for smaller companies. The landscape is changing, however, as standards are being released and more are being developed. ASTM Subcommittee F42.05 on Materials and Processes is a leader with released specifications for multiple materials using laser and electron beam-powder bed fusion (L-PBF and E-PBF respectively) [144] (Table 8.4). These standards provide guidance on component classifications, feedstock, microstructure, mechanical properties, chemical composition, and inspection. ISO TC 261 does not have standards released at the time of writing, but it is developing joint standards with ASTM on finished part properties for metal L-PBF [145]. SAE AMS-AM has standards released for DED and L-PBF (Table 8.4). It also has standards in development at the time of writing for laser and plasma arc DED of Ti–6Al–4V, E-PBF of Ti–6Al–4V, and L-PBF for 17-4PH stainless steel [71].

8.6.2 Inspection

8.6.2.1 Destructive evaluation

Inspecting AM metals is a fundamental challenge prevalent across multiple applications and industries. Destructive testing is a powerful method for characterizing materials that can explore properties and structures at multiple length scales. Digestion processes (e.g., mass spectroscopy, combustion, laser-induced breakdown spectroscopy) are capable of capturing bulk compositions and impurities. Metallography can be performed using optical microscopy, SEM, and TEM to capture microstructural information such as grain size, grain shape, crystal texture, dislocation density, alloy segregation, cold work, and porosity. Mechanical properties are most accurately determined using a tensile, compression, or torsion test to

Table 8.4 Additively manufactured metal material specifications.

Reference number	Title
ASTM International Committee B09 on Metal Powders and Metal Powder Products [112]	
B311-17	Standard Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity
ASTM Committee F42 on Additive Manufacturing Technologies [68]	
F3122-14	Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes
F2924-14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
F3001-14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
F3055-14a	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
F3056-14e1	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion
F3184-16	Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion
F3213-17	Standard for Additive Manufacturing—Finished Part Properties—Standard Specification for Cobalt-28 Chromium-6 Molybdenum via Powder Bed Fusion
F3302-18	Standard for Additive Manufacturing—Finished Part Properties—Standard Specification for Titanium Alloys via Powder Bed Fusion
F3318-18	Standard for Additive Manufacturing—Finished Part Properties—Specification for Al–Si–10Mg with Powder Bed Fusion—Laser Beam
SAE Aerospace Material Specifications—Additive Manufacturing Committee (AMS-AM) [71]	
AMS4999A	Titanium Alloy Direct Deposited Products 6Al-4V Annealed
AMS7000	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Nickel Alloy, Corrosion and Heat-Resistant, 62Ni–21.5Cr–9.0Mo–3.65 Nb Stress Relieved, Hot Isostatic Pressed and Solution Annealed
AMS7004	Titanium Alloy Preforms from Plasma Arc Directed Energy Deposition Additive Manufacturing on Substrate, Ti–6Al–4V, Stress Relieved
Metal Powder Industries Federation (MPIF) [137]	
67	Sample Preparation for the Chemical Analysis of the Metallic Elements in PM Materials
69	Determination of the Porosity in Powder Metallurgy Products Using Automated Image Analysis

quantify modulus of elasticity, yield and ultimate strength, ductility, and work hardening. Three-point bend tests provide similar properties under flexural or bending loads, while Charpy testing yields impact and fracture toughness behavior. Hardness testing provides a useful characterization of material yield strength. It is performed at a local scale and therefore may be destructive or nondestructive based on the part application and test region. These techniques, and others, are extremely important for metallurgists to characterize and understand the fundamental behavior of additive metals. However, they are typically relegated to development activities as they consume the part and material under interrogation. These techniques can be utilized as aspects of production acceptance, but they must be performed on witness artifacts or sacrificial part samples. Establishing similitude and correlation to the performance of other parts from a process then becomes a priority during development.

8.6.2.2 Nondestructive evaluation

Destructive testing of AM metals is extremely informative for material scientists and engineers, but it is impossible for product acceptance, other than in evaluating lot samples and witness artifacts. In its stead, NDE methodologies are necessary to detect critical defects in printed products. The NDE community is relatively mature with a multitude of techniques available for material inspection. ASTM International Committee E07 on Nondestructive Testing [146] is the primary standards body for NDE, and has a host of standards related to the techniques discussed below. While these standards are not specific to metal AM, they are extremely valuable and should be evaluated during development and qualification.

NDE is common in the casting industry, so a range of techniques already exists to identify defects in additive metals. Methods generally rely on defect "signatures," wherein some sensor response varies in the presence of material inhomogeneities, that is, defects. One extremely popular measurand is bulk density, an indicator of void porosity. While bulk density does not provide localized information on defect sizes, shapes, locations, or quantities; it does provide a useful implicit metric for material quality with great utility as an initial screening for process control and validation (Figs. 8.20 and 8.21). It is relatively inexpensive to obtain and is recommended for any product acceptance protocol. The Archimedes method [147] and helium pycnometry [124,148] are the most commonly utilized measurement methods. Eddy current [149] and die-penetrant [150] are surface-based screening techniques used for metal components

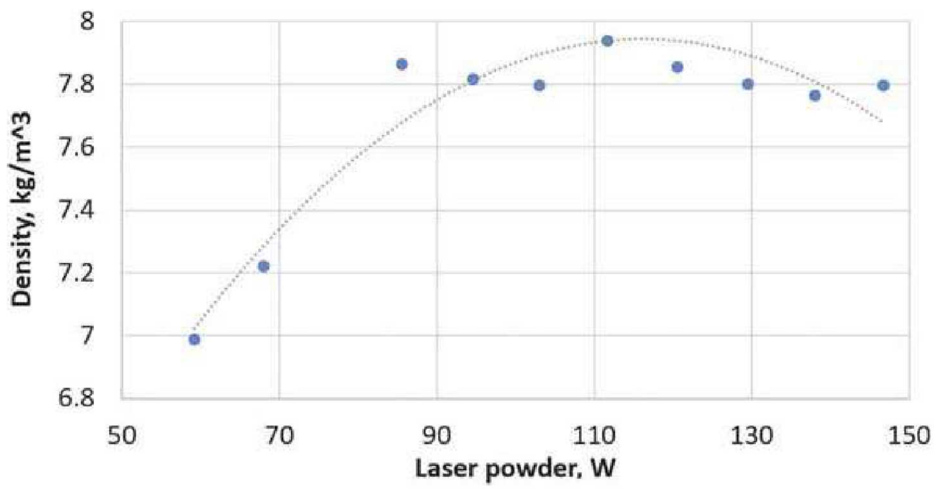

Figure 8.21 Impact of laser power on 316L stainless steel density from laser-powder bed fusion. This data demonstrates that density changes can be used to indicate process fluctuations.

and castings. While they are restricted from identifying bulk information, they can be valuable for screening gross surface defects and cracks.

Resonance methods represent another class of screening methods where parts are subjected to vibration or impact loads to excite their subsequent resonance response. These techniques are not explicit in their identification of individual material defects; but can identify shifts in part quality related to changes in resonance mode frequencies and amplitudes. Therefore measurements are relative in nature and require comparisons against known good reference parts. Testing can rely on low-frequency inputs for exciting low-order resonance modes or frequencies in the tens of kHz to MHz range for higher-order modes [151]. Part response depends on material properties, but also boundary conditions and part geometry. Therefore correlating changes with print quality can be challenging.

The explicit quantification of specific material defects can be an expensive effort, but it is required to provide a high level of confidence in part quality and performance. Multiple NDE techniques are capable of explicit defect characterization which include acoustic emission testing, THz inspection, infrared imaging, neutron imaging, radiography, and resonance inspection [152]. CT is the most common approach for characterizing metal additive parts, and it represents a "gold standard" for commercial NDE methodologies. From it, explicit three-dimensional representations of defects can be generated across a variety of materials and part geometries. Material atomic number, that is, high or low Z, part size, and part volume are primary factors that determine measurement

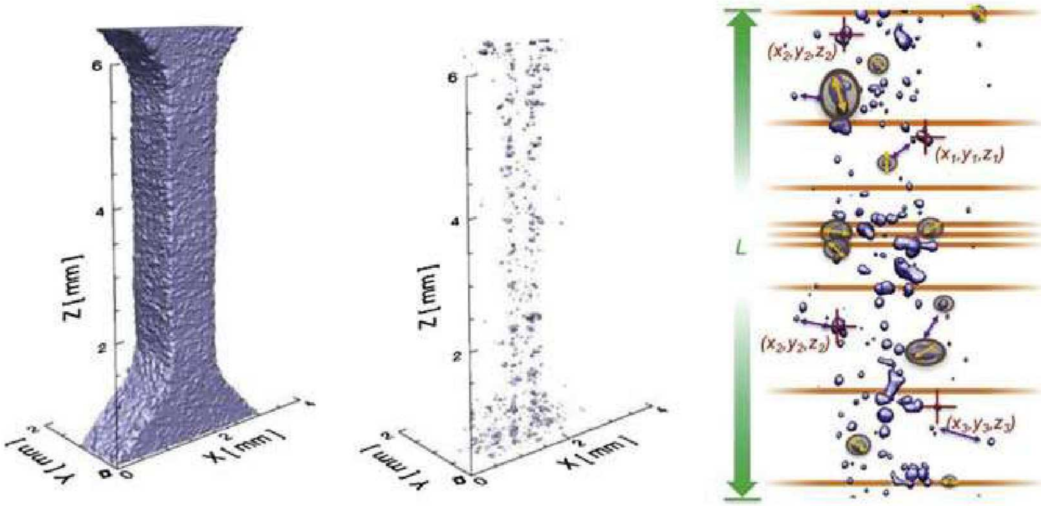

Figure 8.22 Rendering of the gage section of a laser-powder-bed fusion 17-4PH stainless steel tensile bar's exterior surface (left) and internal porosity (center) from computed tomogrpahy. Visual depiction of defects metrics obtained (right) include the total volume of defects, pore volume fraction, spatial location of pores, total number of defects, defects per unit length, defect volumes, equivalent spherical diameters, cross-sectional areas due to porosity and nearest neighbor distances [153].

resolution, feature fidelity, and measurement throughput. Void defects are most commonly identified, but material inclusions or contamination can also be quantified if material atomic number differences provide adequate contrast. Because CT provides a measure of pore topographies, multiple metrics can be explored to establish material requirements which include maximum defect size, total defect volume, number of voids, and nearest neighbors [153] (Fig. 8.22). Use of part zoning is one important approach to consider for improving measurement accuracy and throughput for product acceptance

Material structure is critical to material properties, but it is difficult to quantify without destructive metallography. Therefore it receives limited attention in most production acceptance protocols. X-ray diffraction (XRD) is one technique for quantifying metal phase fractions, although it is a surface technique and therefore constrained in its ability to characterize part geometries. Diffraction contrast tomography is a technique, recently released commercially [154], that performs crystallographic imaging of material texture within a volume. It is limited to single-phase polycrystalline materials, but represents an exciting new capability for material interrogation. Such limited capabilities present a challenge for parts defined and fabricated with intentional material complexity such as gradients [155,156] or site-specific microstructures [157−159]. New inspection technologies and acceptance methodologies may therefore be necessary to validate the performance and structure of such parts for production.

While internal residual stress is not a material property, per se, it is present within the material volume of metal AM parts [160] and can influence part quality [161]. Quantification is challenging and uncertain as X-ray and neutron diffraction [160] represent nondestructive techniques, while hole-drilling and the contour method provide destructive methods [162]. All of these techniques may be explored during development phases, but they are ill-posed for implementation into a production environment for product acceptance. Therefore parts with residual stress concerns are typically stress-relieved using postprocess heat treatments.

8.7 Printing

8.7.1 Requirements

8.7.1.1 Optimization

In theory, process requirements can be derived from and tailored to part requirements to achieve optimal performance with desired margins. In practice, however, metal additive process settings are most commonly determined in a separate development activity based on material metrics, not product metrics. Material density is an extremely common metric, but other properties, like surface finish or strength, can be considered. As a result, process and product development activities are often segregated, typically with process optimization and qualification completing first. Process adjustments, however, are always possible during development, particularly if process—property relationships have been quantified sufficiently to make process adjustments tuned for performance needs.

8.7.1.2 Process

Process requirements couple across the process itself, the printed material, and the part geometry. Process settings vary with the processes and machine platform, but are tied to basic elements of feedstock delivery, energy deposition, thermal history, process environment, and build layout. They are all defined for each OEM platform, material, and build geometry and are either input directly through machine settings or CAM process files. *Feedstock delivery* is dependent on the feedstock form, for example, powder or wire, and includes settings such as layer thickness in PBF and UAM, or flow rate in DED. *Energy deposition* incorporates elements such as laser power, beam diameter, and scan velocities for PBF or DED, sintering temperature for binder jetting, and ultrasonic energy in UAM. *Thermal history* supplements energy deposition and addresses scan paths and preheating for PBF or DED and sintering profiles in binder jetting. *Process environments* include build chamber temperature, oxygen content, cover gas, and flow rates. *Build layout* is defined by the geometry, location, and orientation of parts, test artifacts, and support structures.

An important aspect of any production process is the definition of control bounds outside of which manufactured products do not meet requirements. Thus the sensitivity of part or material performance to process inputs must be quantified. While characterizing process—performance relationships can be expensive, critical trends must be determined, prioritized, and quantified as resources allow. Despite the complexity of PSPP relationships, interactions between different process inputs can be captured in multiple forms. Single parameter correlations (Fig. 8.23) and process maps exploring two parameters (Fig. 8.24), typically input power and scan velocity [163], may be relatively simplistic. Yet, they can be extremely valuable in establishing boundaries for a viable process space. For example, Fig. 8.23 provides ultimate tensile strength versus laser scan velocity for 316L stainless steel using L-PBF. Each data value represents an average of 25 tensile samples with minimum and maximum values also provided. A relatively stable process plateau exists across a range from 1100 to 1700 m/s, where property variations for the dogbones at a single process setting are not dramatically different than values across the entire range. Further, establishing a minimum acceptable ultimate tensile strength of 600 MPa defines a range across 600 m/s for which acceptable properties could be

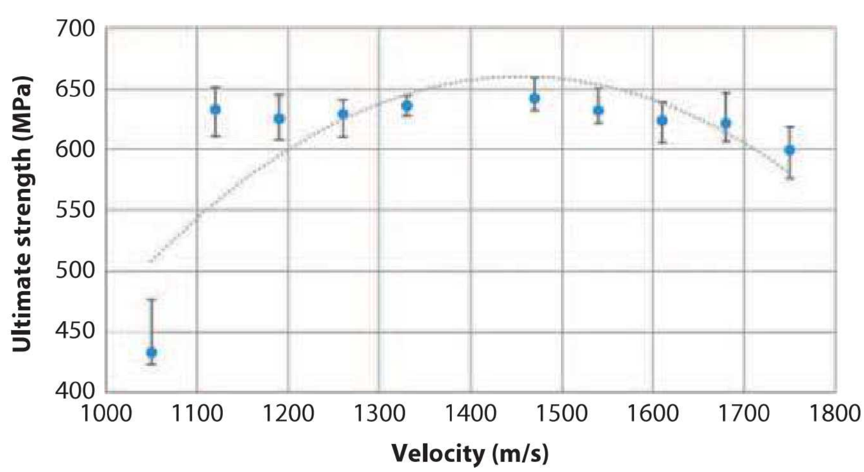

Figure 8.23 Impact of laser scan velocity on ultimate tensile strength for 316L stainless steel from laser-powder bed fusion. Each data point represents the average of 25 samples, with error bars capturing minimum and maximum values.

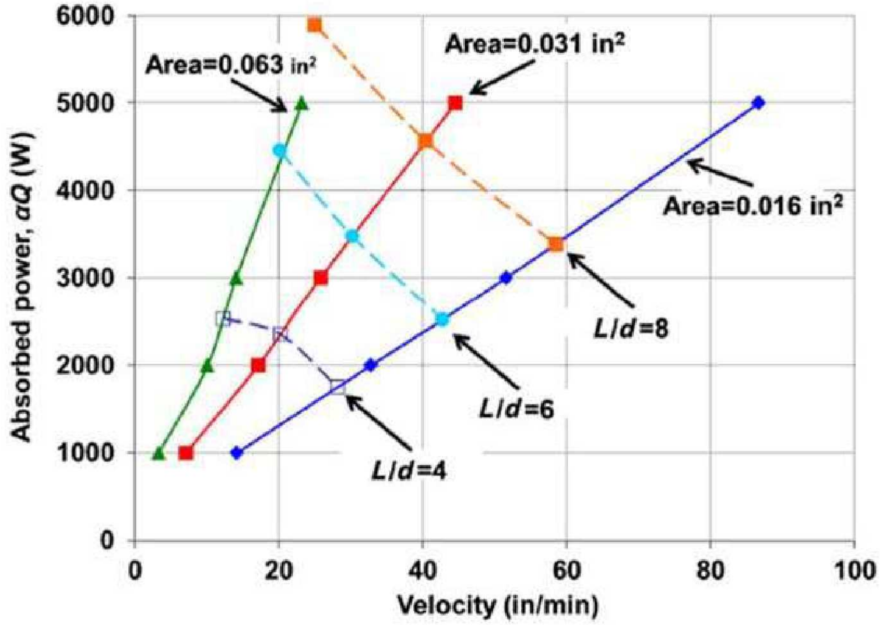

Figure 8.24 Process map for controlling melt pool dimensions for single bead Ti–6Al–4V deposition in wire feed electron beam additive manufacturing [163].

expected with some additional margins. Such knowledge of process and property variations are necessary to truly quantify material margins and process boundaries.

Parameter investigations can be time consuming and expensive, particularly if additional multiple parameter dimensions are addressed. Combining reduced order models with data-mining techniques has been demonstrated as one effective means for reducing process experiments and still capturing process trends necessary to define process bounds [164]. Similarly, an important utility of more complete computational models is to inform process optimization and PSPP relationships. Reaching this state, however, requires additional research investments and faces multiple challenges for pragmatic implementation [88].

8.7.1.3 Standards

Metal AM materials exhibit properties that may best be described by distributions. A commonly cited need for the industry is standards that are process and material specific [73,165,166]. The challenges associated with process complexity, differences, variability, and uncertainty make the establishment of these standards in a systematic, universal form difficult, however. It is unclear at this time how or even if standards organizations will implement process standards for metal additive manufacturing.

8.7.2 Control

Successful control of metal additive processes is crucial to product qualification and acceptance. Characterizing, controlling, and predicting material and part quality is challenging, however, due to the complexity and variability of process physics. Until recently this complexity was acerbated by the limited capabilities for process control or defect tracking in commercially available OEM equipment. Recent equipment advances, however, are beginning to implement different process diagnostic and control capabilities. Advancing these controls and coupling them with PSPP correlations is crucial to wider adoption of metal additive parts and products. Classically, process control involves establishing a nominal process state, monitoring deviations or disturbances from this state, and then correcting or accommodating perturbations using a control action. Successful control for any metal AM process will follow a similar approach.

8.7.2.1 Administrative

Coupling the current gap in process controls with limited quantification of PSPP relationships produces the point source qualification and acceptance paradigms prevalent today. In this paradigm, strict specification of machine hardware, software, process files, and process settings are defined and demonstrated during qualification. Stringent administrative controls are then applied wherein production deviations are impermissible. Process "lock-downs" include specific machines, machine settings, firmware updates, and software versions. Similarly, part CAD models, intermediary STL files, process models, and machine programs must be managed with version controls to prevent inadvertent changes. Part marking and tracking is necessary to insure part pedigree and traceability to machine builds, feedstock use, and part locations. Operator requirements and training must also be determined and defined. The intent of administrative control is to minimize process variations, but contingencies must be prepared when changes are necessary, for example, machine failure. Such contingencies may involve requalification protocols or redundancies, for example, prequalifying multiple machines during development.

8.7.2.2 Process artifacts

A common method for process evaluation, with roots in RP, is the use of design artifacts to quantify process capabilities, to determine material performance, and to quantify machine operation [167]. Such artifacts can be

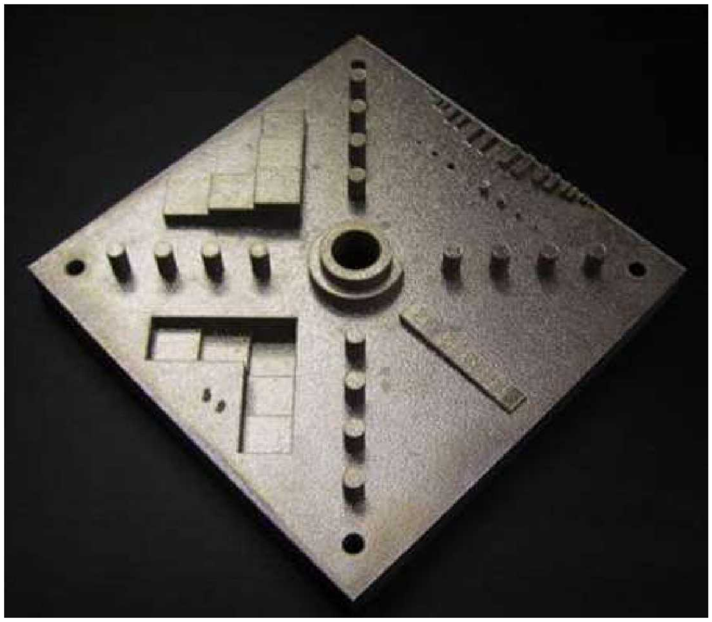

Figure 8.25 Popular additive manufacturing process artifact design [168]. Printed part is 100 × 100 mm in the horizontal plane for scale.

complex, consume valuable build volumes, and require extensive resources for measurement and characterization. One popular example in this vein is the artifact developed by the National Institute of Standards and Technology shown in Fig. 8.25 [167]. Such artifacts exercise the entire process—material—machine chain and are comprehensive in their sensitivity to process variations. However, they also present difficulties in deconvolving root causes when changes are observed. Therefore they provide gross process feedback and can be printed periodically, for example, weekly or monthly, to identify global drifts in machines, processes, or materials.

A more common and informative approach for process controls is the incorporation of process artifacts with every build cycle. Analogous to snap plates in welding, process artifacts are typically simple, consume minimal build volumes, and can be interrogated using both destructive and nondestructive methodologies. Tracking global process changes by quantifying material performance with every build cycle is typical as common examples include density cubes and tensile bars (Fig. 8.26). Tracking artifacts over numerous builds through development and production can establish a baseline for process bounderies to identify process drift and part outliers. When reasonable, artifact geometries strive to represent critical part features, for example, cross-section and orientation, using representative volume elements (RVE). Similitude is often pursued during development to establish a capability for predicting product performance based on

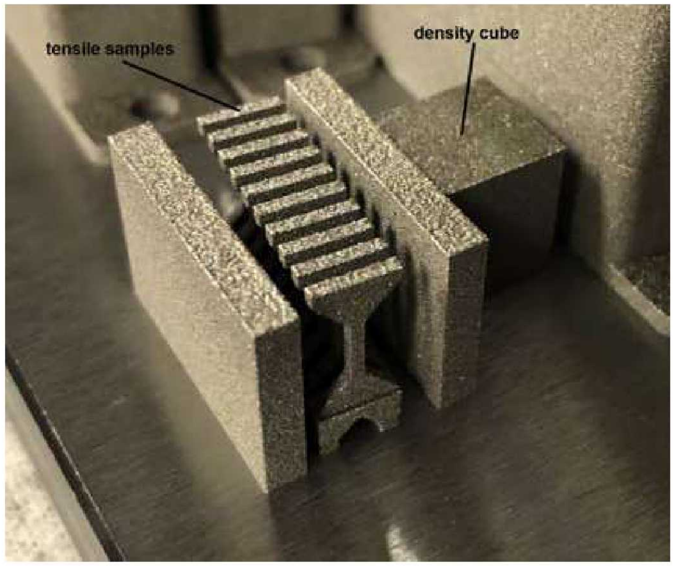

Figure 8.26 10 mm density cube and tensile sample process artifacts on a laser-powder bed fusion build plate.

artifact properties. Establishing such correlations can be extremely difficult, however, and must be performed with caution as localized material variations and defects can skew artifact behavior relative to individual parts. The implications of process artifacts performing outside of desired bounds must also be established, for example, scrap an entire build, perform extensive part testing, and/or explore process or machine corrections.

8.7.2.3 Machine

Machine control suggests a range of potential activities, but here refers to actions ensuring the operation of a machine within specification. One widely regarded challenge in metal additive is the variation observed in the output between machines. This variation can be between products from different OEMs, between different product lines from a single OEM, between machines from the same product line, and even with time and use on a single machine. Thus metrology and maintenance procedures are needed to quantify and ensure machine performance over development and production life cycles. The frequency of these operations is important and may be established for a consistent number of build cycles or for a set schedule, for example, weekly or monthly. Such frequency is driven by the rate at which changes occur in the process, the equipment, the material, and/or the final product.

Machine metrology and monitoring should focus on equipment characteristics with the greatest influence on the process, (e.g., laser power), and/or the highest potential for failure, (e.g., optic contamination). Techniques should generally quantify aspects of feedstock delivery, (e.g., build platen motion); energy deposition, (e.g., laser beam profiles); thermal history, (e.g., sintering oven thermal profiles); and process environment, (e.g., inert gas flow velocities). Such characterization is also extremely valuable, and necessary, during process optimization. Maintenance protocols involve calibration, (e.g., galvanometer motion); cleaning, (e.g., optics); and replacing consumables, (e.g., filters). Numerous standards exist for traditional machine tools, but there are no current standards for the metrology and characterization of metal AM machines. Thus users are reliant on OEM guidance and service, open literature sources, user community best practices, and internally developed procedures and experiences.

8.7.2.4 Process

Administrative controls insure that equipment and process settings are correct; while machine metrology determines whether equipment is operating within specification. Such controls can be adequate for products with large material margins, particularly if part acceptance can be accomplished accurately and cost-effectively using ex-situ sampling, testing, and inspection. Most qualification efforts to date leverage this approach, particularly as many metal machines predominantly operate open loop. Regrettably, these approaches can also be slow, expensive, inaccurate, and unable to prevent part defects in-situ. A different paradigm is desired wherein the digital nature of additive is leveraged by monitoring and controlling the process at every voxel element during fabrication. Such control is necessary to satisfy tighter product margins due to the complex interactions of material feedstocks, process inputs, and machine dynamics which can produce material defects and variations. The implementation of process controls will also accelerate qualification and development cycles.

Process controls are implemented at multiple levels in current machines and should be leveraged in their available form for product qualification and acceptance efforts. Machine data-logs and process metadata should all be recorded and analyzed to capture process, material, and part trends. In-situ monitoring can provide process datasets valuable for informing part build quality and detecting part and process defects. Feedback control is a natural progression, and already exists in elements of some systems, for example, beam control in E-PBF. Controls can be relatively simplistic, yet still improve part quality, correct or reduce defects, increase part yield rates, and increase production throughput. A more advanced, future state will be predictive or feedforward process control where predictive modeling capabilities and detailed quantification of relevant PSPP relationships will both optimize and control the printing process, the resulting material, and the printed parts.

Commercially available metal machines incorporate control at various levels for each element of feedstock delivery, process environment, energy deposition, and thermal history. *Feedstock delivery* addresses the quantity and uniformity of powder spreading in PBF, powder volumetric flow rate in DED, or wire feed velocity in wire-feed deposition. Such controls are now available on multiple machines [169,170]. Similarly, *process environment* addresses build chamber pressure and temperature, cover gas flow rate, and oxygen content; elements that can be controlled using standard industrial controls. Determining these inputs and settings typically falls within general process development and optimization, not qualification activities. Insuring that they are operating within process limits, however, is necessary during production cycles and is commonly recorded in machine log files.

Energy deposition addresses the energy source fundamental to every AM process. It includes laser or electron beam power, beam diameter, beam quality, and scan velocity for powder bed fusion; current and voltage for wire-feed deposition, and ultrasonic energy for UAM. The stability of these energy sources is variable, making the control and quantification of energy into the material interaction zone difficult. Industrial-grade electron beams, lasers, and ultrasonic transducers all contain controls, but still fluctuate within operational tolerances. Additional energy changes are also introduced along the transmission path due to other system elements, for example, time-dependent thermal lens distortions (Fig. 8.27), and localized process conditions, that is, plasma plumes and spatter.

Energy deposition is crucial to every metal additive process, but printed material structure and properties in PBF and DED are ultimately determined by localized *thermal histories* associated with melting and solidification. Thus the temperature in the material interaction zone, that is, the melt pool, is of primary interest. Melt pool temperatures and intensities are also easier to monitor than energy deposition levels, and have therefore been topics of research for over a decade [11,13,172]. Work to date has focused primarily on measuring melt pool characteristics and signatures, striving to establish correlations with part structure, defects, and properties. While UAM is distinct due to its solid-state nature, researchers have explored in-situ process monitoring to insure proper material bonding [173]. Binder

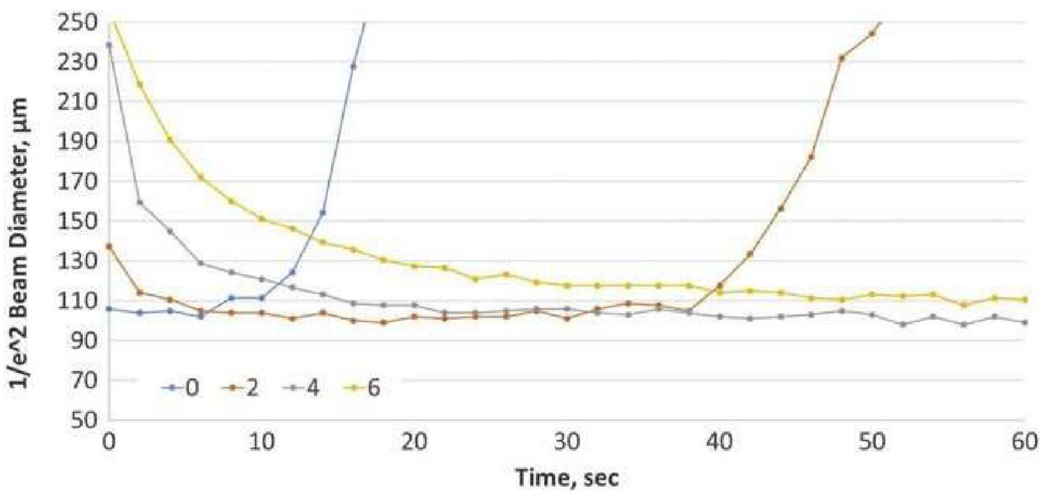

Figure 8.27 Laser-powder bed fusion fiber laser beam diameter variation with time and focus offset [171].

jetting is also unique in that it relies on material sintering, not melting and solidification. While sintering physics occur at a local scale, their control is performed at a global scale within an industrial grade sintering furnace whose thermal profile can be precisely monitored and controlled.

8.7.2.4.1 In-situ melt pool monitoring

The rapid melting and solidification in DED and PBF make melt pool monitoring difficult. Material melting and resolidification involve temperature changes of 1000°C with scan velocities on the order of 1−10 mm/min for energy deposition processes, and 1−5 m/s for powder bed processes. Resulting thermal gradients approach 10^4°C/s for DED [15] and 10^6°C/s for PBF [16], respectively. Further, material interaction zones are small, a few millimeters or less for DED and 100s of microns for PBF. As a result, melt pool monitoring requires sensors with large dynamic range, 1000°C or more, high resolution, tens of microns or less, and fast acquisition rates, hundreds to thousands of Hz. While commercially available sensors are generally adequate for DED processes, no single sensor technology satisfies the demands of powder bed processes. Thus trades must be made, as multiple sensors with different capabilities and modalities are commonly pursued.

Multiple techniques have been explored for melt pool monitoring within the research community. Optical techniques provide high-speed and/or high-resolution measurements at relatively low costs. These include cameras for imaging melt pool motion and geometry,

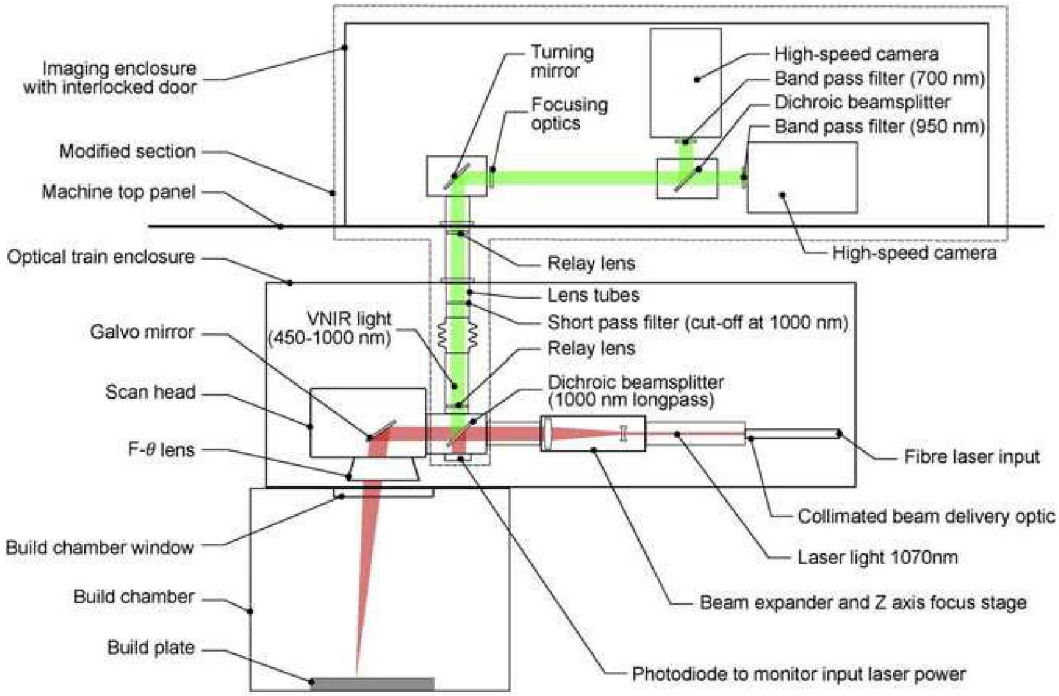

Figure 8.28 Physical layout for co-axial two-color pyrometry imaging of the melt pool in a commercial laser-powder bed fusion machine [16].

photodiodes and spectrometers for capturing melt pool and plasma emission intensities, and optical coherence tomography (OCT) for measuring melt pool and printed surface topographies [174]. Melt pool temperatures can be probed using thermal techniques such as single- and two-color pyrometry [16] (Fig. 8.28) or infrared thermography [175]. Thermal techniques are commonly slower or lower resolution than optical monitoring, but provide a richer, more informative data set. Acoustic techniques have also been explored in the literature [176], although no implementation is known to exist in commercial equipment.

In any melt pool monitoring technique, measurand signatures must be correlated to and predictive of process, material, and ultimately part quality. Otherwise, process control is neither feasible nor practical. To date, researchers have focused predominantly on void detection in lack-of-fusion and key-hole processing regimes. The capture of thermal data, however, also provides a path to estimate material microstructures. Correlating melt pool metrics with material structure remains a topic of exploration, but trends with specific porosity defects have been observed based on melt pool geometry in DED [177] and melt pool emission intensity in PBF thermography [175]. Most OEM and third-party vendor [178] techniques capture process signals based on melt pool intensity and attempt to observe signal shifts that indicate the statistical probability that defects are present. Process signals are commonly compared against known-good reference parts, that is, gold standards, to identify outlier parts residing outside of specification, not to identify specific defects within a part volume. While no standards exist for monitoring techniques, there is work within ASME to develop standards for collecting, managing, analyzing, and communicating advanced manufacturing datasets [179]. Melt pool datasets can be large, that is, GB and TB, due to the data rates and resolutions necessary to monitor them. Therefore any qualification and acceptance method must address data collection and storage, as well as the analyses associated with establishing performance correlations.

8.8 Postprocessing

Metal additive processes provide net shape geometries and materials that commonly require postprocessing. Finish machining, polishing, powder or support removal, cleaning, heat treating, and hot isostatic pressing (HIP) are all commonly performed to address problems with dimensional accuracy, surface finish, residual stress, porosity, and material microstructure. Postprocessing steps vary widely, but can broadly be categorized as cleaning, finishing, or microstructure control. The impact of postprocessing on all aspects of final part and material quality must be well understood and controlled.

Standards and inspection methods for postprocessing, much like the processes themselves, vary widely. Finishing techniques are associated with part geometry, so the requirements and methods discussed in Section 8.4 apply. Cleaning methods are closely tied to the product or application, for example, medical. While standards do exist for cleaning metals [180], cleaning techniques and specifications are commonly developed and implemented within a company or manufacturing industry. Microstructure control of metals, primarily through heat treatment and HIP, are applied throughout a range of industries. To that end, standards exist for their prescription, control, and verification. As-printed AM metals consist of unique microstructures whose behavior can differ dramatically from conventional metals. As a result, guides for heat treatment and HIP cycles may be valid starting points, but optimized process routes may be different [181]. Similarly, all postprocessing techniques should be developed and applied as necessary to adapt to the unique properties and needs of additively manufactured metal products.

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Additive Manufacturing Materials and Technologies

SCIENCE, TECHNOLOGY AND APPLICATIONS OF METALS IN ADDITIVE MANUFACTURING

Additive manufacturing (AM) is a disruptive technology that is changing the landscape of the current manufacturing ecosystem. Metal AM in particular has the potential to revolutionize the industrial manufacturing world by producing parts directly from CAD data without the need for fixtures, molds, or dies. Its ability to perform tool-less manufacturing not only reduces manufacturing cost, but also drastically reduces the time cycle from design-to-market for new products.

Science, Technology and Applications of Metals in Additive Manufacturing provides a holistic picture of metal AM. It looks at the history of metal AM, commercially available metal AM processes, material feedstocks, and resultant materials. The microstructure and mechanical properties of AM materials, as well as advances in modelling and simulations are also discussed. Design for metal AM and design optimization tools are addressed, discussing their merits and demerits. Challenges and approaches for product qualification and acceptance are then presented. The book concludes with a review of applications, cost modelling, and benefits of metal AM. This book will serve as a guide to people who are entering this exciting new field of metal AM, while simultaneously serving as a useful tool for experts.

Key Features

- An overall understanding of metal AM, including steps involved (process flow), design for AM, microstructures, properties, and process modelling.
- A discussion of available commercial metal AM technologies and their relative strengths and weaknesses.
- A review of qualification, various applications, cost modelling, and the benefits of metal AM.

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