Standard Guidelines for Design for Additive Manufacturing [1]

This standard is issued under the fixed designation ISO/ASTM 52910; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision.

1. Scope

1.1 This document gives guidelines and best practices for using additive manufacturing (AM) in product design.

1.2 It is applicable during the design of all types of products, devices, systems, components, or parts that are fabricated by any type of AM system. These guidelines help determine which design considerations can be utilized in a design project or that can be utilized to take advantage of the capabilities of an AM process.

1.3 General guidance and identification of issues are supported, but specific design solutions and process-specific or material-specific data are not supported. The intended audience comprises three types of users:

1.3.1 designers who are designing products to be fabricated in an AM system and their managers,

1.3.2 students who are learning mechanical design and computer-aided design,

1.3.3 developers of AM design guidelines and design guidance systems.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Normative references

2.1 There are no normative references in this document.[2,3]

[1] This test method is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.04 on Design.

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[2] None of the referenced documents are cited as requirements of the document.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3. Terminology

Additive manufacturing processes

3.1 *Definitions:* For the purposes of this document, the terms and definitions given in ASTM F2792-10, for definitions of AM processes and concepts, and ASTM F2921-11, for coordinate systems and test methodologies, and the following apply.[4]

3.1.1 *binder jetting*—AM process in which a liquid bonding agent is selectively deposited to join powder materials.

3.1.2 *directed energy deposition*—AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

3.1.3 *material extrusion*—AM process in which material is selectively dispensed through a nozzle or orifice.

3.1.4 *material jetting*—AM process in which droplets of build material are selectively deposited.

3.1.5 *powder bed fusion*—AM process in which thermal energy selectively fuses regions of a powder bed.

3.1.6 *sheet lamination*—AM process in which sheets of material are bonded to form an object.

3.1.7 *vat photopolymerization*—AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

3.2 *Other definitions:*

3.2.1 *design consideration*—topic that may influence decisions made by a part designer.

3.2.1.1 *Discussion*—The designer determines to what extent the topic may affect the part being designed and takes appropriate action.

3.2.2 *process chain*—sequence of manufacturing processes that is necessary for the part to achieve all of its desired properties.

4. Summary of purpose

4.1 This document provides guidelines for designing parts and products to be produced by AM processes. Conditions of the part or product that favor AM are highlighted. Similarly,

[4] ISO and IEC maintain terminological databases for use in standardization at the following addresses: IEC Electropedia: available at http://www.electropedia.org/, and ISO Online browsing platform: available at http://www.iso.org/obp.

conditions that favor conventional manufacturing processes are also highlighted. The main elements include the following:

4.1.1 the opportunities and design freedoms that AM offers designers (Clause 5).

4.1.2 the issues that designers should consider when designing parts for AM, which comprises the main content of these guidelines (Clause 6), and

4.1.3 warnings to designers, or "red flag" issues, that indicate situations that often lead to problems in many AM systems (Clause 7).

4.2 The overall strategy of design for AM is illustrated in Fig. 1. It is a representative process for designing mechanical parts for structural applications, where cost is the primary decision criterion. The designer could replace cost with quality, delivery time, or other decision criterion, if applicable. In addition to technical considerations related to functional, mechanical, or process characteristics, the designer should also consider risks associated with the selection of AM processes.

4.3 The process for identifying general potential for fabrication by AM is illustrated in Fig. 2. This is an expansion of the "Identification of general AM potential" box on the left side of Fig. 1. As illustrated, the main decision criteria focus on material availability, whether or not the part fits within a machine's build volume, and the identification of at least one part characteristic (customization, lightweighting, complex geometry) for which AM is particularly well suited. These criteria are representative of many mechanical engineering applications for technical parts, but are not meant to be complete.

4.4 An expansion for the "AM process selection" box in Fig. 1 is presented in Fig. 3, illustrating that the choice of material is critical in identifying a suitable process or processes. If a suitable material and process combination can be identified, then consideration of other design requirements can proceed, including surface considerations and geometry, static physical, and dynamic physical properties, among others. These figures are meant to be illustrative of typical practice for many types of mechanical parts, but should not be interpreted as prescribing necessary practice.

5. Design opportunities and limitations

5.1 *General*

Additive manufacturing differs from other manufacturing processes for several reasons and these differences lead to unique design opportunities and freedoms that are highlighted here. As a general rule, if a part can be fabricated economically using a conventional manufacturing process, that part should probably not be produced using AM. Instead, parts that are good candidates for AM tend to have complex geometries, custom geometries, low production volumes, special combinations of properties or characteristics, or some combination of these characteristics. As processes and materials improve, the emphasis on these characteristics will likely change. In Clause 5, some design opportunities are highlighted and some typical limitations are identified.

5.2 *Design opportunities:*

5.2.1 AM fabricates parts by adding material in a layer-by-layer manner. Due to the nature of AM processes, AM has many more degrees of freedom than other manufacturing processes. For example, a part may be composed of millions of droplets if fabricated in a material jetting process. Discrete control over millions of operations at micro to nano scales is both an opportunity and a challenge. Unprecedented levels of interdependence are evident among considerations and manufacturing process variables, which distinguishes AM from conventional manufacturing processes. Capabilities to take advantage of design opportunities can be limited by the complexities of process planning.

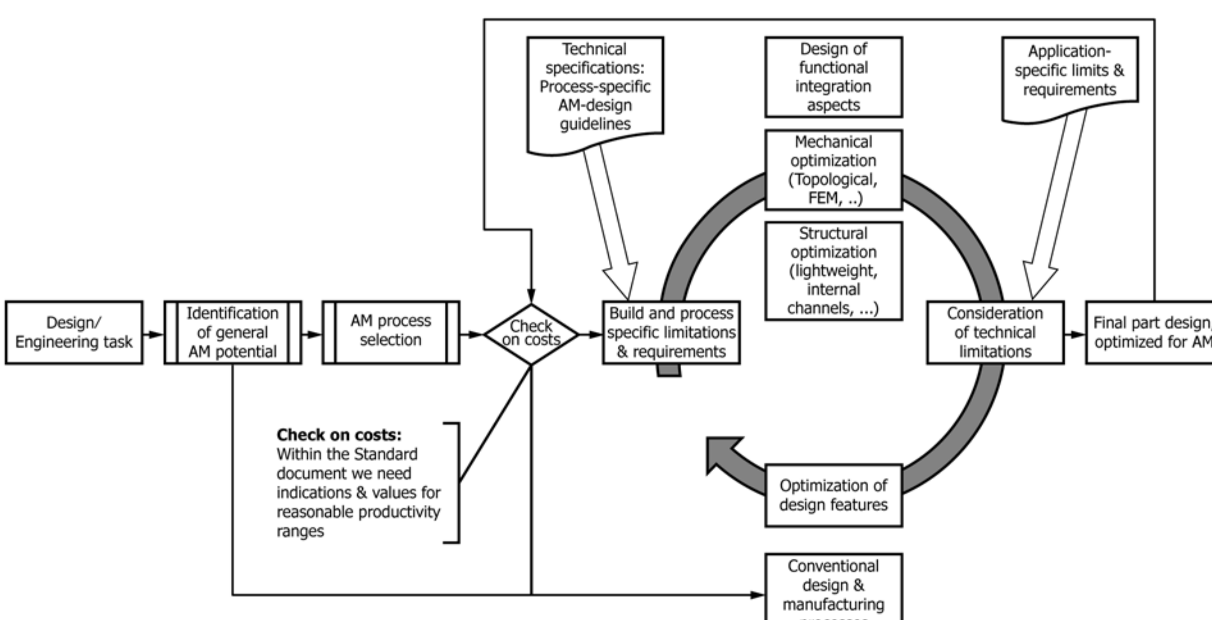

FIG. 1 Overall Strategy for Design for AM

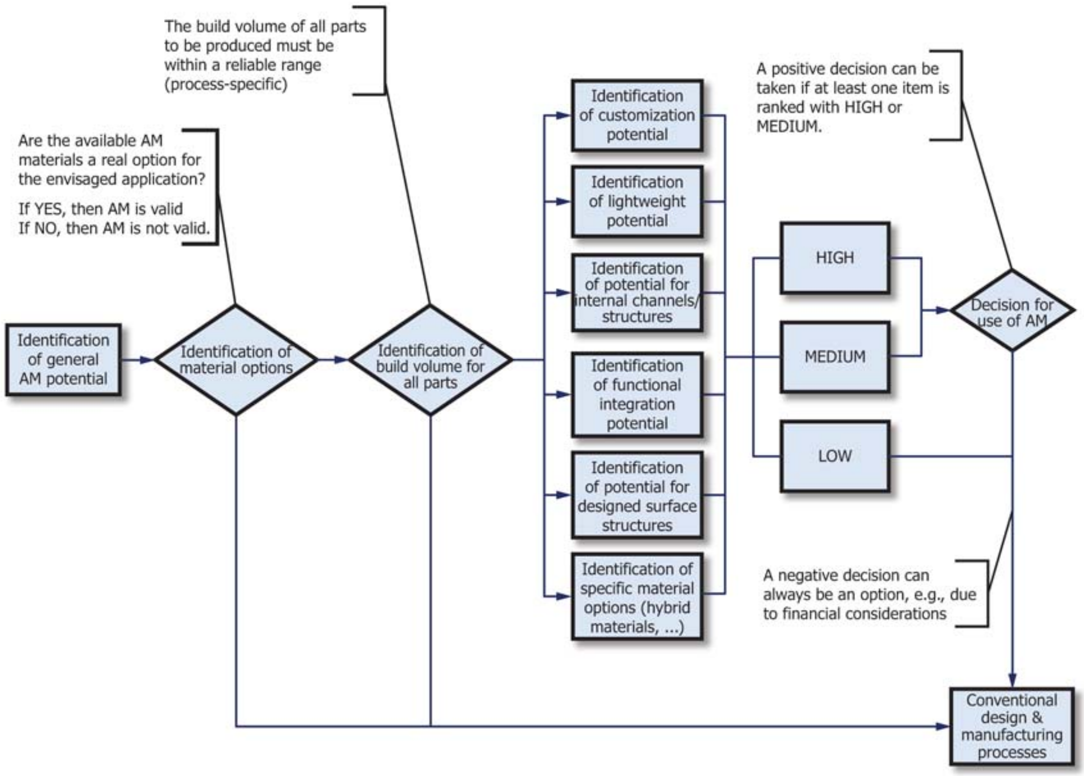

FIG. 2 Procedure for identification of AM potential

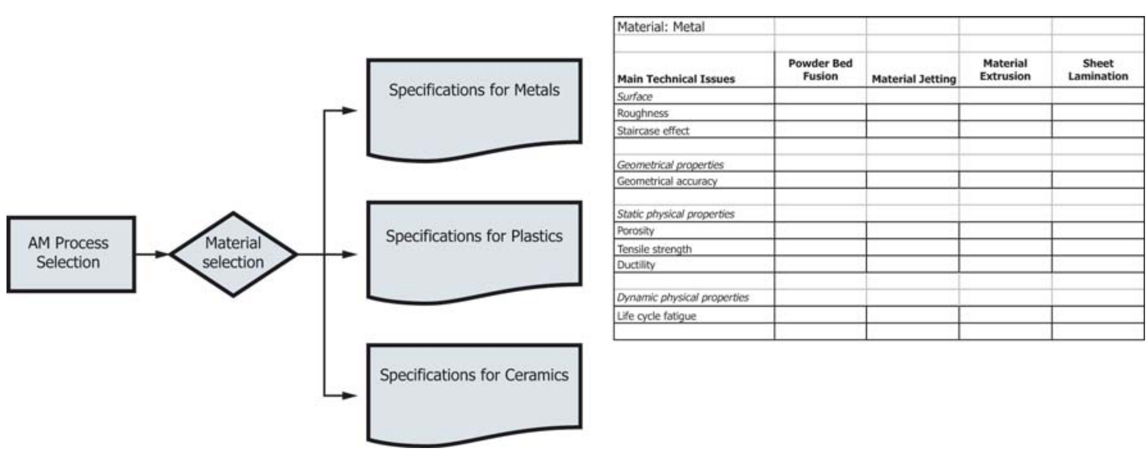

FIG. 3 AM process selection strategy

5.2.2 The layer-based, additive nature means that virtually any part shapes can be fabricated without hard tooling, such as molds, dies, or fixtures. Geometries that are customized to individuals (customers or patients) can be economically fabricated. Very sophisticated geometric constructions are possible using cellular structures (honeycombs, lattices, foams) or more general structures. Often, multiple parts that were conventionally manufactured can be replaced with a single part, or smaller number of parts, that is geometrically more complex than the parts being replaced. This can lead to the development of parts that are lighter and perform better than the assemblies they replace. Furthermore, such part count reduction (called part consolidation) has numerous benefits for downstream activities. Assembly time, repair time, shop floor complexity, replacement part inventory, and tooling can be reduced, leading to cost savings throughout the life of the product. An additional consideration is that geometrically complex medical models can be fabricated easily from medical image data.

5.2.3 In many AM processes, material compositions or properties can be varied throughout a part. This capability leads to functionally graded parts, in which desired mechanical property distributions can be fabricated by varying either material composition or material microstructure. If effective mechanical properties are desired to vary throughout a part, the designer can achieve this by taking advantage of the geometric complexity capability of AM processes. If varying material composition or microstructure is desired, then such variations can often be achieved, but with limits dependent on the specific process and machine. Across the range of AM processes, some processes enable point-by-point material variation control, some provide discrete control within a layer, and almost all processes enable discrete control between layers (vat photopolymerization is the exception). In the material jetting and binder jetting processes, material composition can be varied in virtually a continuous manner, droplet-to-droplet or even by mixing droplets. Similarly, the directed energy deposition process can produce variable material compositions by varying the powder composition that is injected into the melt pool. Discrete control of material composition can be achieved in material extrusion processes by using multiple deposition heads, as one example. Powder bed fusion (PBF) processes can have limitations since difficulties may arise in separating unmelted mixed powders. It is important to note that specific machine capabilities will change and evolve over time, but the trend is toward much more material composition flexibility and property control capability.

5.2.4 A significant opportunity exists to optimize the design of parts to yield unprecedented structural properties. The concept of "design for functionality" can be realized, meaning that if a part's functions can be defined mathematically, the part can be optimized to achieve those functions. Novel topology and shape optimization methods have been developed in this regard. Resulting designs may have very complex geometric constructions, utilizing honeycomb, lattice, or foam internal structures, may have complex material compositions and variations, or may have a combination of both. Research is needed in this area, but some examples of this are emerging.

5.2.5 Other opportunities involve some business considerations. Since no tooling is required for part fabrication using AM, lead times can be very short. Little investment in part-specific infrastructure is needed, which enables mass customization and responsiveness to market changes. In the case of repair, remanufacturing of components could be highly advantageous both from cost as well as lead time perspectives.

5.3 *Limitations:*

5.3.1 *Overview*—It is also useful to point out design characteristics that indicate situations when AM should probably not be used. Stated concisely, if a part can be fabricated economically using a conventional manufacturing process and can meet requirements, then it is not likely to be a good candidate for AM. The designer should balance cost, value delivered, and risks when deciding whether to pursue AM.

5.3.2 A primary advantage of AM processes is their flexibility in fabricating a variety of part shapes, complex and customized shapes, and possibly complex material distributions. If one desires mass production of simple part shapes in large production volumes, then AM is not likely to be suitable without significant improvements in fabrication time and cost.

5.3.3 A designer must be aware of the material choices available, the variety and quality of feedstocks, and how the material's mechanical and other physical properties vary from those used in other manufacturing processes. Materials in AM will have different characteristics and properties because they are processed differently that in conventional manufacturing processes. Designers should be aware that the properties of AM components are highly sensitive to process parameters and that process variability is a significant issue that may constrain freedom of design. Additionally, designers should understand the anisotropies that are often present in AM processed materials. In some processes, properties in the build plane (X, Y directions) will be different than in the build direction (Z axis). With some metals, mechanical properties better than wrought can be achieved. However, typically fatigue and impact strength properties are not as good in AM processed parts in their as-built state as in conventionally processed materials.

5.3.4 All AM machines discretize part geometry prior to fabricating a part. The discretization can take several forms. For example, most AM machines fabricate parts in a layer-by-layer manner. In material and binder jetting, discrete droplets of material are deposited. In other processes, discrete vector strokes (e.g., of a laser) are used to process material. Due to the discretization of part geometry, external part surfaces are often not smooth since the divisions between layers are evident. In other cases, parts may have small internal voids.

5.3.5 Geometry discretization has several other effects. Small features can be ill-formed. Thin walls or struts that are slanted, relative to the build direction, may be thicker than desired. Also, if the wall or strut is nearly horizontal, the wall or strut may be very weak since relatively little overlap may occur between successive layers. Similarly, small negative features such as holes may suffer the opposite affect, becoming smaller than desired and having distorted shapes.

5.3.6 Post-processing is required for many AM processes or may be desired by the end-user. A variety of mechanical, chemical, and thermal methods may be applied. Several AM process types utilize support structures when building parts which need to be removed. In some cases, supports can be removed using solvents, but in others the supports must be mechanically removed. One should be aware of the additional labor, manual component handling, and time these operations require. Additionally, designers should understand that the presence of support structures may affect the surface finish or accuracy of the supported surfaces. In addition to support structure removal, other post-processing operations may be needed or desired, including excess powder removal, surface finish improvement, machining, thermal treatments, and coatings. If a part has any internal cavities, the designer should design features into the part that enable support structures, unsintered powder (PBF), or liquid resin (VP) to be removed from those cavities. Depending on accuracy and surface finish requirements, the part may require finish machining, polishing, grinding, bead blasting, or shot-peening. Metal parts may require a thermal treatment for relieving residual stresses, for example. Coatings may be required, such as painting, electroplating, or resin infiltration.

5.3.7 Each AM process has a limited build envelope. If a part is larger than the build envelope of an AM process, then it can be divided into multiple parts, which must be assembled after fabrication. In some cases, this may not be technically or economically feasible.

6. Design considerations

6.1 *General*

Several categories of design considerations have been identified, including product, usage, sustainability, business, geometric, material property, process and communication considerations.

6.2 *Product considerations:*

6.2.1 *Design effectiveness*—The designer can generate part shapes and configurations that optimize performance and efficiency. Parts can be designed for desired properties, such as minimum weight, maximum stiffness, etc., by designing shapes that are as efficient as possible. It may also be possible to design a part to perform multiple functions, through the use of multiple materials, complex shapes or part consolidation, which can have significant efficiency benefits.

6.2.2 *Part or product consolidation*—It is good design practice to minimize the number of parts in a product or module, but not at a loss of functionality. A part may be merged into neighboring part(s) if they: can be fabricated out of the same material as a neighboring part, do not need to move relative to each other, and do not need to be removed to enable access to another part. This practice is often called part consolidation, which is a standard design-for-assembly consideration.

6.2.3 *Assembly features*—This is a standard design-for-assembly consideration. One should design parts with features that enable easy insertion and fixation during assembly operations. AM can enable integration of assembly features into most part designs, such as snap-fits, alignment features, and features to support other parts (ribs, bosses). The capability of AM to fabricate geometrically complex designs provides a greater degree of design flexibility/freedom and designers are encouraged to be innovative in designing assembly features.

6.2.4 *Multi-part mechanisms*—In many AM processes, it is possible to design working mechanisms, i.e., parts that move relative to one another, without the need for secondary assembly operations. Kinematic joints, such as revolute, sliding, and cam joints, can be designed to enable relative motion between parts. In powder bed fusion processes, joints can provide motion if powder can be removed. In vat photopolymerization processes, liquid resin easily flows out of joints, which enables motion. In other processes requiring support structures, moving mechanisms are possible if the support material can be removed easily from joint regions, for example if soluble support material is used.

6.2.5 *Compliant Mechanisms*—AM can enable creative designs of complex 2D and 3D mechanisms. In contrast to multi-part mechanisms, other types of mechanisms cause relative movement between the input and the output through designed bending patterns. That is, structural elements of the mechanism bend in a manner that causes desired input-output behavior. The simplest types of compliant mechanisms simply replace pin joints with thin plates that act as compliant hinges. More sophisticated compliant mechanisms consist of beams with different thicknesses, and possibly varying thicknesses. AM should enable creative designs of complex 2D and 3D mechanisms.

6.2.6 *Relationships with processes and process chains*—The accuracy and surface finish of part surfaces will depend on build orientation and other process variables. A sequence of processes ("process chain") may be needed in order to achieve desired accuracy and finish requirements, which the designer needs to consider. By designing a suitable process chain, it may be possible to use an AM process for part fabrication, even if that process alone is not capable of meeting all design requirements.

6.3 *Product use considerations:*

6.3.1 *General*

Design considerations must also be based upon the type of environment which the product experiences throughout its useful life. This can include operating conditions, but can also refer to conditions in storage or during maintenance and repair. Material properties may be affected by the following environmental conditions.

6.3.2 *Thermal environment:*

6.3.2.1 *Exposure temperature range (extremes)*—The maximum and minimum temperatures to which the product is exposed need to be defined. Ensure that the selected part material maintains the required physical properties over the entire temperature range that the product will experience during its operational life. Product designs need to be functional over the entire temperature range.

6.3.2.2 *Operational temperature range*—The material properties should exceed the required functional performance during the temperatures the product will experience over the majority of its operational life. Ensure that the selected part material maintains required physical geometry and material properties over its operational temperature range.

6.3.2.3 *Cyclic thermal exposure (or thermal fatigue)*—Periodic thermal changes that the product experiences during its operational life can permanently degrade material properties.

6.3.2.4 *Coefficient of thermal expansion (CTE) properties*—Thermal expansion of the product while operating near or at the extremes of its temperature range may change part geometry and material properties. CTE mismatch between mating components can lead to induced stresses and potentially failures. This is commonly reported using ASTM E228.

6.3.3 *Chemical Exposure:*

6.3.3.1 *Chemicals*—Identification of chemicals that may come in contact with the product should be determined due to possible chemical reactivity with the product material.

6.3.3.2 *Liquid Absorption*—Some AM materials may absorb certain liquids that contact them, possibly causing the material to swell, to degrade, or suffer other unintended negative consequences.

6.3.3.3 *Degradation/Aging of Material*—This is a possible consequence of exposure to chemicals, whether they are gases, liquids, or solids. This may also be a consequence of usage, wear-and-tear, etc. An example is humidity; a product may not have a problem in dry (arid) areas but fail when it is operating in a more humid environment.

6.3.3.4 *Forms of Corrosion*—The surrounding materials and the environment in which the AM metallic product will be in contact needs to be understood to mitigate all possible forms of corrosion.

6.3.4 *Radiation exposure:*

6.3.4.1 *Non-ionizing*—Damaging radiation such as visible light, radio waves, microwaves and low level exposures to UV light may affect material properties depending upon exposure levels.

6.3.4.2 *Ionizing*—Alpha, beta, cosmic rays, gamma rays, and X-ray radiation exposure levels need to be considered for possible effects to material properties.

6.3.5 *Other exposure:*

6.3.5.1 *Biological exposure*—Exposure to biological materials may cause material degradation or changes in properties. These materials may include human fluids or tissues, other animal fluids or tissues, plants or plant tissues, and algae or other microscopic organisms. Many of these considerations are covered by US FDA or other international regulations and designers should reference the relevant regulations.

6.3.5.2 *Environmental combinations*—Combinations of all environmental considerations (thermal, chemical, and radiation) need to be considered as material properties are affected when multiple conditions are present.

6.4 *Sustainability considerations:*

6.4.1 Companies, consumers, and governments often want to understand the impact of a product and its manufacturing process on the Earth's environment and natural resources. Sustainability typically deals with ecological impact and the desire to reduce negative human impact. As such, the topic of sustainability deserves attention when designing parts to be fabricated by AM. The presentation of considerations will start with the concept of reduce, recycle, and reuse.

6.4.2 *Reduce*—Reduction in material content in parts can yield significant savings over the lifetime of a product. For example, a 1 kg reduction in airplane mass across a fleet can save many thousands of litres of jet fuel and eliminate millions of kilograms of CO_2 emissions per year. Compared to conventional manufacturing processes, no tooling is needed, which reduces the usage of material during fabrication. Another example is the elimination of initial "stock" for machining and the need to machine off the majority of the material in order to fabricate a complex part. Designers are encouraged to use available design freedom to creatively design parts to be as efficient as possible while achieving all requirements.

6.4.3 *Recycle*—Recyclability refers to the capability of recovering the materials used in a part or product. Recycled materials become raw materials for a subsequent manufacturing process. Typically, metals are easily recycled, many thermoplastics are recyclable (to an extent), but thermoset polymers are not typically recyclable. ABS, polycarbonate (used in extrusion processes), and polyamide (used in polymer powder bed fusion) tend to be recyclable; however, designers should check the particular polymer blends used for AM processes. Typically, the photopolymers used in material jetting and vat photopolymerization processes are not recyclable.

NOTE 1—Although most materials are, technically, recyclable, limitations exist in many instances where specific materials are not commercially recycled due to various factors including, logistics, separation issues, or economics. Users are advised to take this into consideration when evaluating this aspect of material selection.

6.4.4 *Recycling logos*—Originally developed by the Society of Plastics Industry (SPI), the resin identification coding system dictates the symbols to be used on plastic parts to indicate the specific polymer composition of the part. The ASTM committee D20 currently manages the resin identification coding system and has developed a standard practice for this topic as ASTM D7611-13. The identification symbols are readily visible on consumer parts and are often used in community recycling programs to assist workers in separating different materials. Part designers should add these resin identification code symbols to their designs if parts are to be used for production purposes.

6.4.5 *Reuse*—Reuse refers to using a part after its original use without destroying its geometry, as is done in material recycling. Often, a reused part is used for a different purpose, one that is not as demanding on the part's properties. Other times, a part can be refurbished and reused for its original purpose. If a company wants to pursue a reuse strategy, then designers should design parts for extended lifetimes. Hence, there may be a tradeoff between "reduce" objectives and "reuse" objectives.

6.4.6 *Input stream*—This generally refers to the materials that are inputs to the various manufacturing processes, including the materials from which parts will be fabricated, support structure materials, etc. In many powder bed fusion processes, powder is reused from one build to the next. This powder recycling is very important from an economic viewpoint, but has limits. Typically, AM process feedstock is very carefully controlled by the AM machine vendors to ensure quality parts, reducing the importance of input stream considerations. However, as a wider variety of feedstocks is accepted, part designers will need to consider material choices carefully so that they have confidence that claimed physical properties are representative of as-fabricated properties.

6.4.7 *Waste stream*—The materials that remain after a product is dismantled and recyclable materials are separated are typically considered waste; these materials become the waste stream. In the case of AM processes, the products of part post-processing must also be considered wastes, including support structures (except metal supports), cleaning solvents, and powders that can no longer be recycled in powder bed fusion machines.

6.4.8 *Energy consumption*—Considerable energy can be consumed during part fabrication. AM machines use energy while heating up, processing materials, and even during cool-down if fans are running. This is not something that is easy to evaluate when designing parts or selecting manufacturing processes, but should become of increasing interest to AM machine vendors. Designers should also include energy consumption during post processing and finishing of parts.

6.4.9 *Water consumption*—Many companies are very concerned about water usage in factories, since in many parts of the US and the world, water is a scarce resource. Some vat photopolymerization processes require considerable amounts of water for post-processing.

6.4.10 *Carbon footprint*—This is a more general type of sustainability analysis that deals with most aspects of part manufacture across the supply chain. Carbon footprint is an overall measure of resources consumed and pollution emitted that starts with the extraction and processing of raw materials (e.g., mining) and ends with the recycling of product materials or reuse of parts. Good databases and tools are available for evaluating the carbon footprint of parts manufacturing for many common materials and many common manufacturing processes.

6.4.11 *Life-cycle impact*—Some summary comments can be made. It is important to consider that AM processes may be replacing other manufacturing processes and evaluations of the impact of AM production should be determined relative to the impacts of these other processes. Just because an AM process may consume significant energy, for example, does not mean it should not be used. The total impact (energy, water, carbon footprint, wastes, etc.) should be considered of the entire alternative process chains. Furthermore, the overall life-cycle impact of the product, given material and process choices, should be determined before adopting or rejecting the use of AM.

6.5 *Business considerations:*

6.5.1 There are several considerations business must entertain when deciding if AM is the best method for production of a part.

6.5.2 *Cost*—There are several aspects to the consideration of cost: AM fabrication cost, total part fabrication cost, and up front engineering cost, among others.

6.5.2.1 *AM fabrication cost*—Is it more effective to use AM? This consideration requires a cost analysis capability for the target process. Furthermore, it will be helpful if cost analyses are available for several AM processes and for one or more conventional manufacturing processes so that relative comparisons can be made. The capability of considering multiple materials will also be useful.

6.5.2.2 *Total part fabrication cost*—A process chain may be necessary to fabricate a part, where AM is only one process in the chain. Costs for all of these processes should be considered.

6.5.2.3 *Up front engineering costs*—Extensive design freedom can be a significant benefit, but considerable time and cost may be expended in searching extensive design spaces. Additionally, considerable time may be spent iterating with the fabrication process to determine the best process parameter settings, part orientation, supports and anchors, etc. Such iteration can become very expensive. In comparison, if an organization understands conventional processes and materials well, it may be more cost-effective to not employ AM.

6.5.3 *Material considerations*—Will the materials used in AM meet specifications for the product? Mechanical and other physical properties should be considered, as well as the operating environment, as described in earlier sections.

6.5.4 *Number of parts in the order*—Does the production run warrant use of AM or would another method be more effective? This consideration is similar to that of fabrication cost. Also, if low production volumes or customized parts are required, AM is likely to be less expensive than conventional manufacturing processes that require significant set-up or tooling costs.

6.5.5 *Time for AM fabrication*—Is the AM production turnaround time appropriate for the parts order? Production time will depend on how many parts can be fabricated in one build. It is important to distinguish between those AM processes that can fabricate multiple parts in one build vs. those where it is more suitable to build one part at a time. For small parts, it may be possible to fabricate thousands of the parts in a powder bed fusion process, where parts can be arrayed and stacked in 3 dimensions. This can greatly reduce average build time and overall production time for an order. Production time is also a function of how densely the platform or powder bed is packed. Practical limits exist on packing density due to the necessity of removing parts and support structures (e.g., vat photopolymerization) or managing the temperature distribution (powder bed fusion).

6.5.6 *Machine usage*—How many AM machines are needed for production? This is of course coupled with the previous two considerations. Overall production time for a batch of parts can be reduced, in many cases, by allocating more machines to the job.

6.5.7 *Post processing*—How detailed is the post processing step in the production of final parts? Support structure removal, polishing, thermal cycles (e.g., annealing), coatings, finishing, etc. are all possible post-processing steps that may be needed to achieve desired part qualities or properties. It is important to understand the time and expertise needed for manual post-processing. If a large volume of parts is needed over an extended period of time, it may be worthwhile to consider or develop automated post-processing methods.

6.5.8 *Waste disposal*—Can process wastes be disposed of easily? This is related to the sustainability considerations.

6.5.9 *Inspection*—Part inspection for accuracy, surface finish, mechanical properties, and other requirements should be considered during the design process. The designer may design inspection features onto the part to allow, for example, the presence of anisotropic scaling to be checked. Part design should also include consideration as to whether nondestructive testing of structural integrity will be required.

6.5.10 *Man-hours*—How many labor-hours will need to be expended using AM vs. conventional manufacturing processes? This is similar to the cost and time considerations discussed earlier. The skill level required should be considered also.

6.5.11 *Packaging and shipping*—Are there any special packaging and shipping considerations for the product? Is the device fabricated the final product that needs to be packaged for consumers? Will the part be delivered to a production facility for final assembly? Or, is the part a prototype that does not require special handling? A range of customer expectations exists that needs to be considered before delivering product.

6.5.12 *Supply chain and enterprise level decisions*—Several strategic decisions should be considered that impact supply chains. Should the company fabricate the part in-house or out-source its production? How much of the work should be out-sourced? By what criteria should suppliers be selected? Should a centralized or distributed production model be utilized? The company's strategy regarding its desire to compete on cost, flexibility, dependability, or other criteria affect how these decisions are made.

6.6 *Geometry considerations:*

6.6.1 Designer considerations related to geometry fall into two broad categories: part geometry and characteristics, and electronic file and exchange considerations. Considerations related to part geometry will be presented first.

6.6.2 *Accuracy and precision*—Accuracy provides an indication of how close the physical dimensions on an AM part agree with the specified dimensions. Precision provides an indication of how repeatable an AM process is. The mean and standard deviation of dimensional error are often taken as measures of accuracy and precision for a process. These values are often dependent on build orientation and/or part size for AM processes.

6.6.3 *Surface roughness*—Surface roughness is a measure of the deviations normal to the surface of an additively manufactured surface from the ideal surface (i.e., surface texture). Surface roughness is often dependent on the orientation, feed stock, and process parameters (e.g., layer thickness) for AM processes.

6.6.4 *Minimum feature size*—The minimum feature size refers to the smallest feature that a process is capable of producing. Features may involve positive volumes (i.e., ribs, bosses) or negative volumes (i.e., holes). Removal of support material is an important consideration for some AM processes with respect to minimum feature size (i.e., support removal from deep blind holes). As CAD model feature sizes approach the machine's feature resolution limits, designers should keep in mind that many AM processes will not produce shapes with sharp corners or other fine details.

6.6.5 *Maximum aspect ratio*—Related to minimum feature size is the maximum aspect ratio for a feature. Short thin features may build correctly, but if the feature is taller, the feature may break, crumble, or otherwise fail. Maximum aspect ratio expresses the relationship between feature width and height or length.

6.6.6 *Minimum feature spacing*—This refers to the minimum space that must be specified between adjacent features. For example, the minimum gap between moving parts in an additively manufactured assembly may be important to ensure that parts or features do not fuse together during manufacture.

6.6.7 *Recommended assembly fits*—This is the recommended clearance or interference between mating features on parts that are to be assembled after production. The recommended dimensions depend upon the function of the assembly. Clearances between mating features are appropriate when the parts must move freely with respect to one another. Clearances may also be appropriate when parts are to be glued together. Interferences between mating features are appropriate when the parts must be securely held together. Transitional fits may be appropriate when parts are intended to be assembled and disassembled.

6.6.8 *Maximum part size*—Maximum part size refers to the largest part dimensions along the X, Y, and Z axes as defined by ASTM F2921-11 that can be produced on a given AM machine. Parts may be larger than the build envelope of the selected process or machine. Designers can break part designs into multiple parts, each of which fits into the desired build envelope. Parts should be designed with assembly features that facilitate assembly operations, such as pins, holes, and mating joints (e.g., dovetails). Designers should analyze the economics of the assembly operations to compare with alternative manufacturing processes.

6.6.9 *Maximum unsupported feature*—This consideration is applicable to those AM processes that require support structures. Surfaces that face downward in the build may require supports. Typically, a process has a minimum angle (measured from vertical) for surfaces that indicates a surface requires supports. This threshold angle may depend on feature size or length. The concept of maximum unsupported feature refers to the largest feature size that can be built accurately at that threshold angle without support structures.

6.6.10 *Physical considerations*—To be suitable for AM, the part must be designed such that all thin areas of the part are thick enough to accommodate the minimum thickness requirements of the target AM machine as well as pre-processing software such as slicers. The designer must also consider the physical orientation of the part during manufacturing. For example, material extrusion processes may require greater or lesser support structures depending upon the orientation of the part in 3D space. It is a good idea to design the part for at least one orientation that minimizes overhangs, or areas of the part requiring support, in order to reduce wasted material and expedite production, if design freedom allows. Consideration of the effects of residual stresses and shrinkage may be important when determining part orientation as well. The part should be arranged in the software in the desired manufacturing orientation for maximum clarity of intended build orientation to the machine operator. The physical mass of the part being manufactured must also be considered, depending upon the selected manufacturing process, to ensure that gravity or other external forces do not cause the manufacturing process to fail.

6.6.11 *Mesh considerations*—It is currently standard practice in the AM industry to convert a 3D CAD model of a part into a triangular mesh ("mesh" for short) in the AMF format or STL format, since a mesh is the required form of input to AM build preparation software. Mesh models should satisfy several conditions. Designers should view their part's triangular mesh representation to ensure that it meets their requirements.

6.6.11.1 The designer should utilize an appropriate number of polygonal facets for accurate representation at the target scale, balanced against the size of the mesh data.

6.6.11.2 The mesh must be watertight, meaning the facets of the mesh completely enclose a positive volume without areas having zero thickness and without holes, gaps, or cracks. There should be no non-manifold edges, meaning an edge shared by more than two facets. There should also be no coincident edges or facets, meaning two edges or facets occupying the same space.

6.6.11.3 Sometimes meshing software will produce "flipped normal vectors," a situation where a triangle in the mesh has an orientation opposite to that of its neighbors. The normal vector of a triangle in a mesh must point outward, not inward toward the part's interior, in a valid STL or AMF file.

6.6.11.4 Internal facets, or those enclosed within the watertight volume, should be eliminated.

6.6.12 *Data interchange considerations*—If the design process will include multiple software components operating in a tool chain, the designer must take the import and export capabilities of all the software in the tool chain into consideration. The data file used as a transport between any two software components should retain the highest complexity representation of the data that is required by any software component later in the tool chain. For example, if one software component requires a non-uniform rational B-spline (NURBS) representation of the part, it should not be placed in the tool chain downstream of a software component incapable of importing a NURBS representation. Likewise, if final scale is unknown, higher resolution mesh or volumetric data should be preserved until the scale is known. Because of the limitations of import and export among software packages, care must be exercised in sequencing the software in the tool chain. Note that this tool chain might include the final additive manufacturing pre-processing software or firmware on the target manufacturing device. If the tool chain spans multiple devices or computers, ensure there are no disruptive differences in how the transport data file is interpreted on those devices or computers, in terms of architecture, endian-ness (ordering or sequencing of bytes of a word of digital data), floating point precision, dependency on graphics hardware, and so on.

6.7 *Material Property Considerations:*

6.7.1 *General*

The following is a list of material properties to assist in the selection of AM technologies and material type. It should be noted that AM processes typically produce parts with anisotropic properties, where the anisotropy is greater than in most conventional manufacturing processes. Designers must be aware of these anisotropies and design for them. In some cases, designers can take advantage of the anisotropy and are encouraged to explore creative design solutions, rather than view anisotropy as negative. Also, it is important to note that standards are being developed for characterizing properties of feedstock materials, such as metal powders for powder bed fusion processes (ASTM F3049-14).

6.7.2 *Mechanical properties*

6.7.2.1 *Mechanical properties*—Comprehensive standards are emerging for classes of materials which would subsume some aspects of this section. For example, ASTM F3122-14 is a guide on evaluating mechanical properties of metal AM parts. It should also be noted that uncertainties exist regarding test specimens, e.g., their location in the build, ensuring that the specimen's properties are representative of those of the part, how to capture process information along with the test data, etc.

6.7.2.2 *Tensile strength, tensile modulus, tensile elongation*—These are common tensile mechanical properties that are determined using standard dog-bone samples, according to ASTM D638 and E8. For parts fabricated using AM processes, these properties commonly vary for parts built in different orientations.

6.7.2.3 *Flexural strength, flexural modulus*—Other common mechanical properties that address the ability of a material to resist deformation under bending loads, commonly reported using ASTM D790. Again, the properties may vary for different build orientations.

6.7.2.4 *IZOD impact, notched/un-notched*—This test measures a material's resistance to impact from a swinging pendulum, which is often referred to as impact strength. The test is commonly reported using ASTM D256 and ASTM D4812. Parts produced using many AM processes have impact strengths less than those fabricated using same/similar materials on conventional manufacturing processes, particularly if porosity is evident. For this property, build orientation has not been investigated to understand the effect in test results.

6.7.2.5 *Compression strength, compression modulus*—These properties refer to the ability of a material to resist axially directed pushing forces that attempt to squeeze or compress the material together, commonly reported using ASTM D695and ASTM E9. For many AM processes, these properties tend to be less sensitive to build orientations than tensile or flexural properties.

6.7.2.6 *Shear strength*—This property refers to the ability of a material to resist forces that attempt to cause it to become permanently deformed by sliding against itself without rupture. This is commonly reported using ASTM D732. For this property, build orientation has not been investigated to understand the effect in test results.

6.7.2.7 *Fatigue strength and fatigue limit*—These properties are defined as the value of stress at which failure occurs after a specified number of cycles, and as the limiting value of stress at which failure occurs as the number of cycles becomes very large, respectively. In many cases, AM-produced parts in their as-built state have poor fatigue performance compared to their traditionally manufactured counterparts due to crack propagation from layer, scan, or material deposition interfaces, or from residual porosity. However, if well designed, voids intentionally induced could act as crack arrestors. The orientation of the part with respect to the primary fatigue load axis will have an impact on fatigue life, in the part's as-built state. Part surface finish will likely have an effect on fatigue life, although exceptions may arise. In some cases, AM-produced parts can be better than traditionally manufactured parts for fatigue if these issues are well understood and controlled.

6.7.3 *Thermal properties:*

6.7.3.1 *Heat deflection (HDT)*—The temperature at which a polymer material deforms under a specific load. The test is often performed at multiple pressures, including at 0.455 MPa and 1.82 MPa (66 psi and 264 psi), and is commonly reported using ASTM D648. This parameter is of interest for parts that are used at temperatures above room temperature.

6.7.3.2 *Glass transition temperature (Tg)*—The temperature at which a polymer material transitions from a hard and relatively brittle state into a molten or rubber-like state. For processes that utilize a solid-to-liquid-to-solid set of phase changes, Tg is an important parameter for both AM processing as well as part usage at elevated temperatures.

6.7.3.3 *Melt point*—The temperature at which a solid becomes a liquid at standard atmospheric pressure.

6.7.4 *Electrical properties:*

6.7.4.1 *Volume resistivity*—The resistance to leakage current through the body of an insulating material, commonly reported using ASTM D257.

6.7.4.2 *Dielectric constant*—The ratio of the amount of energy stored in a material by an applied voltage relative to that stored in a vacuum. This consideration and the next two have relevance to dielectric materials that are used in capacitors, piezoelectric materials and actuators, antennas, and more generally the response of materials to electromagnetic fields. This is commonly reported using ASTM D150-98.

6.7.4.3 *Dissipation factor*—The ratio of the power loss in a dielectric material to the total power transmitted through the dielectric, commonly reported using ASTM D150-98.

6.7.4.4 *Dielectric strength*—The maximum electrical potential gradient that a material can withstand without rupture, commonly reported using ASTM D149-09.

6.7.5 *Other:*

6.7.5.1 *Specific gravity/density*—The measure of the ratio of mass of a given volume of material at 23°C to the same volume of deionized water, commonly reported using ASTM D792.

6.7.5.2 *Rockwell hardness*—This is a hardness measurement of a metal based on the net increase in depth of impression as a load is applied and is commonly reported using ASTM D785.

6.7.5.3 *Durometer*—This is a hardness measurement for polymers, elastomers, and rubbers. There are several durometer scales; the ASTM D2240-00 standard defines 12 scales.

6.7.5.4 *Flame classification/flammability*—Flammability is the ability of a material to support combustion. This consideration is of high relevance for any applications in human transportation, such as in the aerospace and automotive industries, and is commonly reported using UL94.

6.7.5.5 *Water absorption*—The amount of weight gain (%) experienced in a polymer material after immersion in water for a specific length of time under controlled environment, commonly reported using ASTM D570.

6.8 *Process considerations:*

6.8.1 *General*

The following topics cover general process considerations and considerations that may be important for process selection for the seven classes of AM processes that are defined in Clause 3. Process selection involves choosing among these and choosing appropriate materials. Designers may find it useful to consider polymer vs. metal, thermoplastic vs. thermoset polymers, and vector vs. raster processing. Part quality and properties will be influenced by the specific process variable settings that are chosen to fabricate the part. To support those considerations, primary process variables are identified for each process.

6.8.2 *Specific process considerations*

6.8.2.1 *Binder jetting*—Binder jetting is capable of fabricating the full spectrum of powder materials (ceramics, metals and polymers) and offers the capability to control pore characteristics (size, morphology and volume fraction) with repeatability and reproducibility. Printing a binder into a bed of powder provides a means to manipulate chemical, physical and mechanical properties. Support structures are rarely needed since the powder itself supports the parts being fabricated. This is called "self supporting." The key process variables to consider include powder selection, binder selection and formulation, powder-binder interactions, infiltrant selection, saturation (amount of binder printed per unit volume of powder), and post-processing treatments.

6.8.2.2 *Directed energy deposition*—Directed energy deposition is a process of spraying or feeding a metal feedstock into a focused energy source, creating a weld pool, which traverses to build the object. This is essentially a welding process that utilizes either a powder spray or wire feed. In principle, any metal alloy that can be welded should be processable using directed energy deposition. Steels and a variety of alloys are commercially available. It is also possible to mix powders, enabling graded material compositions. Good metallurgy can be achieved since the feedstock is fully melted and typically rapidly cooled, yielding properties that are usually as good as or better than cast. However, residual stresses can be an issue. This process can be utilized to fabricate parts or to repair metal parts, since the process is flexible enough to build on virtually any metal substrate. 5-axis machine architecture is needed in order to fabricate parts of arbitrary complexity due to the nature of the deposition process and since the process does not utilize support structures. For part fabrication (as opposed to repair), the part is built on a platform and must be removed using a machining operation. The key process variables include laser power, material feed rate, scan speed, and the atmosphere (pressure, choice of inert gas, gas flow rate).

6.8.2.3 *Material extrusion*—In material extrusion processes, a filament of material or a paste material is extruded through a nozzle which traverses to build up the object, layer by layer. Support structures are often employed to support overhanging features, and can consist of either the part material or a secondary material (often soluble, e.g. wax, soluble polymer, etc.). Filament-based material extrusion systems typically utilize amorphous thermoplastic polymer materials. Composite (filled) materials are available also consisting of a thermoplastic polymer matrix material with one or more filler constituents, for example, ceramic nanoparticles or short fibres. Paste extruders utilize a variety of materials, from glue to ceramic or metal slurries (suspensions) to silicones. Due to the layer-based extrusion process, material properties are anisotropic: stronger in the build plane than in the Z-direction due to limitations of inter-layer bonding. Key process variables include material composition, nozzle diameter (extruded filament diameter), material feed rate, scan speed, and build chamber atmosphere and temperature.

6.8.2.4 *Material jetting*—Material jetting processes deposit liquid materials via droplet formation processes such as ink-jet, aerosolization, or atomization processes. Materials, also called inks, may include photopolymers, nano-ink dispersions, solutions, wax, biomaterials, etc. Typically, banks of jetting nozzles are utilized to enable high rate material deposition. In some processes, multiple jets provide a means of locally controlling material composition by depositing different materials in different areas or even by combining multiple materials. If conductive inks are deposited, electronic circuits can be fabricated either on external part surfaces or embedded inside parts. Parts tend to be fully dense and have good surface finish due to the small size of the droplets, which range from 16 to 30 µm. Support structures are needed; depending on the materials deposited, soluble supports may be available. Key process variables include ink formulation (composition, solvent system, solid loading fraction), deposition temperature, substrate temperature, carrier gas (aerosol jetting), substrate stand-off distance, print pattern, and deposition pattern (scan speed, droplet generation rate, hatch spacing, etc.).

6.8.2.5 *Powder bed fusion*—In powder bed fusion processes, an energy source is used to melt powder particles to form part cross-sections. Typically, the energy source is a laser or electron beam, but other variants are possible, such as heat lamps if material patterning mechanisms are used. After fusing powder on one layer, a new layer of powder is spread across the build area in preparation for the next powder fusing operation. Primarily, metals and semi-crystalline thermoplastic polymers are used, but ceramics and other materials have been demonstrated as well. For polymers, polyamide (trade name Nylon) materials are most commonly used, but elastomers, glass-filled polyamide, and some other reinforced variants are available. In the metals area, a wide variety of alloys is available, including steels and titanium, nickel-based, cobalt-chrome, and aluminium alloys. For polymers, the process typically produces parts with some porosity, in order to maintain dimensional accuracy. For metals, full melting is typical, resulting in parts that approach full density. For polymer PBF processes, support structures are typically not needed since the powder bed supports the parts. In contrast, metal PBF typically requires support structures to anchor the part to the platform in order to maintain part accuracy and prevent warpage. Key process variables include laser/electron-beam power, scan speed, scan pattern, powder composition, powder size distribution, and powder bed temperature.

6.8.2.6 *Sheet lamination*—Sheet lamination processes fabricate parts by layering sheets of material, cutting them into shapes of desired part cross sections, and bonding the sheets together. Different processes implement these operations in different orders, with some cutting then stacking and bonding, while others stack then bond and cut. Different bonding approaches have been used including glue, thin polymer layers that are melted, consolidation at elevated temperatures and pressures, and ultrasonic welding. The first sheet lamination process used paper, but other research and commercial systems have been developed for plastic, metal, and ceramic sheets, including composites. Fabricated parts are typically fully dense. Particularly for processes that stack then cut sheets, the stack of sheets has parts embedded inside, necessitating post-processing operations to remove the excess material. Key process variables include sheet material composition, sheet thickness, bonding mechanism and materials, cutting process selection (e.g., laser, knife), and others that depend upon these choices.

6.8.2.7 *Vat photopolymerization*—Similar to powder bed fusion, vat photopolymerization processes fabricate part cross sections using patterned energy beams. However, the material used is a liquid resin that polymerizes when the energy beam shines on the resin surface. Photopolymerization is the most common type of reaction, but thermal initiation of reactions has also been explored in some research systems. Materials are limited to thermosets that can be photo or thermally initiated. Commercial and many research processes utilize acrylate or epoxy material systems, although some research processes are exploring other materials including polyurethanes, hydrogels, and other chemistries. Commercial stereolithography machines are generally regarded as having the best accuracy and very good surface finish, compared to other AM processes for equally sized parts. Support structures are required and are typically fabricated using the material in the resin vat, which is the same as the part material. Key process variables include process configuration (laser scan vs. mask projection), energy beam power, scan pattern or mask pattern, laser scan speed or mask display duration, and layer thickness.

6.8.3 *Other considerations*

6.8.3.1 *Post-processing considerations*—Post processing requirements depend greatly on the specific process and material under consideration. If support structures are used, they must be removed. In some cases, supports must be removed mechanically, while in other cases they may be dissolved in a solvent. For processes using metals, parts are typically anchored to a platform in order to support the part and maintain its proper shape during fabrication; machining operations must be used to remove the parts. Support structures almost always produce a rougher surface than would otherwise be fabricated. In vat photopolymerization processes, the part is immersed in a resin bath and a thin coating of the resin will remain on the part after removal from the machine. This resin must be cleaned off and, in many cases, a subsequent post-cure operation performed to fully cure the part's surfaces and any remaining uncured resin inside the part. For processes that utilize a powder bed (powder bed fusion or binder jetting), the parts must be removed from the bed and cleaned off. Since fine powders are used typically, this part clean up should be performed with some protection for the personnel performing the post-processing. In many cases, users may have control over support structure generation through variables that control support density and placement, as well as touch point size or position. Finally, end use requirements may require the part to be finish machined, sanded, painted, or have other operations performed. Specific recommendations are process, material, and situation dependent, so more detailed considerations are difficult to provide.

6.8.3.2 *Qualification requirements*—For some component suppliers and AM component designers/users, it is critical to define the actions needed to demonstrate or confirm that a given AM process, using a particular AM material for a particular AM design, will produce a component having the properties necessary for the part to perform successfully. Furthermore, the process must be repeatable. Qualification is particularly important for production applications. Designers should be aware of these requirements and identify relevant standards in their company or industry.

6.8.3.3 *Inspection method considerations*—Qualification and inspection are quality assurance processes that are complementary. When inspections are more robust and practical, qualification requirements may be reduced. Conversely, when inspections are difficult or impossible, qualification requirements are made to be more stringent. A wide variety of inspection processes is available, including destructive and non-destructive methods. Designers should work with their quality groups to ascertain if appropriate inspection and qualification processes are available or need to be developed for the types of parts that they are designing.

6.9 *Communication considerations:*

6.9.1 Considerations in this category address issues that arise in communicating design intent and requirements. Examples include how to specify conditions that ensure that parts fit together properly, clearances, etc. Also, shrink factors may be important. The context is important here: part geometry is typically exchanged using STL or AMF files, so how should all the information that is conveyed in CAD models, notes on CAD drawing, email messages, etc. be conveyed from designer to manufacturer?

6.9.2 *Design intent*—The beauty of growing designs using AM rather than conventional processes is many-sided but one key windfall is the reduction of risk of manufacturing error. Complex assemblies can be reduced to a single part. Though attractive, from a simplistic and potentially "paperless" approach, the successful conveyance and implementation of design intent should not be taken lightly. If the designer neglects communicating more than the CAD requirements the resulting component may not meet the designer's and user's expectations. Therefore, communication between the designer and producers of AM components is essential. Helping the AM producer fully understand what is expected of their services is the responsibility of the designer and a clear understanding is needed to successfully produce a part design. In some cases the design may be simple enough to pass to one or several AM systems and based on industry norms for a given system a desired part can often result. When part designs begin including more function and moving parts with clearances or properties such as chemical, mechanical, or thermal, the designer must successfully communicate these expectations and preferably use multiple forms of verbal and non-verbal, perhaps traceable, communication. Sometimes if a supplier is not receiving the designer's message about expectations, extra steps must be taken to confirm successful communication. Designers also must be aware of AM limitations and AM producers are ideally equipped to convey their capabilities.

6.9.3 *Process limitations*—Similar to design intent, a dialog between designers and manufacturers is sometimes needed to communicate process limitations and their implications for part design. One example arises in the design of support structures for metal PBF processes. It can be difficult to design appropriate support structures that maintain part accuracy and prevent warpage, so this dialog can be very useful. Another issue is the consideration of build orientation as it relates to the achievement of tolerances, surface finish, and mechanical properties. Furthermore, it may be necessary for calibration runs to be fabricated in order to characterize scale factors or other minor shape modifications. Communications between designers and manufacturers will be necessary to understand and quantify process limitations, then make design and/or process changes to compensate.

7. Warnings to designers

7.1 Clause 7, warnings to designers, or "red flag" issues, are presented that indicate situations that often lead to problems in many AM systems, including overhangs, abrupt thickness transitions, trapped volumes, layering, cleanliness, fine part details, non-destructive testing requirements, tessellation, scale and units, and file sources.

7.2 *Overhangs*—Overhangs in some AM systems can become problematic when support structure is required to prevent the overhangs from sagging or curling. If support structure is required (for the selected process) the designer must plan for support removal. For some feature-rich designs, such as lattice structures or hollow, closed volumes, support removal can be problematic. In some processes, such as polymer powder bed fusion, the unused build material becomes the support structure. Designers must plan for support removal by designing access into the component or orienting the component in a manner to minimize support requirements. Communication with the AM supplier is critical to fully understand the support requirements for the selected process. Often components can be oriented to become "self-supporting." Minimizing down-facing flat surfaces is key.

7.3 *Abrupt thickness transitions*—In thermally driven processes (powder bed fusion, directed energy deposition, and material extrusion), abrupt thickness transitions can cause distortions or accuracy problems. The thicker section can retain heat, causing the distortions, similar to the effects seen in injection molding and die casting.

7.4 *Trapped volumes*—If a component has a design leading to volumes of unused build material becoming trapped, this can lead to extra mass and in the case of powder or liquid build materials the material could be considered hazardous if it leaks. A simple method for addressing these trapped volumes is to create access holes, slots, or other features. In many cases access holes can later be closed using a secondary step of welding or patching if needed. Having two points of access to a trapped volume can provide an advantage when using compressed air or solvent to completely remove the unused materials.

7.5 *Layering*—The layer-based nature of AM often leaves layer marks or small surface transitions along the external surfaces of parts, which are informally called "stair steps." These layer marks can be sites of stress concentration that may serve as crack initiation sites and can reduce fatigue life. Although external part surfaces can be machined or finished to remove the marks, internal part surfaces may not be easily finished. Designers should be aware of the impact of layer marks on the fatigue life and fracture characteristics of the parts they design.

7.6 *Cleanliness*—Cleanliness for some applications, including medical and hydraulic systems, is often critical. Traces of metal powder can easily damage fluid power systems, such as pumps and actuators. For medical application, power or resin contamination can become a problem if the component is an implant or needs to be sterilized and inert. In some applications additional measures may be required to ensure an AM component is particularly clean.

7.7 *Fine part details*—Small features on parts may become degraded during part removal from the machine or during post-processing. Sand blasting or similar abrasive post-processing is often used with metal parts, but can adversely impact features or surface finishes. Similarly, solvents used for vat photopolymerization processes or soluble support materials may degrade features or surfaces as well.

7.8 *Nondestructive testing (NDT) requirements*—AM can produce different types of flaws and weaknesses within a component than are typically seen with conventional manufacturing. Different AM processes produce different types of flaws, such as inclusions, voids, or layer delaminations, depending on the details of the process, which could compromise the performance of the component. For components that would be subjected to NDT examination, the proper NDT method and unacceptable flaw sizes and locations should be specified.

7.9 *Tessellation*—Typically, AM component models are converted to STL or AMF files that have geometries defined by surface triangles. Triangle sizing has a significant impact on surface smoothness and accuracy. The quality of the tessellated file, exported by the CAD system, can usually be adjusted and tuned to achieve a desired quality. A good practice is to specify a tessellation quality (resolution of the tessellation) that is compatible with the resolution of the fabrication process. Smaller resolutions result in larger STL or AMF files, but provide no improvement in part quality. The output file intended for AM should always be viewed by the designer in an appropriate viewing software package to ensure the AM build file accurately conveys the design intent. Taking measurements of critical features is recommended using the tessellated geometry viewer.

7.10 *Scale and units*—STL files are unit-less and quite often as AM files are prepared for build an error in units can occur. If the designer does not successfully communicate the units for the file, an undersized or oversized part can be produced. Including the units in the filename is helpful to avoid this common error. In contrast, the usage of AMF will avoid scale and unit errors, since units must be specified in an AMF file.

7.11 *File source – CAD vs. CT*—There are a number of file sources used to generate STL and AMF files including scanned data and CAD. Errors can occur due to CT-slice scan thickness and resolution, point-cloud quality from scanners, and similar resolution limitations from other sources of scanned data. Designers need to understand and evaluate the quality of files being used to design components intended for AM.

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