ISO/ASTM 52900:2021(E)

Additive manufacturing — General principles — Fundamentals and vocabulary[1,2]

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INTRODUCTION

Additive manufacturing (AM) is the general term for those technologies that successively join material to create physical objects as specified by 3D model data. These technologies are presently used for various applications in engineering industry as well as other areas of society, such as medicine, education, architecture, cartography, toys and entertainment.

During the development of additive manufacturing technology, there have been numerous different terms and definitions in use, often with reference to specific application areas and trademarks. This is often ambiguous and confusing, which hampers communication and wider application of this technology.

It is the intention of this document to provide a basic understanding of the fundamental principles for additive manufacturing processes, and based on this, to give clear definitions for terms and nomenclature associated with additive manufacturing technology. The objective of this standardization of terminology for additive manufacturing is to facilitate communications between people involved in this field of technology on a worldwide basis.

1. Scope

1.1 This document establishes and defines terms used in additive manufacturing (AM) technology, which applies the additive shaping principle and thereby builds physical three-dimensional (3D) geometries by successive addition of material.

1.2 The terms have been classified into specific fields of application.

1.3 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Normative references

2.1 There are no normative references in this document.

[1] This international standard is under the jurisdiction of Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.91 on Terminology, and is also under the jurisdiction of ISO/TC 261, Additive manufacturing, on the basis of a partnership agreement between ISO and ASTM International with the aim to create a common set of ISO/ASTM standards on additive manufacturing.

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[2] Through a mutual agreement with ASTM International (ASTM), the Society of Manufacturing Engineers (SME) contributed the technical expertise of its RTAM Community members to ASTM to be used as the technical foundation for this ASTM standard. SME and its membership continue to play an active role in providing technical guidance to the ASTM standards development process.

3. Terms and definitions

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

– ISO Online browsing platform: available at https://www.iso.org/obp
– IEC Electropedia: available at http://www.electropedia.org/

3.1 *Definitions:*

General terms

3D printer, *n*—machine used for **3D printing**.

additive manufacturing (AM), *n*—process of joining materials to make **parts** from 3D model data, usually **layer** upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.

DISCUSSION—Historical terms include: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication and freeform fabrication.

DISCUSSION—The meaning of "additive-", "subtractive-" and "formative-" manufacturing methodologies is further discussed in Annex A2.

additive system, *n*—
additive manufacturing system
additive manufacturing equipment
machine and auxiliary equipment used for **additive manufacturing**.

AM machine, *n*—section of the **additive manufacturing system** including hardward, machine control software, required set-up software and peripheral accessories necessary to complete a **build cycle** for producing **parts**.

AM machine user, *n*—operator of or entity using an **AM machine**.

AM system user, *n*—
additive system user
operator of or entity using an entire **additive manufacturing system** or any component of an **additive system**.

front, *n—of a machine, unless otherwise designated by the machine builder*, side of the machine that the operator faces to access the user interface or primary viewing window, or both.

material supplier, *n*—provider of material/**feedstock** to be processed in an **additive manufacturing system**.

multi-step process, *n*—type of **additive manufacturing** process in which **parts** are fabricated in two or more operations where the first typically provides the basic geometric shape and the following consolidates the part to the fundamental properties of the intended material.

Discussion—Fundamental properties of the intended product material are typically metallic properties for intended metallic products, ceramic properties for intended ceramic products, polymer properties for intended polymer (plastic) products and composite material properties for products intended to be made of a composite material.

Discussion—Removal of the support structure and cleaning can many times be necessary; however, in this context, this operation is not considered as a separate process step.

Discussion—The principle of **single-step** and multi-step processes is further discussed in Annex A2.

single-step process, *n*—type of **additive manufacturing** process in which **parts** are fabricated in a single operation where the basic geometric shape and basic material properties of the intended product are achieved simultaneously.

Discussion—Removal of the support structure and cleaning can many times be necessary; however, in this context, this operation is not considered as a separate process step.

Discussion—The principle of single-step and **multi-step processes** is further discussed in Annex A2.

3.2 *Definitions:*

Process categories

binder jetting (BJT), *n*—**additive manufacturing** process in which a liquid bonding agent is selectively deposited to join powder materials.

Discussion—Identification of different binder jetting processes shall be consistent with the method described in Annex A1.

directed energy deposition (DED), *n*—**additive manufacturing** process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

Discussion—"Focused thermal energy" means that an energy source (for example, laser, electron beam or plasma arc) is focused to melt the materials being deposited.

Discussion—Identification of different directed energy deposition processes shall be consistent with the method described in Annex A1.

material extrusion (MEX), *n*—**additive manufacturing** process in which material is selectively dispensed through a nozzle or orifice.

Discussion—Identification of different material extrusion processes shall be consistent with the method described in Annex A1.

material jetting (MJT), *n*—**additive manufacturing** process in which droplets of feedstock material are selectively deposited.

Discussion—Example feedstock materials for material jetting include photopolymer resin and wax.

Discussion—Identification of different material jetting processes shall be consistent with the method described in Annex A1.

powder bed fusion (PBF), *n*—**additive manufacturing** process in which thermal energy selectively fuses regions of a **powder bed**.

Discussion—Identification of different powder bed fusion processes shall be consistent with the method described in Annex A1.

sheet lamination (SHL), *n*—**additive manufacturing** process in which sheets of material are bonded to form a **part**.

Discussion—Identification of different sheet lamination processes shall be consistent with the method described in Annex A1.

vat photopolymerization (VPP), *n*—**additive manufacturing** process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

Discussion—Identification of different vat photopolymerization processes shall be consistent with the method described in Annex A1.

3.3 *Definitions:*

Processing: general

3D printing, *n*—fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology.

Discussion—This term is often used in a non-technical context synonymously with **additive manufacturing** and, in these cases, typically associated with machines used for non-industrial purposes including personal use.

build chamber, *n*—enclosed location within the **additive manufacturing system** where the **parts** are fabricated.

build cycle, *n*—single process cycle in which one or more components are built by successive joining of material within the **build space** of the **additive manufacturing system**.

build platform, *n—of a machine*, base which provides a surface upon which the building of the **parts** is started and supported throughout the build process.

Discussion—In some systems, the **parts** are built attached to the build platform, either directly or through a **support** structure. In other systems, such as certain types of **powder bed** systems, a direct mechanical fixture between the part and the build platform is not necessarily required.

build space, *n*—location where it is possible for **parts** to be fabricated, typically within the **build chamber** or on a **build platform**.

build surface, *n*—area where material is added, normally on the last deposited **layer** which becomes the foundation upon which the next layer is formed.

Discussion—For the first layer, the build surface is often the **build platform**.

Discussion—In the case of **directed energy deposition** processes, the build surface can be an existing part onto which material is added.

Discussion—If the orientation of the material deposition or consolidation means, or both, is (are) variable, it may be defined relative to the build surface.

build volume, *n*—total usable volume available in the machine for building **parts**.

layer, *n—matter*, material laid out, or spread, to create a surface.

manufacturing lot, *n*—set of manufactured **parts** having commonality between **feedstock**, **production run**, **additive manufacturing system**, and **post-processing** steps (if required) as recorded on a single manufacturing work order.

Discussion—The additive manufacturing system can include one or several **AM machines** and/or post-processing machine units, as agreed by **AM** provider and customer.

manufacturing plan, *n*—document setting out the specific manufacturing practices, technical resources and sequences of activities relevant to the production of a particular product including any specified acceptance criteria at each stage.

Discussion—For **additive manufacturing**, the manufacturing plan typically includes, but is not limited to, **process parameters**, preparation and **post processing** operations as well as relevant verification methods.

Discussion—Manufacturing plans are typically required under a quality management system such as ISO 9001(**1**)[3] and ASQ C1(**2**).

process chain, *n*—sequence of operations necessary for the **part** to achieve desired functionality and properties.

process parameters, *n*—operating parameters and system settings used during a **build cycle**.

production run, *n*—set of all **parts** produced in one **build cycle** or sequential series of build cycles using the same **feedstock** batch and process conditions.

support, *n*—structure separate from the **part** geometry that is created to provide a base and anchor for the part during the building process.

Discussion—Supports are typically removed from the part prior to use.

Discussion—For certain processes such as **material extrusion** and **material jetting**, the support material can be different from the part material and deposited from a separate nozzle or print head.

Discussion—For certain processes such as metal **powder bed fusion** processes, auxiliary supports can be added to serve as an additional heat sink for the part during the building process.

system set-up, *n*—configuration of the **additive manufacturing system** for a build cycle.

3.4 *Definitions:*

Processing: data

3D scanning, *n*—
3D digitizing

method of acquiring the shape and size of an object as a 3-dimensional representation by recording x, y, z coordinates on the object's surface and through software converting the collection of points into digital data.

Discussion—Typical methods use some amount of automation, coupled with a touch probe, optical sensor or other device.

Discussion—In additive manufacturing process chains, 3D scanning can typically be used for generation of surface models, in situ monitoring, non-destructive testing, as well as verification of the part geometry.

Additive Manufacturing File Format (AMF), *n*—file format for communicating **additive manufacturing** model data including a description of the 3D surface geometry with native support for color, materials, lattices, textures, constellations and metadata.

Discussion—Additive Manufacturing File Format (AMF) can represent one of multiple objects arranged in a constellation. Similar to **STL**, the surface geometry is represented by a triangular mesh, but in AMF the triangles can also be curved. AMF can also specify the material and color of each volume and the color of each triangle in the mesh. ISO/ASTM 52915(**3**) gives the standard specification of AMF.

AMF consumer, *n*—software reading (parsing) the **AMF** file for fabrication, visualization or analysis.

Discussion—AMF files are typically imported by **additive manufacturing equipment**, as well as viewing, analysis and verification software.

AMF editor, *n*—software reading and rewriting the **AMF** file for conversion.

Discussion—AMF editor applications are used to convert an AMF from one form to another, for example to convert all curved triangles to flat triangles or convert porous material specification into an explicit mesh surface.

AMF producer, *n*—software writing (generating) the **AMF** file from original geometric data.

Discussion—AMF files are typically exported by CAD software, scanning software or directly from computational geometry algorithms.

attribute, *n—data*, characteristic representing one or more aspects, descriptors or elements of the data.

Discussion—In object-oriented systems, attributes are characteristics of objects. In Extensible Markup Language (XML(**4**)), attributes are characteristics of **elements**.

Discussion—In the **AMF**-file, attributes can, for example, be used to carry notices enabling backwards traceability to CAD components, or markers that allow track and trace mechanisms for the file.

comment, *n—data*, remark in source code which does not affect the behavior of the program.

Discussion—Comments are used for enhancing human readability of the file and for debugging purposes.

Discussion—In the **AMF**-file, comments can, for example, be used to carry material specification or notices enabling backwards traceability to CAD components.

element, *n*—information unit within an XML(**4**) document consisting of a start tag, an end tag, the content between the tags and any **attributes**.

Discussion—In the XML framework of **AMF**, an element can contain data, attributes structures such as constellations, as well as including other elements.

[3] The boldface numbers in parentheses refer to a bibliography at the end of this standard.

facet, *n*—three- or four-sided polygon that represents an element of a 3D polygonal mesh surface or model.

DISCUSSION—Triangular facets are used in the file formats most significant to **AM**: **AMF** and **STL**; however, AMF files permit a triangular facet to be curved.

Product Data Exchange Specification (PDES), *n*—data exchange specification using **STEP**.

DISCUSSION—Originally, a product data exchange specification developed in the 1980s by the IGES/PDES Organization, a program of U.S. Product Data Association (USPRO). It was adopted as the basis for and subsequently superseded by ISO 10303(**5**) STEP.

STEP, *n*—standard for the exchange of product model data.

DISCUSSION—This is an International Standard that provides a representation of product information, along with the necessary mechanisms and definitions to enable product data to be exchanged. ISO 10303(**5**) applies to the representation of product information, including components and assemblies; the exchange of product data, including storing, transferring, accessing and archiving.

DISCUSSION—ISO 10303-238, commonly referred to as STEP-NC, specifies the slicing operation and other mechanical commands to the AM process.

STL, *n*—file format for model data describing the surface geometry of an object as a tessellation of triangles used to communicate 3D geometries to machines in order to build physical **parts**.

DISCUSSION—The STL file format was originally developed as part of the CAD package for the early STereoLithography Apparatus, thus referring to that process. It is sometimes also described as "Standard Triangulation Language" or "Standard Tesselation Language", though it has never been recognized as an official standard by any standards developing organization.

surface model, *n*—mathematical or digital representation of an object as a set of planar or curved surfaces, or both, that can, but does not necessarily have to represent a closed volume.

3.5 *Definitions:*

Processing: positioning, coordinates and orientation

arbitrarily oriented bounding box, *n—of a part*, **bounding box** calculated without any constraints on the resulting orientation of the box.

bounding box, *n—of a part*, orthogonally oriented minimum perimeter cuboid that can span the maximum extents of the points on the surface of a 3D **part**.

DISCUSSION—Where the manufactured part includes the test geometry plus additional external features (for example, labels, tabs or raised lettering), the bounding box may be specified according to the test part geometry excluding the additional external features if noted. Different varieties of bounding boxes are illustrated in ISO/ASTM 52921(**6**).

build envelope, *n*—largest external dimensions of the **x-axis**, **y-axis**, and **z-axis** within the **build space** where **parts** can be fabricated.

DISCUSSION—The dimensions of the build space are larger than the build envelope.

build origin, *n*—**origin** most commonly located at the center of the **build platform** and fixed on the build facing surface.

DISCUSSION—The location of the build origin can be defined otherwise by the build set-up.

geometric center, *n*—
centroid
of a bounding box, location at the arithmetic middle of the **bounding box**.

DISCUSSION—The geometric center of the bounding box can lie outside the **part** that is enclosed by the bounding box.

initial build orientation, *n—of a part*, orientation of the part as it is first placed in the **build volume**.

DISCUSSION—Initial build orientation is illustrated in ISO/ASTM 52921(**6**).

machine bounding box, *n—of a part*, **bounding box** for which the surfaces are parallel to the **machine coordinate system**.

machine coordinate system, *n*—three-dimensional coordinate system as defined by a fixed point on the **build platform**, with the three principal axes labelled **x-axis**, **y-axis** and **z-axis** with rotary axis about each of these axes labelled A, B and C, respectively, where the angles between x-, y- and z-, can be Cartesian or defined by the machine manufacturer.

DISCUSSION—Machine coordinate system is fixed relative to the machine, as opposed to coordinate systems associated with the **build surface**, which can be translated or rotated. Machine coordinate system is illustrated in ISO/ASTM 52921(**6**).

machine origin, *n*—
machine home
machine zero point
origin as defined by the machine manufacturer.

master bounding box, *n*—**bounding box** which encloses all of the **parts** in a single build.

nesting, *participle*—situation when **parts** are made in one **build cycle** and are located such that their **bounding boxes**, **arbitrarily oriented** or otherwise, will overlap.

origin, *n*—
zero point
(0, 0, 0)
when using x-, y- and z-coordinates, designated universal reference point at which the three primary axes in a coordinate system intersect.

DISCUSSION—Coordinate system can be Cartesian or as defined by the machine manufacturer. The concept of origin is illustrated in ISO/ASTM 52921(**6**).

orthogonal orientation notation, *n*—description of the orientation of the **bounding box** according to overall length in decreasing magnitude, parallel to the axes of the **machine coordinate system**.

DISCUSSION—Notation typically consists of a combination of X, Y and Z, each referring to the corresponding axis as defined by the machine coordinate system.

DISCUSSION—Orthogonal orientation notation requires that the bounding box be aligned with the machine coordinate system. Machine coordinate system and different bounding boxes, including examples of orthogonal orientation notation, are illustrated in ISO/ASTM 52921(**6**).

part location, *n*—location of the **part** within the **build volume**.

DISCUSSION—The part location is normally specified by the x-, y- and z-coordinates for the position of the **geometric center** of the part's

bounding box with respect to the **build origin**. Part location is illustrated in ISO/ASTM 52921(**6**).

part reorientation, *n*—rotation around the **geometric center** of the part's **bounding box** from the specified **initial build orientation** of that **part**.

DISCUSSION—Part reorientation is illustrated in ISO/ASTM 52921(**6**).

x-axis, *n—of a machine; unless otherwise designated by the machine builder*, axis in the **machine coordinate system** that runs parallel to the **front** of the machine and perpendicular to the **y-axis** and **z-axis**.

DISCUSSION—Unless otherwise designated by the machine builder, the positive x-direction runs from left to right as viewed from the front of the machine while facing toward the **build volume origin**.

DISCUSSION—It is common that the *x*-axis is horizontal and parallel to one of the edges of the **build platform**.

y-axis, *n—of a machine; unless otherwise designated by the machine builder*, axis in the **machine coordinate system** that runs perpendicular to the **x-axis** and **z-axis**.

DISCUSSION—Unless otherwise designated by the machine builder, the positive direction is defined in ISO 841(**7**) to make a right-hand set of coordinates. In the most common case of an upwards z-positive direction, the positive y-direction then runs from the **front** to the back of the machine as viewed from the front of the machine.

DISCUSSION—In the case of building in the downwards *z*-positive direction, the positive y-direction then runs from the back of the machine to the front as viewed from the front of the machine.

DISCUSSION—It is common that the *y*-axis is horizontal and parallel to one of the edges of the **build platform**.

z-axis, *n—of a machine; unless otherwise designated by the machine builder*, axis in the **machine coordinate system** that runs perpendicular to the **x-axis** and **y-axis**.

DISCUSSION—Unless otherwise designated by the machine builder, the positive direction is defined in ISO 841(**7**) to make a right-hand set of coordinates. For processes employing planar layer-wise addition of material, the positive z-direction then runs normal to the **layers**.

DISCUSSION—For processes employing planar layer-wise addition of material, the positive z-direction is the direction from the first layer to the subsequent layers.

DISCUSSION—Where addition of material is possible from multiple directions (such as with certain **directed energy deposition** systems), the z- axis can be identified according to the principles in ISO 841:2001(**7**), 4.3.3, which addresses "swivelling or gimballing."

3.6 *Definitions:*

Processing: material

batch, *n—of feedstock*, defined quantity of **feedstock** with uniform properties and composition.

DISCUSSION—One batch of any feedstock can be used in one or more production runs using different process parameters.

DISCUSSION—For some types of feedstock, for example powders and resins, one batch can consist of **virgin** material, used material or a blend of virgin and used materials.

cure, *v*—change the physical properties of a material by means of a chemical reaction.

DISCUSSION—One of the most important curing operations in additive manufacturing is the changing of a polymer resin from liquid to solid by light-activated cross-linking of molecule chains.

feedstock, *n*—

DEPRECATED: source material
DEPRECATED: starting material
DEPRECATED: base material
DEPRECATED: original material

bulk raw material supplied to the **additive manufacturing** building process.

DISCUSSION—For additive manufacturing building processes, the bulk raw material is typically supplied in various forms such as liquid, powder, suspensions, filaments, sheets, etc.

feedstock manufacturer, *n*—entity that produces the **feedstock**.

DISCUSSION—In additive manufacturing, the feedstock manufacturer can often be a different entity than the **feedstock supplier**.

feedstock supplier, *n*—

feedtock vendor

provider of **feedstock**.

DISCUSSION—In additive manufacturing, the feedstock supplier can often be a different entity than the **feedstock manufacturer**.

fusion, *n*—act of uniting two or more units of material into a single unit of material.

lot, *n—of feedstock*, quantity of **feedstock** produced under traceable controlled conditions from a single manufacturing process cycle.

DISCUSSION—The size of a feedstock lot is determined by the **feedstock supplier**. It is common that the supplier distributes a portion of a lot to different **AM system users**.

DISCUSSION—Source documentation of the feedstock lot is required for several **AM** product applications. Source documentation is referred to as a "statement of conformity" and an "inspection document", or sometimes also referred to as a "certificate of conformance", "factory certificate" or "certificate of analysis".

post-processing, *n*—process step, or series of process steps, taken after the completion of an **additive manufacturing-build cycle** in order to achieve the desired properties in the final product.

spreadability, *n—of feedstock*, ability of a **feedstock** material to be spread out in **layers** that fulfil the requirements for the **AM** process.

DISCUSSION—The specification of the conditions for the spreading of a layer in an **AM machine**, including, but not limited to, the machine setup and the process parameters, are typically determined by the process requirements with respect to the intended application of the final part.

DISCUSSION—The spreading behavior of a specific feedstock material depends on the physical properties of that material under the given process conditions.

virgin, *adj—feedstock*, condition of **feedstock** from a single manufacturing **lot** before being applied to the **additive manufacturing** process.

DISCUSSION—Virgin condition typically means that the feedstock is in the condition as intended by the supplier.

DISCUSSION—The requirements for virgin feedstock can vary depending on process, material and application of the final product. A further distinction can be necessary for some materials in specific applications.

DISCUSSION—Feedstock without significant change from its original condition may still be regarded as virgin.

DISCUSSION—Feedstock can degrade over time, independent of being applied to the additive manufacturing process. Feedstock that has undergone any significant change under any condition cannot be regarded as virgin.

DISCUSSION—The significance and the permissible variation from the original state are typically determined based on the requirements for the application of the final product.

3.7 *Definitions:*

Processing: material extrusion

build sheet, *n—material extrusion*, removable sheet, to which the **part** is attached during the **build cycle**.

DISCUSSION—The purpose for the build sheet is to provide a disposable barrier between the part and **build platform** in certain machines.

DISCUSSION—The build sheet is usually fastened to the build platform by vacuum or by other means.

extruder head, *n*—
extrusion head
assembly comprising **feedstock** delivery mechanism and **extrusion nozzle**(s).

DISCUSSION—A common design of the head contains a motorized pinch wheel delivery mechanism to push filament through the extrusion head. The head often contains a heating element.

extrusion nozzle, *n*—component with an orifice through which **feedstock** is extruded.

filament, *n*—**feedstock** characterized by extreme length relative to its uniform cross section.

DISCUSSION—Polymer filaments are typically manufactured by extrusion and metal filaments by drawing.

DISCUSSION—Filaments made of metal are commonly referred to as wire.

pellets, *n*—small mass of preformed **feedstock** material, having relatively uniform dimensions in any given batch.

DISCUSSION—Pellets of smaller size can be referred to as micropellets.

3.8 *Definitions:*

Processing: powder bed fusion

batch feed processing, *n—of feedstock*, method of preparation and delivery operations performed on a specific batch of **feedstock** as needed for the **build cycle**.

DISCUSSION—Powder batch feed operations can typically include blending or mixing powders to the desired composition, or drying, alternatively humidifying the powder to reach properties desirable for the **AM** process.

DISCUSSION—Batch feed processing is distinguished from **continuous feed processing** by being limited to a finite amount of feedstock sufficient to complete one or more full build cycles.

continuous feed processing, *n—of feedstock*, method of preparation and delivery operations performed to supply **feedstock** in an uninterrupted process as needed for the **build cycle**.

DISCUSSION—Powder feedstock operations can typically include blending or mixing powders to the composition desired for the build cycle.

DISCUSSION—Continuous feed processing is distinguished from **batch feed processing** by not being limited to a finite amount of feedstock.

feed region, *n—in powder bed fusion*, location in the machine where **feedstock** is stored and from which a portion of the feedstock is repeatedly conveyed to the **powder bed** during the build cycle.

laser sintering (LS), *n*—**powder bed fusion** process used to produce objects from powdered materials using one or more lasers to selectively fuse or melt the particles at the surface, **layer** upon layer, in an enclosed chamber.

DISCUSSION—Most LS machines partially or fully melt the materials they process. The word “sintering” is a historical term and a misnomer, as the process typically involves full or partial melting, as opposed to traditional powdered metal sintering using a mold and heat and/or pressure.

overflow region, *n—in powder bed fusion*, location in the machine where excess powder is collected and stored after a layer has been deposited during a **build cycle**.

DISCUSSION—For certain machine types, the overflow region can consist of one or more dedicated chambers or a powder recycling system.

part cake, *n—in a powder bed fusion process that uses a heated build chamber*, lightly bound powder surrounding the fabricated **parts** at the end of a **build cycle**.

powder bed, *n*—
part bed
location in an **additive manufacturing system** where **feedstock** is deposited and selectively fused by means of a heat source or bonded by means of an adhesive to build up **parts**.

powder blend, *n*—quantity of powder made by thoroughly intermingling powders originating from one or several **powder lots** of the same nominal composition.

DISCUSSION—A common type of powder blend consists of a combination of **virgin powder** and **used powder**. The specific requirements for a powder blend are typically determined by the application, or by agreement between the supplier and end-user.

DISCUSSION—A distinction is made between blended powders and mixed powders, in which case blended powders are combinations of powders with nominally identical composition, whereas mixed powders are combinations of powders with different compositions.

powder mix, *n*—
powder mixture
quantity of powder made by thoroughly intermingling powders of different nominal composition.

DISCUSSION—A distinction is made between blended powders and mixed powders, in which case blended powders are combinations of powders with nominally identical composition, whereas mixed powders are combinations of powders with different compositions.

used powder, *n*—powder that has been supplied as **feedstock** to an **AM machine** during at least one previous **build cycle**.

3.9 *Definitions:*

Parts: general

lattice, *n*—
lattice structure

geometric arrangement composed of connective links between vertices (points) creating a functional structure.

part, *n*—joined material forming a functional element that can constitute all or a section of an intended product.

Discussion—The functional requirements for a part are typically determined by the intended application.

3.10 *Definitions:*

Parts: applications

prototype, *n*—physical representation of all or a component of a product that, although limited in some way, can be used for analysis, design and evaluation.

Discussion—Requirements for **parts** used as prototypes depend on the individual needs for analysis and evaluation and are therefore typically determined in agreement between supplier and end-user.

prototype tooling, *n*—set of molds, dies and other devices used for prototyping purposes.

Discussion—This type of tooling can sometimes be used to trial the tool design and/or to produce end-use **parts** while production tooling is being manufactured. On these occasions, the tooling is typically referred to as bridge tooling.

Discussion—Prototype tooling is sometimes referred to as bridge tooling or soft tooling.

rapid prototyping, *n—in additive manufacturing*, application of **additive manufacturing** intended for reducing the time needed for producing **prototypes**.

Discussion—Historically, rapid prototyping (RP) was the first commercially significant application for additive manufacturing and has therefore been commonly used as a general term for this type of technology.

rapid tooling, *n—in additive manufacturing*, application of **additive manufacturing** intended for the production of tools or tooling components with reduced lead times as compared to conventional tooling manufacturing.

Discussion—Rapid tooling can be produced directly by the additive manufacturing process or indirectly by producing patterns that are in turn used in a secondary process to produce the actual tools.

Discussion—Besides additive manufacturing, the term "rapid tooling" can also apply to the production of tools with reduced lead times by subtractive manufacturing methods, such as CNC milling, etc.

3.11 *Definitions:*

Parts: properties

accuracy, *n*—closeness of agreement between a measured result and an accepted reference value.

Discussion—In the context of **additive manufacturing**, the accepted reference is typically the digital model.

Discussion—The accuracy of an additive manufacturing process can be different in *x*, *y* and *z*-directions. This means that a part accuracy in these cases is dependent on the part orientation relative to the machine coordinate system.

as-built, *adj*—state of **parts** made by an additive process before any **post-processing**, besides, if necessary, the removal from a **build platform** as well as the removal of **support** and/or unprocessed **feedstock**.

Discussion—As-built condition can refer to parts with or without supports, on or off the build platform.

as-designed, *adj*—state representing the **part** to be built by an additive process in digital form, typically as 3D model data.

Discussion—The digital model can be expressed as a proprietary CAD-file, **AMF-file**, **STL-file**, **STEP-file** or any other similar form of 3D model data.

fully dense, *adj*—state in which the material of the fabricated part is without significant content of voids.

Discussion—In practice, material completely free of voids is difficult to produce by any manufacturing process and some micro-porosity is generally present.

Discussion—The significance and the permissible content of voids are typically determined based on the requirements for the application of the final product.

near net shape, *adj*—condition where the components require little **post processing** to meet dimensional tolerance.

porosity, *n—property*, presence of small voids in a **part** making it less than **fully dense**.

Discussion—Porosity may be quantified as a ratio, expressed as a percentage of the volume of voids to the total volume of the part.

precision, *n—build process*, closeness of agreement between the results obtained on multiple parts under prescribed conditions.

Discussion—The precision of an **additive manufacturing** process can be dependent on the location within the **build space** and can also be different in *x*, *y* and *z*-directions.

Discussion—Precision depends on inherent variations in the build process and does not relate to the accepted reference value.

repeatability, *n*—degree of alignment of two or more measurements of the same property using the same equipment and in the same environment.

Discussion—In **additive manufacturing**, repeatability typically refers to the degree of alignment of measurable properties between identical **parts**) produced using the same **process parameters** and **system set-up** but in different **build cycles**.

resolution, *n*—dimensions of the smallest part feature that can controllably be built.

Discussion—In the context of **additive manufacturing**, the dimensions are typically recorded in *x*- , *y*- and *z*-directions.

Discussion—In a layer-wise building process, the resolution in z-direction is typically identical to the layer thickness.

Discussion—The resolution of the **part** can vary in different directions due to the orientation of the part during the **build cycle**.

3.12 *Definitions:*

Parts: evaluation

final inspection, *n*—
pre-shipment inspection
process of verification of manufactured **parts** prior to shipment in order to confirm the fulfilment of the requirements stipulated by a purchase order or otherwise.

first article, *n*—
first production part
part submitted for testing and evaluation for conformance with specified requirements stipulated by a purchase order or otherwise before or in the initial stages of production.

inspection plan, *n*—set of instructions specifying the process of verification including appropriate resources and sequence of inspections to be referenced by the **manufacturing plan**.

qualification, *n*—process of demonstrating whether an entity is capable of fulfilling specified requirements.

DISCUSSION—In **additive manufacturing**, qualification typically involves **parts**, materials, equipment, operators and processes.

ISO/IEC/IEEE 12207:2017*(8)*, 3.1.40, modified — *Discussion was added.*

reference part, *n*—**part** with characteristics similar to the desired final part(s) which may have different geometry, scale or features that can be easily measured or characterized.

DISCUSSION—Reference parts are typically sacrificial parts with simple geometries that are used to verify build properties and reduce measurement effort.

ANNEXES

A1. IDENTIFICATION OF AM PROCESSES BASED ON PROCESS CATEGORIES AND DETERMINING CHARACTERISTICS

(normative)

A1.1 General

A1.1.1 Additive manufacturing process categories are used to provide a general, structural distinction between different AM processes, based on the process architecture and typical process characteristics. However, sometimes there is need for further specification of different processes within each process category; for example, distinction between powder bed fusion of polymers and powder bed fusion of metals, or powder bed fusion of metals using a laser beam or powder bed fusion of metals using an electron beam. This annex is intended to serve as an aid for those who wish to identify a process in more detail than just through the process categories, using generic terms and abbreviations.

A1.2 Structure, use of markers and acronyms

A1.2.1 Specification of different processes within a process category should follow a general-to-specific principle, beginning with specification of the process category, followed by distinguishing features for the AM process and the materials processed.

A1.2.1.1 In this specification, the process features should be preceded by a dash, "-", and materials be preceded by a slash, "/".

NOTE A1.1—EXAMPLE: Process category–process feature/material(s). The specification can be brought into further detail by adding distinguishing features and more specified material distinction.

A1.2.1.2 Abbreviations for process categories shall be applied as specified under 3.2.

A1.2.1.3 Abbreviations for process features should be as follows:

(1) For binder jetting:

— If the parts are joined directly with the bonding of the intended part material in a single process step, this type of process is identified by: -SSt (single-step process).

— If the parts need further process steps for consolidation and formation of the bonds of the intended part material, -MSt (multi-step process).

(2) For directed energy deposition: -LB for laser beam, -EB for electron beam and -Arc when the directed energy source is an electric arc.

(3) For material extrusion: -CRB if the material is bonded by a chemical reaction, -TRB if the material is bonded by a thermal reaction.

(4) For material jetting: -UV if the jetted material needs curing by ultraviolet light exposure, -CRB if the jetted material is bonded by a chemical reaction, -TRB if the jetted material is bonded by a thermal reaction.

(5) For powder bed fusion: -LB for laser beam, -EB for electron beam and -IrL when the thermal energy source is infrared light.

(6) For sheet lamination: -AJ for adhesive joining and -UC for ultrasonic consolidation.

(7) For vat photopolymerization: -UVL for curing by ultra violet laser beam exposure, -UVM for curing by exposure to ultra violet light selectively shining through a mask, -LED for curing by exposure to lights from light emitting diodes.

A1.2.1.4 Abbreviations for basic types of materials should be as follows:

— M for metallic materials;
— P for polymer materials;
— C for ceramic materials;
— Cp for composite materials of different basic type, for example polymer matrix with metal or ceramic filler.

A1.2.1.5 The composition of composite materials should be listed starting with the most significant component material, followed by the second most significant component material separated by a comma (,), etc.

NOTE A1.2—EXAMPLE: Photopolymer with alumina filler: /PP, Al2O3, or tungsten carbide in cobalt matrix: /WC,Co.

A1.2.1.6 The meaning of the abbreviations used for specification of a process in a document should be specified in a list of terms and abbreviations within the same document, unless the abbreviations have been included and defined in a published standard, in which case the document should refer to this standard.

A1.3 Examples

A1.3.1 Powder bed fusion of Ti6Al4V using an electron beam: PBF-EB/M/Ti6Al4V.

A1.3.1.1 *Discussion*—The process category is powder bed fusion (PBF), an electron beam is used for consolidation (-EB), it is a metallic material (/M), more specifically Ti6Al4V (/Ti6Al4V). However, since electron beams only can be used to consolidate conductive material and the alloy Ti6Al4V hardly can be mistaken for anything but a metallic material, the "/M" can in this case be omitted and the specification is thus: PBF-EB/Ti6Al4V.

A1.3.2 Powder bed fusion of cobalt chrome using a laser based system: PBF-LB/M/CoCr.

A1.3.2.1 *Discussion*—The process category is powder bed fusion (PBF), using a laser beam (-LB), in a metallic material (/M), and Cobalt Chrome alloy (/CoCr). Similar to the example above, this can be shortened to PBF-LB/CoCr.

A1.3.3 Powder bed fusion of glass filled polyamide-12 (PA12): PBF-LB/P/PA12GF.

A1.3.3.1 *Discussion*—The process category is powder bed fusion (PBF), a laser beam is used for consolidation (-LB), which can be used for both polymers and metals (/P), the specific material is glass filled polyamide (/PA12GF).

A1.3.4 Binder jetting on stainless steel with subsequent sintering and bronze infiltration: BJT-MSt/M/StS,BI.

A1.3.4.1 *Discussion*—The process category is binder jetting (BJT), a multi-step process (-MSt), for metallic materials (/M), in this case a composite consisting of stainless steel (/StS) with bronze infiltration (,BI).

A1.3.5 Material extrusion of ABS plastic from a heated nozzle: MEX-TRB/P/ABS.

A1.3.5.1 *Discussion*—The process category is material extrusion (MEX), the material is joined by thermal reaction bonding (-TRB), it is a polymer (/P), in this case ABS (/ABS).

A1.3.6 Material extrusion of silicone: MEX-CRB/P/Silicone.

A1.3.6.1 *Discussion*—The process category is material extrusion (MEX), the material is joined by chemical reaction bonding (-CRB), it is a polymer (/P), in this case Silicone (/Silicone).

A1.3.7 Material extrusion of concrete: MEX-CRB/C/Concrete.

A1.3.7.1 *Discussion*—The process category is material extrusion (MEX), the material is joined by chemical reaction bonding (-CRB), it is a ceramic material (/C), in this case Concrete (/Concrete).

A2. BASIC PRINCIPLES

(informative)

A2.1 Additive shaping of materials

A2.1.1 The functionality of a manufactured object is derived from the combination of the object's geometry and material properties. In order to achieve this combination, a manufacturing process is made up of a series of operations and sub-processes that brings the shape of the intended geometry to a material capable of possessing the desired properties. The shaping of materials into objects within a manufacturing process can be achieved by one or combinations of three basic principles:

A2.1.1.1 *Formative Shaping*—The desired shape is acquired by application of pressure to a body of raw material.

NOTE A2.1—EXAMPLES: Forging, bending, casting, injection molding, the compaction of green bodies in conventional powder metallurgy or ceramic processing, etc

A2.1.1.2 *Subtractive Shaping*—The desired shape is acquired by selective removal of material.

NOTE A2.2—EXAMPLES: Milling, turning, drilling, EDM, etc.

A2.1.1.3 *Additive Shaping*—The desired shape is acquired by successive addition of material.

A2.1.2 The objects, or parts, with the acquired shapes can be combined into more complex shaped products by joining different parts in a physical, chemical or mechanical operation, such as welding, soldering, adhesive, fasteners, etc.

A2.1.3 Additive manufacturing technology applies the additive shaping principle and thereby builds physical 3D geometries by successive addition of material.

A2.1.4 "Addition of material" means that units of feedstock material are brought together and joined (e.g., fused or bonded), most commonly layer by layer to build a part. The determining factor for each process is in the technique used for adding the materials. This determines, for example, what types of materials are possible in the process, since different materials have different principles of fusion or adhesion. Basically, for additive manufacturing processing, the products' fundamental properties are determined by:

(a) type of material (polymer, metal, ceramic or composite),

(b) principle applied for fusion or bonding (melting, curing, sintering etc.),

(c) feedstock that is used for adding material (liquid, powder, suspension, filament, sheet etc.), and

(d) how the material is brought together, i.e., machine architecture.

A2.1.5 The process of successively adding material to build a part makes the properties of the material in this part highly dependent on the machine type and the process parameters in the additive operation. Therefore it is not possible to accurately predict these material properties without coupling them to a specific type of machine and process parameters.

A2.1.6 A layered approach to the additive building of parts can also cause directional dependence in the material properties of that part. Material properties in an AM part can therefore depend on the part's orientation and position in the build space during processing.

A2.2 Single-step and multi-step additive manufacturing processes

A2.2.1 It is rare that the manufacturing of a finished product can be entirely completed with use of a single process principle. Normally, a series of operations and sub-processes are required to achieve the intended combination of geometrical shape and desired properties. However, in the context of AM, there is a distinction between which operations are indispensable to the additive process, and which are more product and application dependent preparations and post-processing operations. When additive manufacturing is applied within an industrial manufacturing system, this distinction is needed to clarify what part of the entire manufacturing process constitutes the actual additive manufacturing process as well as what part of the entire manufacturing system constitutes the actual additive manufacturing system, so that standards can be appropriately applied.

A2.2.2 The fundamental principle of AM processes is forming three dimensional parts by the successive addition of material. Depending on process, the parts can acquire the basic geometry and fundamental properties of the intended material in a single process step, i.e., a single-step process, or acquire the geometry in a primary process step, and then acquire the fundamental properties of the intended material (e.g. metallic properties for an intended metallic part and ceramic properties for an intended ceramic part) in a secondary process step, i.e. a multi-step process, see Fig. A2.1. For example, the object acquires the basic geometry by joining of powder with a binder in the primary process step which is followed by material consolidation by sintering, with or without infiltration, in subsequent process steps. Depending on the final application, both single-step and multi-step can require one or more additional post-processing operations, such as heat treatments (including HIP), finishing machining, and others, (see further ISO 17296-2(**9**)), to obtain all the intended properties in the final product.

A2.2.3 AM technology can be used to produce tools molds and casting patterns, which subsequently are used in the production of the intended products. However, in this scenario, it is the casting patterns, molds or tools that are produced by the AM process, not the intended final product. Therefore, the manufacturing of the intended final products in these processes should be considered as being enabled by applications of AM technology rather than as one of the AM production processes.

A2.3 Additive manufacturing processing principles

A2.3.1 *General*—There are numerous ways in which units of material can be joined together to form a part. Different types of materials are being held together by different types of atomic bonds: metallic materials are typically held together by metallic bonds, polymer molecules typically by covalent bonds, ceramic materials typically by ionic-, and/or covalent bonds, and composite materials by any combination of the above mentioned. The type of bonding provides the most fundamental conditions for how that type of material can be joined in an additive process. Besides the type of material, the joining operation is also dependent on the form in which the material is delivered to the system and how it is distributed to the surface where it is to be added to the part. For additive manufacturing processes, the feedstock, the bulk raw material that is fed into the process, can typically come in the form of powder (dry, paste or slurry), filament, sheet, melted, and for polymers also in the shape of uncured liquid resin. Dependent on the form, the feedstock can then be distributed layer by layer in a powder bed, deposited by a nozzle, applied as layers in a sheet stack, deposited through a print head, or applied as a liquid, paste or slurry in a vat. In respect to the great possibilities for variation in different types of materials, different types of feedstock and means of distribution of the feedstock, there is a large number of possible principles that can be used for additive manufacturing processes. However, while there are significant research and development activities in this area world-wide, far from all potential solutions have been realized in a working process, and fewer still have reached the market. Figs. A2.2-A2.5 give an overview of process principles that are presently available on the market and have been proven viable in an industrial context.

A2.3.2 *Overview of AM Single-step Processing Principles*—The parts are fabricated in a single operation where the basic geometric shape and basic material properties of the intended product are achieved in a single operation simultaneously. Removal of the support structure and cleaning may be necessary. Figs. A2.2-A2.4 represent overviews of single step AM processing principles for metallic materials, polymer materials and ceramic materials.

A2.3.3 *Overview of AM Multi-step Processing Principles*—The parts are fabricated in two or more operations where the first typically provides the basic geometric shape and the following consolidates the part to the intended basic material properties. If desired, the process can be concluded after the first operation thus producing a part in a composite material, joined together by material adhesion. Fig. A2.5 represents an overview of multi-step AM processing principles for metallic, ceramic and composite materials.

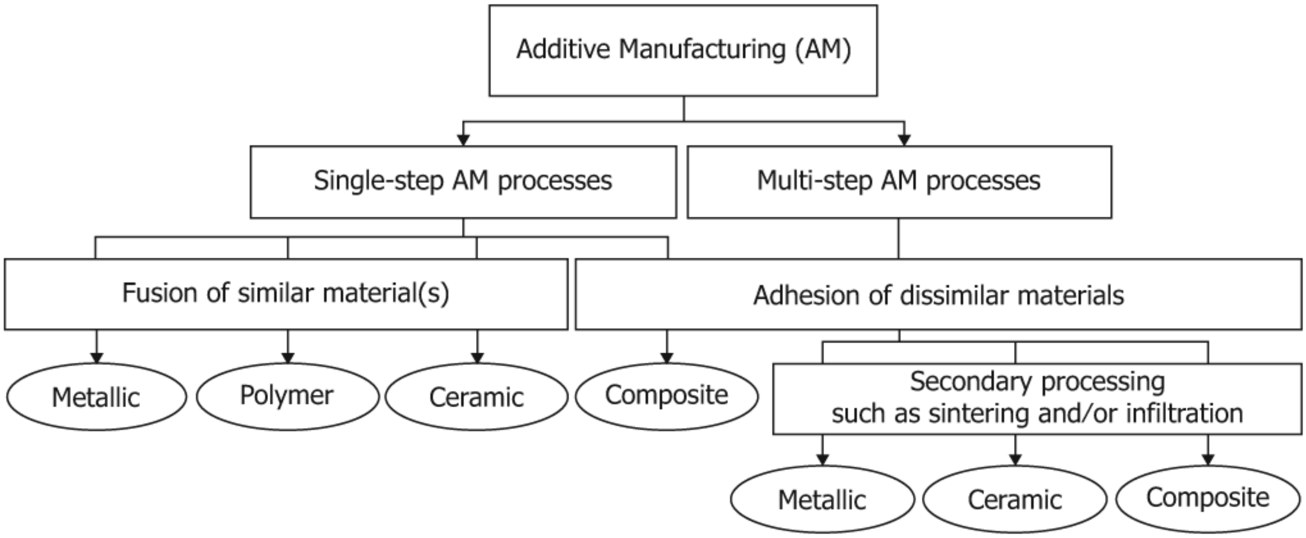

FIG. A2.1 Single-step and multi-step AM process principles

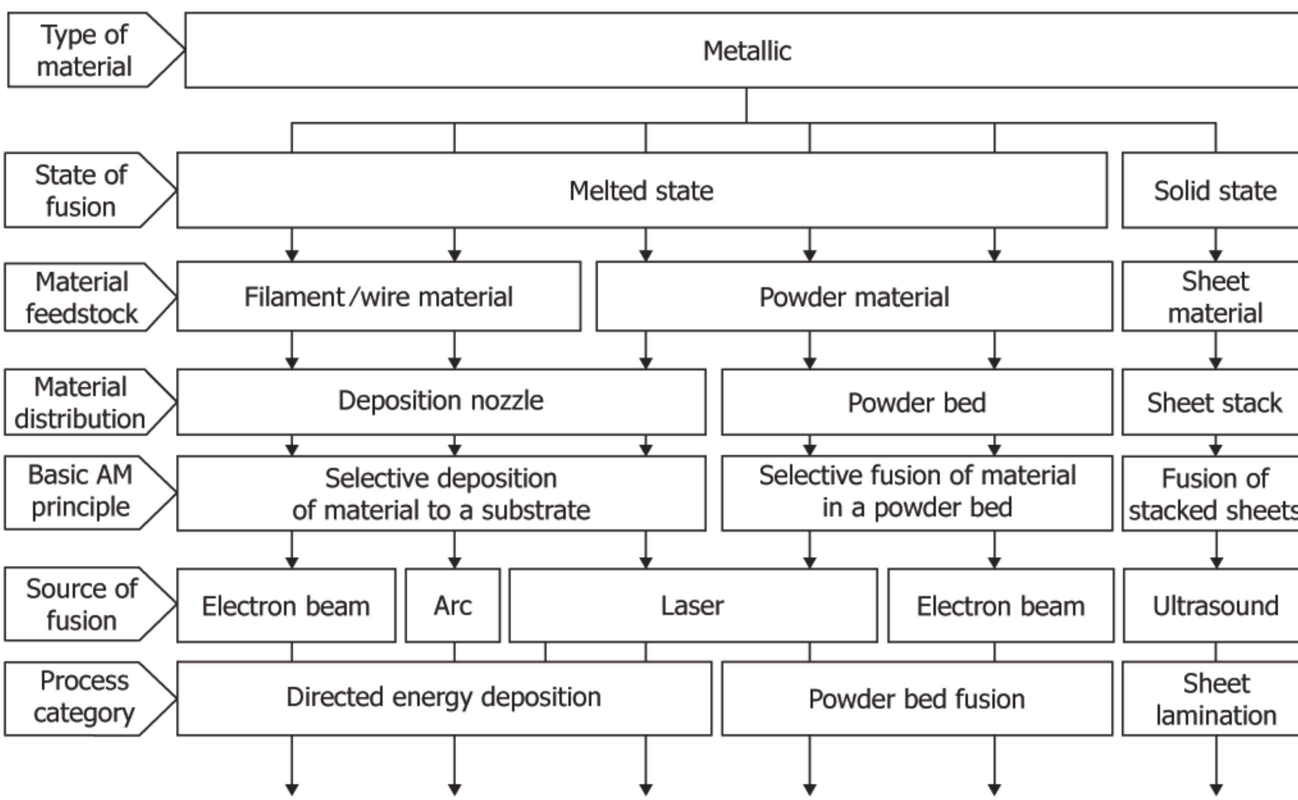

FIG. A2.2 Overview of single-step AM processing principles for metallic materials

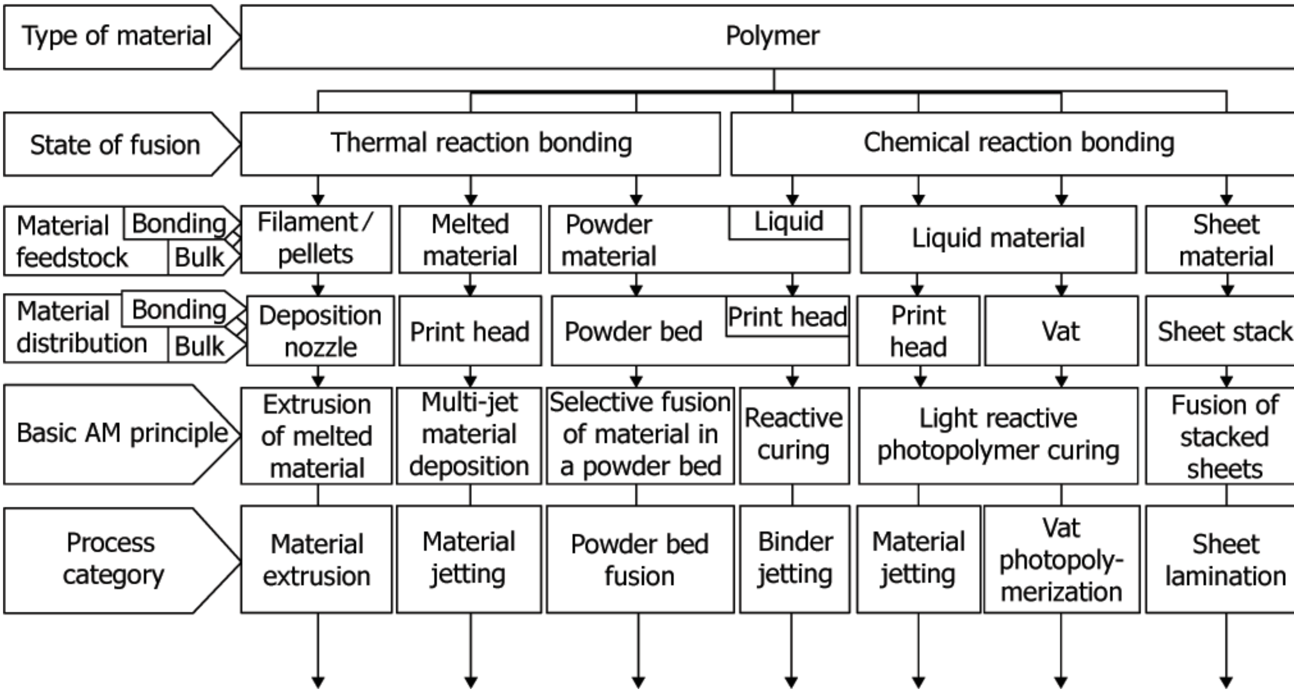

FIG. A2.3 Overview of single-step AM processing principles for polymer materials

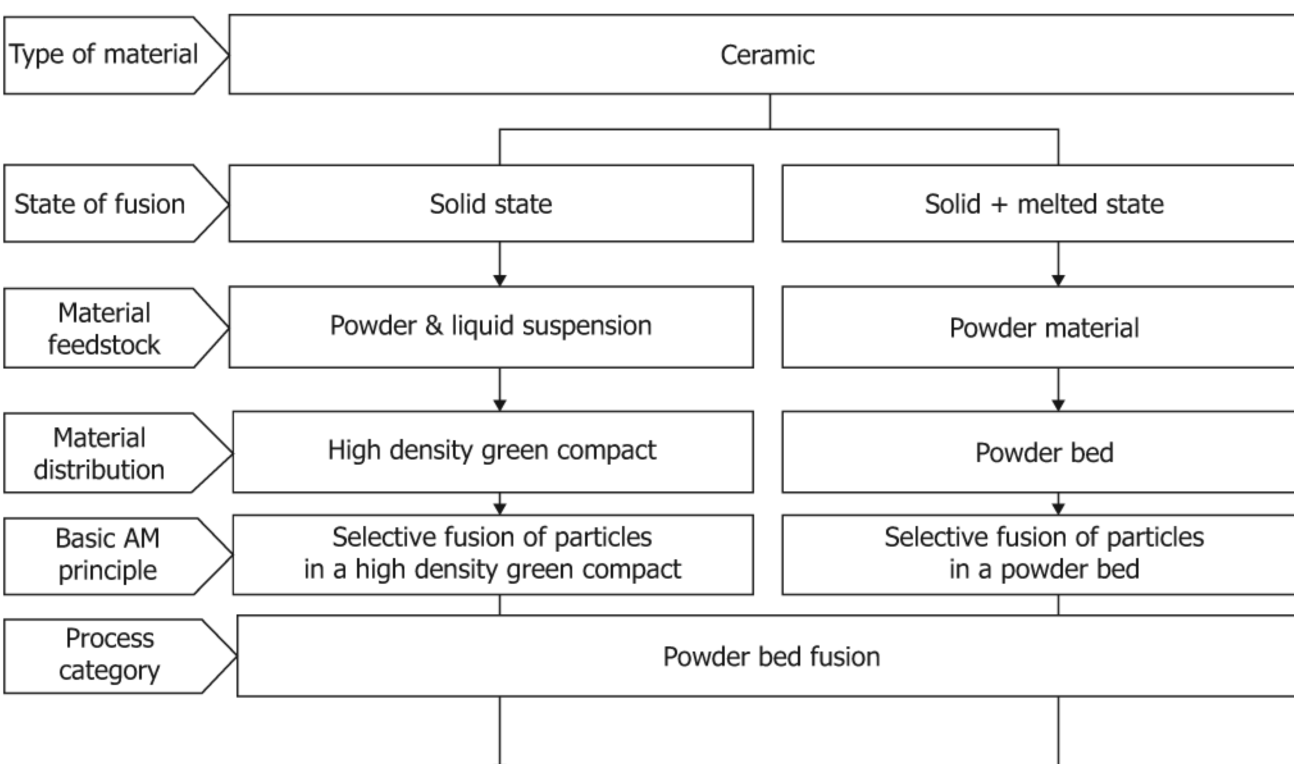

FIG. A2.4 Overview of single-step AM processing principles for ceramic materials

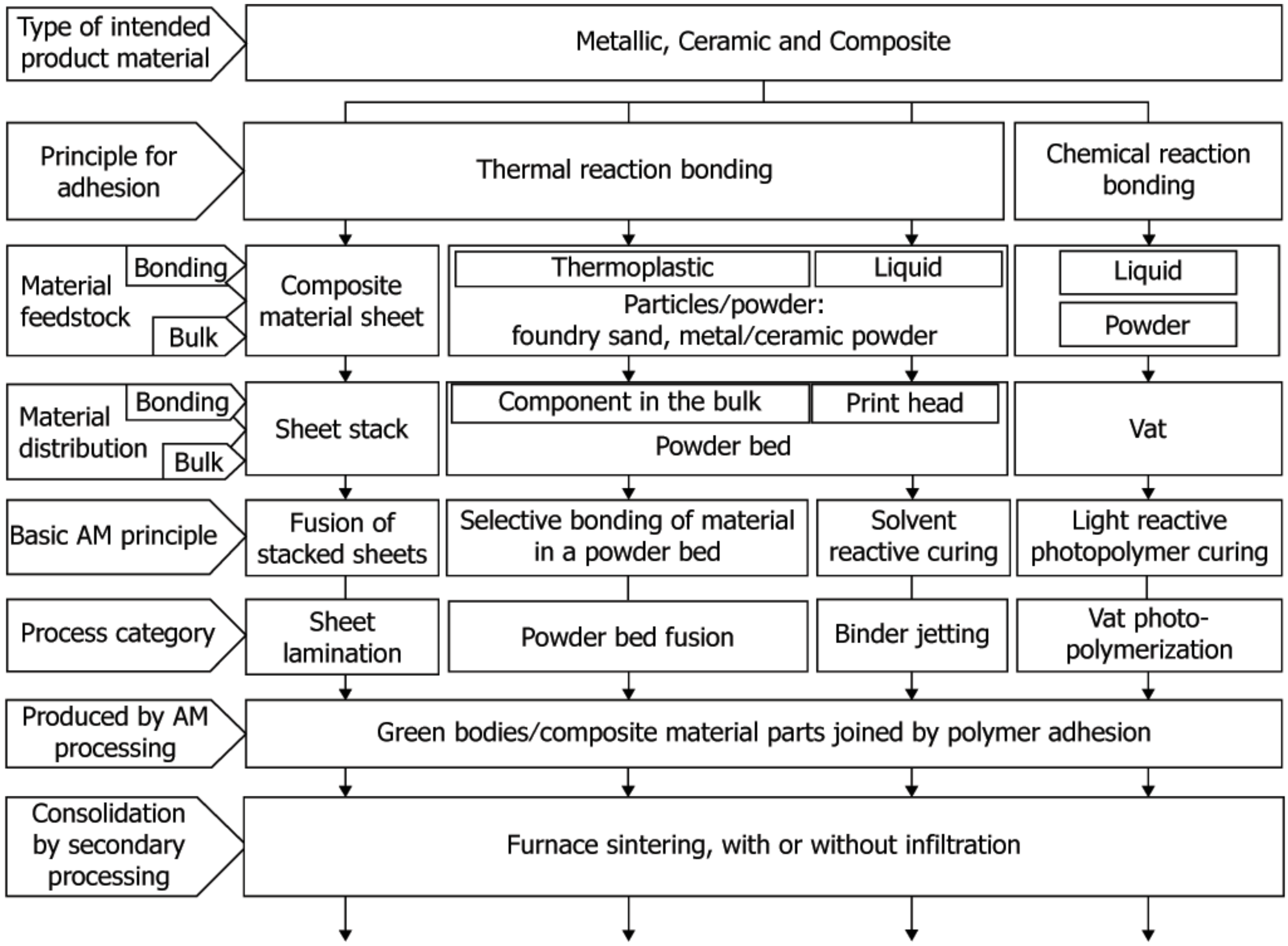

FIG. A2.5 Overview of multi-step AM processing principles for metallic, ceramic and composite materials

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(3) ISO/ASTM 52915, *Specification for additive manufacturing file format (AMF), Version 1.2*

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(5) ISO 10303, *Industrial automation systems and integration – Product data representation and exchange*

(6) ISO/ASTM 52921, *Standard terminology for additive manufacturing – Coordinate systems and test methodologies*

(7) ISO 841:2001, *Industrial automation systems and integration – Numerical control of machines – Coordinate system and motion nomenclature*

(8) ISO/IEC 12207:2017, *Systems and software engineering — Software life cycle processes*

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(10) ISO 10241-1, *Terminological entries in standards – Part 1: General requirements and examples of presentation*

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Additive manufacturing — Design — Requirements, guidelines and recommendations[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 requirements, guidelines and recommendations 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. This document helps determine which design considerations can be utilized in a design project or 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.

1.4 The intended audience comprises three types of users:

1.4.1 designers who are designing products to be fabricated in an AM system and their managers;

1.4.2 students who are learning mechanical design and computer-aided design; and

1.4.3 developers of AM design guidelines and design guidance systems.

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 The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the reference document (including any amendments) applies.

2.2 *ISO/ASTM Standard:*[2]

ISO/ASTM 52921 Standard terminology for additive manufacturing – Coordinate systems and test methodologies

3. Terms and Definitions

3.1 *Definitions:* For the purposes of this document, the terms and definitions given in ISO/ASTM 52921 and the following apply.[3]

Additive manufacturing processes categories

3.1.1 *binder jetting*—additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials. **[SOURCE: ISO/ASTM 52900:—[4]]**

3.1.2 *directed energy deposition*—additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. **[SOURCE: ISO/ASTM 52900: —Note to entry has been deleted]**

3.1.3 *material extrusion*—additive manufacturing process in which material is selectively dispensed through a nozzle or orifice. **[SOURCE: ISO/ASTM 52900]**

3.1.4 *material jetting*—additive manufacturing process in which droplets of build material are selectively deposited. **[SOURCE: ISO/ASTM 52900: —Note to entry has been deleted]**

3.1.5 *powder bed fusion*—additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. **[SOURCE: ISO/ASTM 52900]**

3.1.6 *sheet lamination*—additive manufacturing process in which sheets of material are bonded to form an object. **[SOURCE: ISO/ASTM 52900: —"a part" has been replaced with "an object"]**

3.1.7 *vat photopolymerization*—additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization. **[SOURCE: ISO/ASTM 52900]**

3.2 *Other definitions:*

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

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

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[1] This international standard is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.04 on Design and is also under the jurisdiction of ISO/TC 261.

Current edition approved July 23, 2018. Published July 2018. DOI: 10.1520/ISO_ASTM59210-18.

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

[4] Under preparation. Stage at the time of publication: ISO/DIS 52900:2018.

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

4. Purpose

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

5.2.2 *Overview*—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

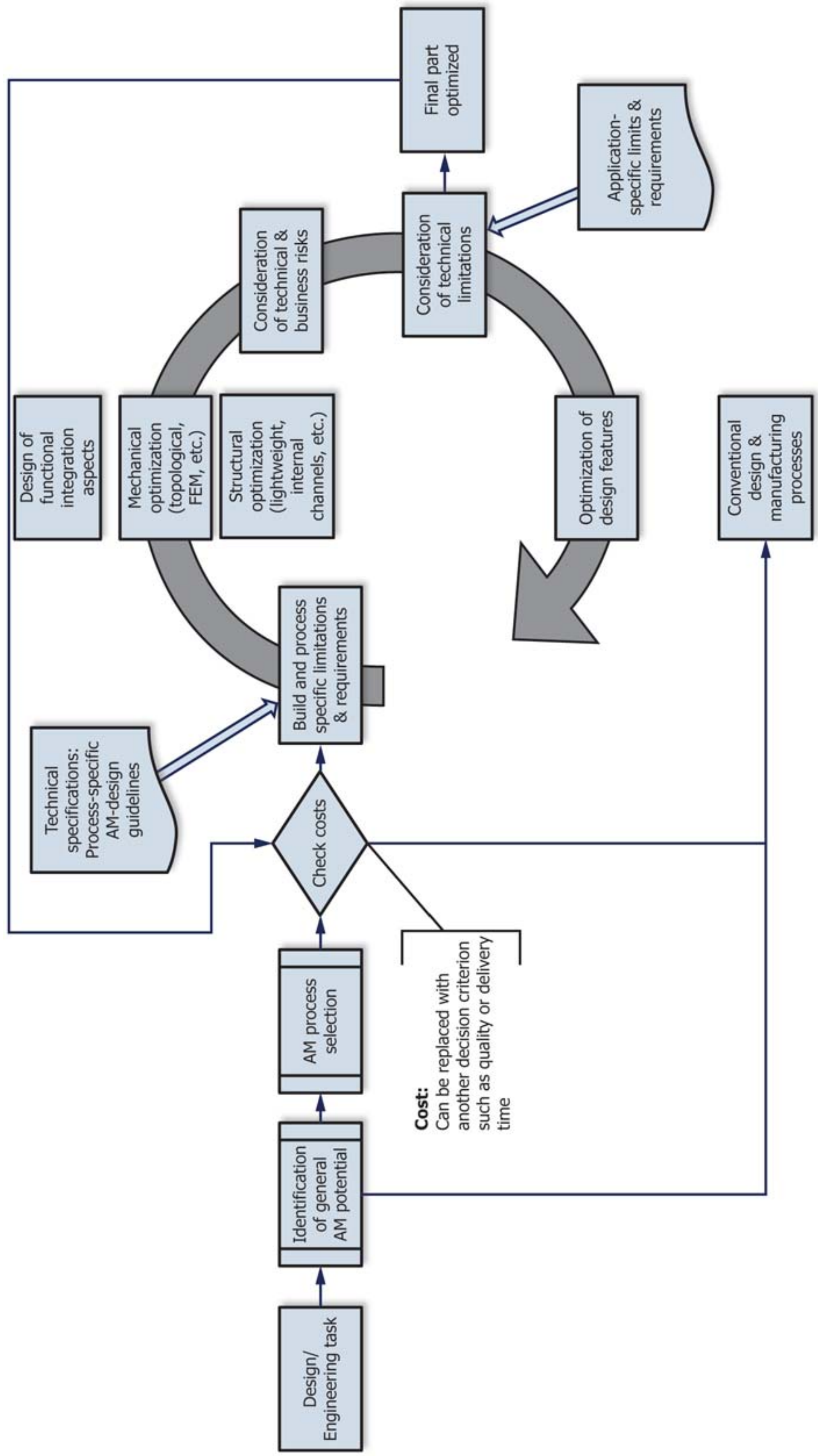


FIG. 1 Overall Strategy for Design for AM

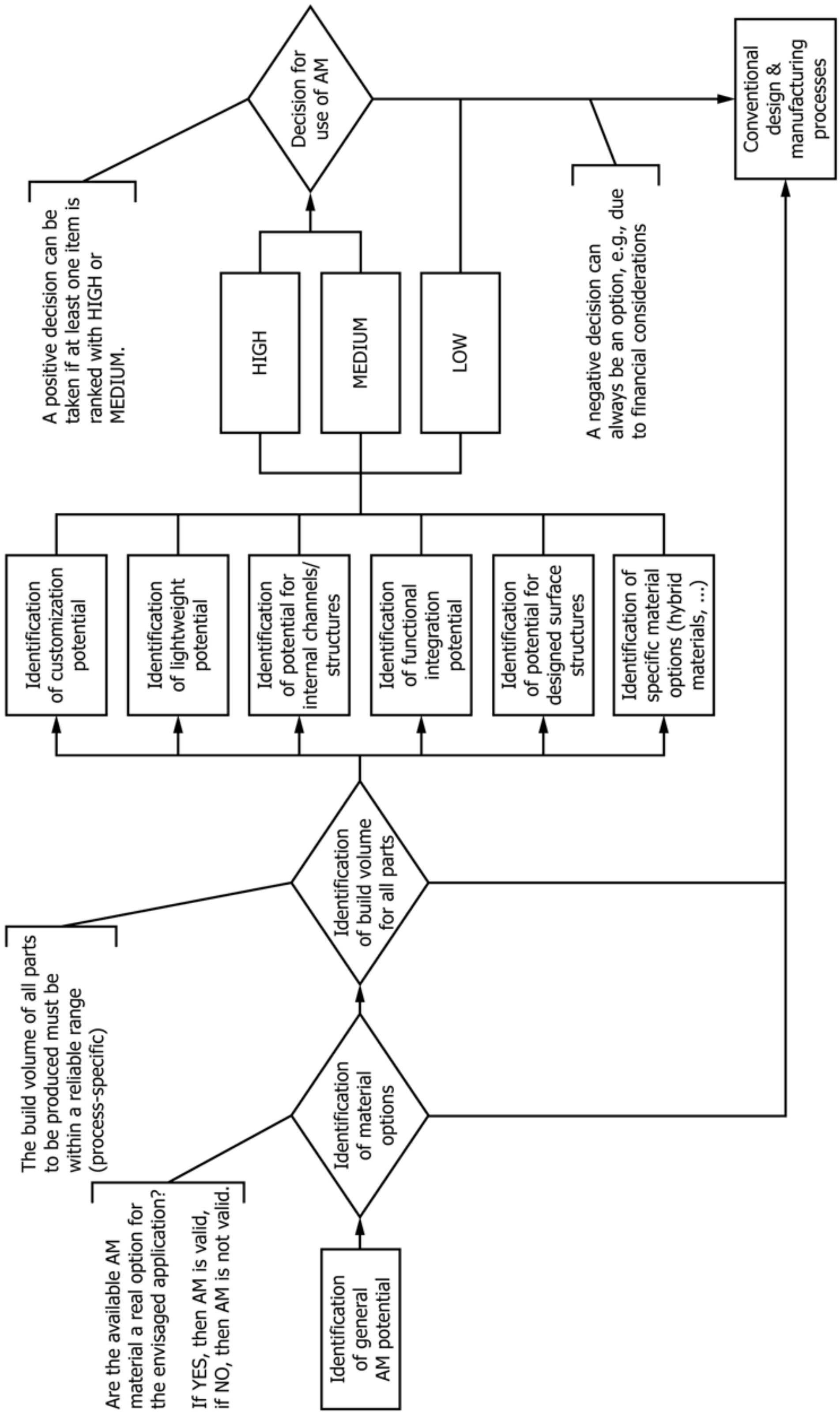
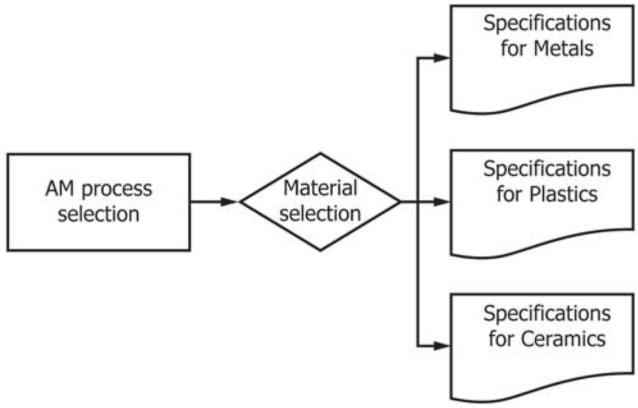


FIG. 2 Procedure for identification of AM potential



Material: metal				
Main technical issues	**Powder bed fusion**	**Material jetting**	**Material extrusion**	**Sheet lamination**
Surface				
Roughness				
Staircase effect				
Geometrical properties				
Geometrical accuracy				
Static physical properties				
Porosity				
Tensile strength				
Ductility				
Dynamic physical properties				
Life cycle fatigue				

FIG. 3 Parameters for the AM process selection

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 can 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 increasing 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 can have very complex geometric constructions, utilizing honeycomb, lattice or foam internal structures, can have complex material compositions and variations, or can 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 *Design Limitations:*

5.3.1 *Overview*—It is 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 shall 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 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 can 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) are 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 can 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, can be thicker than desired. Also, if the wall or strut is nearly horizontal, the wall or strut can be very weak since relatively little overlap can occur between successive layers. Similarly, small negative features such as holes can suffer the opposite effect, becoming smaller than desired and having distorted shapes.

5.3.6 Post-processing is required for many AM processes or can 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 have to 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 can affect the surface finish or accuracy of the supported surfaces. In addition to support structure removal, other post-processing operations can 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 (vat photopolymerization) to be removed from those cavities. Depending on accuracy and surface finish requirements, the part can require finish machining, polishing, grinding, bead blasting or shot-peening. Metal parts can require a thermal treatment for relieving residual stresses, for example. Coatings can be required, such as painting, electroplating, or resin infiltration. Post processing operations increase the cost of AM components.

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 are to be assembled after fabrication. In some cases, this is not 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 can 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 can be merged into neighboring part(s) if they can be fabricated out of the same material, 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. Parts should be designed 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. Designers should also take note of the assembly requirements where mating surfaces require additional traditional machining, for AM metal parts in particular. For example, there are design considerations where a part is designed for conventional machining followed by assembly.

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.

6.2.6 *Relationships with processes and process chains*—The accuracy and surface finish of part surfaces depend on build orientation and other process variables. A sequence of processes ("process chain") can be needed in order to achieve desired accuracy and finish requirements, which the designer needs to consider. By designing a suitable process chain, it can 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 usage 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 can be affected by the environmental conditions outlined in 6.3.2, 6.3.3, 6.3.4 and 6.3.5.

6.3.2 *Thermal environment:*

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

6.3.2.2 *Operational temperature range*—The material properties should exceed the required functional performance when exposed to the entire temperature range the product will experience over the majority of its operational life. The designer should 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 (i.e. aging).

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 can 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.[2]

6.3.3 *Chemical exposure:*

6.3.3.1 *Chemicals*—Identification of chemicals that can 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 can absorb certain liquids that contact them, possibly causing the material to swell, 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 can also be a consequence of usage, wear-and-tear, etc. An example is humidity; a product might 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 shall 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 can affect material properties depending upon exposure levels.

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

6.3.5 *Other exposure:*

6.3.5.1 *Biological exposure*—Exposure to biological materials can cause material degradation or changes in properties. These materials can 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) shall 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 starts 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 on Plastics 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 can 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 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 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 shall 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 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*—It is important to consider that AM processes can 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 can 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 for the expected product life. 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 business considerations 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 including but not limited to AM fabrication cost, total part fabrication cost, life cycle cost and up front engineering cost.

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 can 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 can be expended in searching extensive design spaces. Additionally, considerable time can 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 can be more cost-effective to not employ AM.

6.5.3 *Material considerations*—To determine if a material used in AM meets the specifications for a 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 turn-around time appropriate for the parts order? Production time depends 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 and those where it is more suitable to build one part at a time. For small parts, it can 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 can 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 can 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 can 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 non-destructive testing of structural integrity is required.

6.5.10 *Man-hours*—How many labor-hours need to be expended using AM vs. conventional manufacturing processes? This is similar to the cost and time considerations 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 outsource its production? How much of the work should be outsourced? 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 affects 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 are 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 can 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 take into account that many AM processes do 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 can build correctly, but if the feature is taller, the feature can 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 shall be specified between adjacent features. For example, the minimum gap between moving parts in an additively manufactured assembly can 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 shall move freely with respect to one another. Clearances can also be appropriate when parts are to be glued together.

Interferences between mating features are appropriate when the parts shall be securely held together. Transitional fits can 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 ISO/ASTM 52921 that can be produced on a given AM machine. Parts can 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 (i.e. overhangs) in the build can require supports. Typically, a process has a minimum angle (measured from vertical) for surfaces that indicates a surface requires supports. This threshold angle can 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 shall 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 shall also consider the physical orientation of the part during manufacturing. For example, material extrusion processes can require greater or lesser support structures depending upon the orientation of the part in 3D space. It is advisable 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 can 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 shall 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 shall 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 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 shall 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 shall be exercised in sequencing the software in the tool chain. 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, endianness (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. AM processes typically produce parts with anisotropic properties, where the anisotropy is greater than in most conventional manufacturing processes. Designers shall 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 a negative characteristic. Designers should also realize that material properties can be highly dependent on subsequent post-processing steps, such as heat treatments, that can be applied to fabricated components. 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 (see 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 ASTM E8/E8M. For parts fabricated using AM processes, these properties commonly vary for parts built in different orientations.

6.7.2.3 *Flexural strength, flexural modulus*—These are 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 can 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 / 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 D695 and 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 has an impact on fatigue life, in the part's as-built state. Part surface finish likely has an effect on fatigue life, although exceptions can arise. In some cases, AM-produced parts can be better than traditionally manufactured parts for fatigue if these issues are well understood and controlled.

6.7.2.8 *Creep behavior*—This property refers to the behavior of parts that elongate under load when subject to elevated temperatures. This is commonly reported using ASTM E139 for metals and ASTM D2990 for plastics.

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 ANSI/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 *Considerations related to different process categories:*

6.8.1 *General*

The following topics cover general process considerations and considerations that can be important for process selection for the seven categories of AM processes that are defined in 3.1. Process selection involves choosing among these and choosing appropriate materials. Designers can find it useful to consider polymer vs. metal, thermoplastic vs. thermoset polymers, and vector vs. raster processing. Part quality and properties are 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 category.

6.8.2 *Specific considerations for different process categories:*

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. Jetting 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 deposited per unit volume of powder) and post-processing treatments.

6.8.2.2 *Directed energy deposition*—Directed energy deposition is a process category based on 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 metallic material properties 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. Five-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 shall 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, extrusion temperature, 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, can 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 μm to 30 μm. Support structures are needed; depending on the materials deposited, soluble supports can 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. For metals, a wide variety of alloys are 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/e-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 shall be removed. In some cases, supports are to be removed mechanically, while in other cases they can 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 are to be used to remove the parts. Support structures usually 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 remains on the part after removal from the machine. This resin shall 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 shall 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 can 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 can 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 can 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 can 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*—There are many advantages in developing designs using AM rather than conventional processes. One such benefit 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 cannot 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 can 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 shall 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 shall be taken to confirm successful communication.

Designers also shall be aware of AM limitations and AM producers are ideally equipped to convey their capabilities. These considerations are addressed in ISO/ASTM 52901.

6.9.3 *Process limitations*—Similar to design intent, a dialogue 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 dialogue 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 can be necessary for calibration runs to be fabricated in order to characterize scale factors or other minor shape modifications. Communication between designers and manufacturers is necessary to understand and quantify process limitations, then make design and/or process changes to compensate.

7. Warnings to designers

7.1 In 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 shall 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 shall 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 can 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 cannot 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 applications, powder 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 can be required to ensure an AM component is particularly clean.

7.7 *Fine part details*—Small features on parts can 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 can degrade features or surfaces as well.

7.8 *Non-destructive 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 *File part details*—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 shall be specified in an AMF file.

7.11 *File source – CAD vs. Computed Tomography (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 shall understand and evaluate the quality of files being used to design components intended for AM.

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