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Additive manufacturing — Design — Requirements, guidelines and recommendations

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by ISO/TC 261, *Additive manufacturing*, in cooperation with ASTM F42, *Additive Manufacturing Technologies*, 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.

Additive manufacturing — Design — Requirements, guidelines and recommendations

CAUTION — This document 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 document to establish appropriate Health and Safety (H&S) practices and determine the applicability of limitations prior to use.

1 Scope

This document gives requirements, guidelines and recommendations for using additive manufacturing (AM) in product design.

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.

General guidance and identification of issues are supported, but specific design solutions and process-specific or material-specific data are not supported.

The intended audience comprises three types of users:

- designers who are designing products to be fabricated in an AM system and their managers;
- students who are learning mechanical design and computer-aided design; and
- developers of AM design guidelines and design guidance systems.

2 Normative references

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 referenced document (including any amendments) applies.

ISO/ASTM 52921, *Standard terminology for additive manufacturing — Coordinate systems and test methodologies*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/ASTM 52921 and the following apply.

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 Additive manufacturing process 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:—1), 3.2.1]

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:—, 3.2.2 — Note 1 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:—, 3.2.3]

3.1.4
material jetting
additive manufacturing process in which droplets of build material are selectively deposited

[SOURCE: ISO/ASTM 52900:—, 3.2.4 — Note 1 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:—, 3.2.5]

3.1.6
sheet lamination
additive manufacturing process in which sheets of material are bonded to form an object

[SOURCE: ISO/ASTM 52900:—, 3.2.6 — “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:—, 3.2.7]

3.2 Other definitions

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

Note 1 to entry: The designer determines to what extent the topic can affect the part being designed and takes appropriate action.

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1) 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 favour AM are highlighted. Similarly, conditions that favour conventional manufacturing processes are also highlighted. The main elements include the following:

- the opportunities and design freedoms that AM offers designers (Clause 5);
- the issues that designers should consider when designing parts for AM, which comprises the main content of these guidelines (Clause 6); and
- 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 Figure 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 Figure 2. This is an expansion of the "identification of general AM potential" box on the left side of Figure 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 Figure 1 is presented in Figure 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.

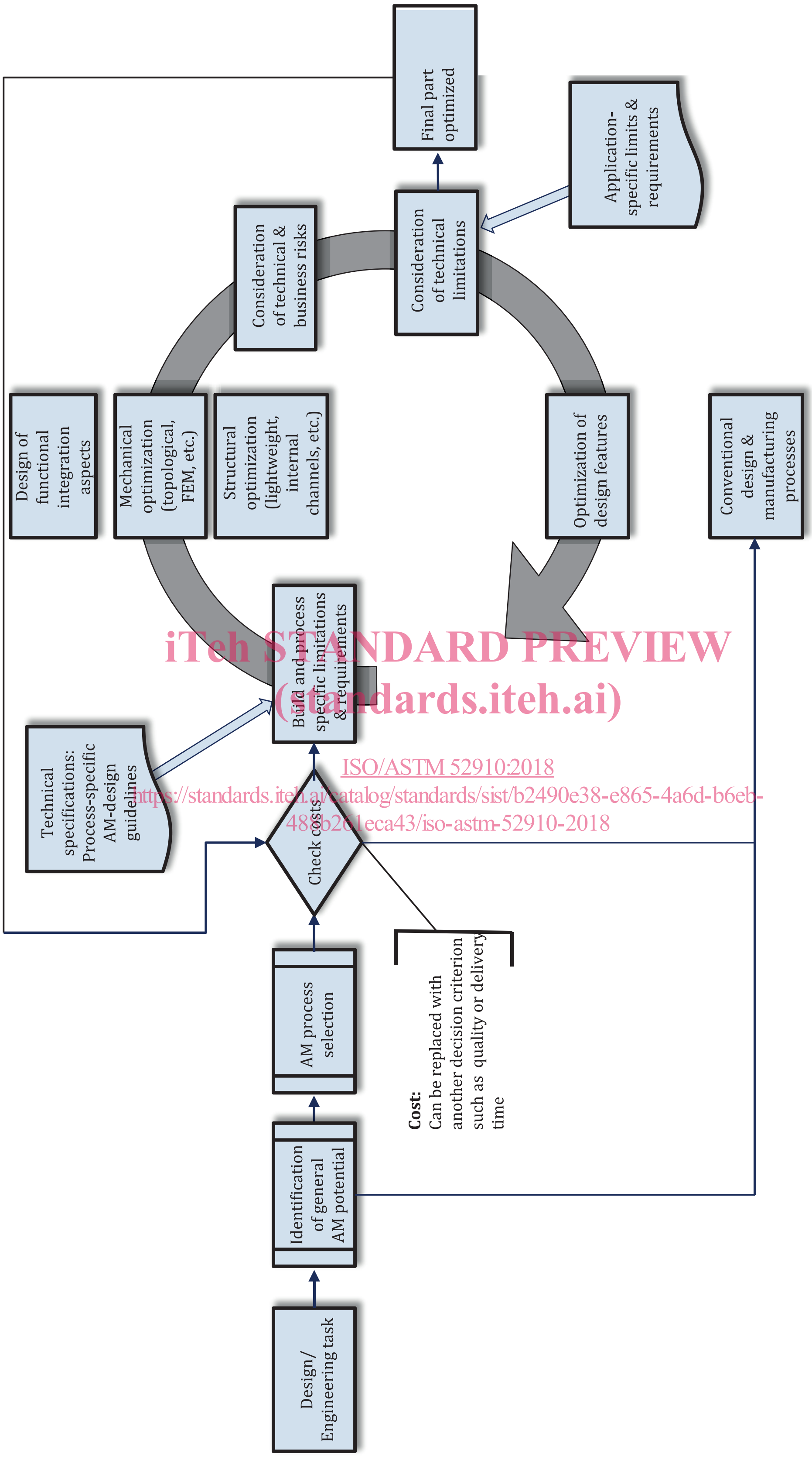


Figure 1 — Overall strategy for design for AM

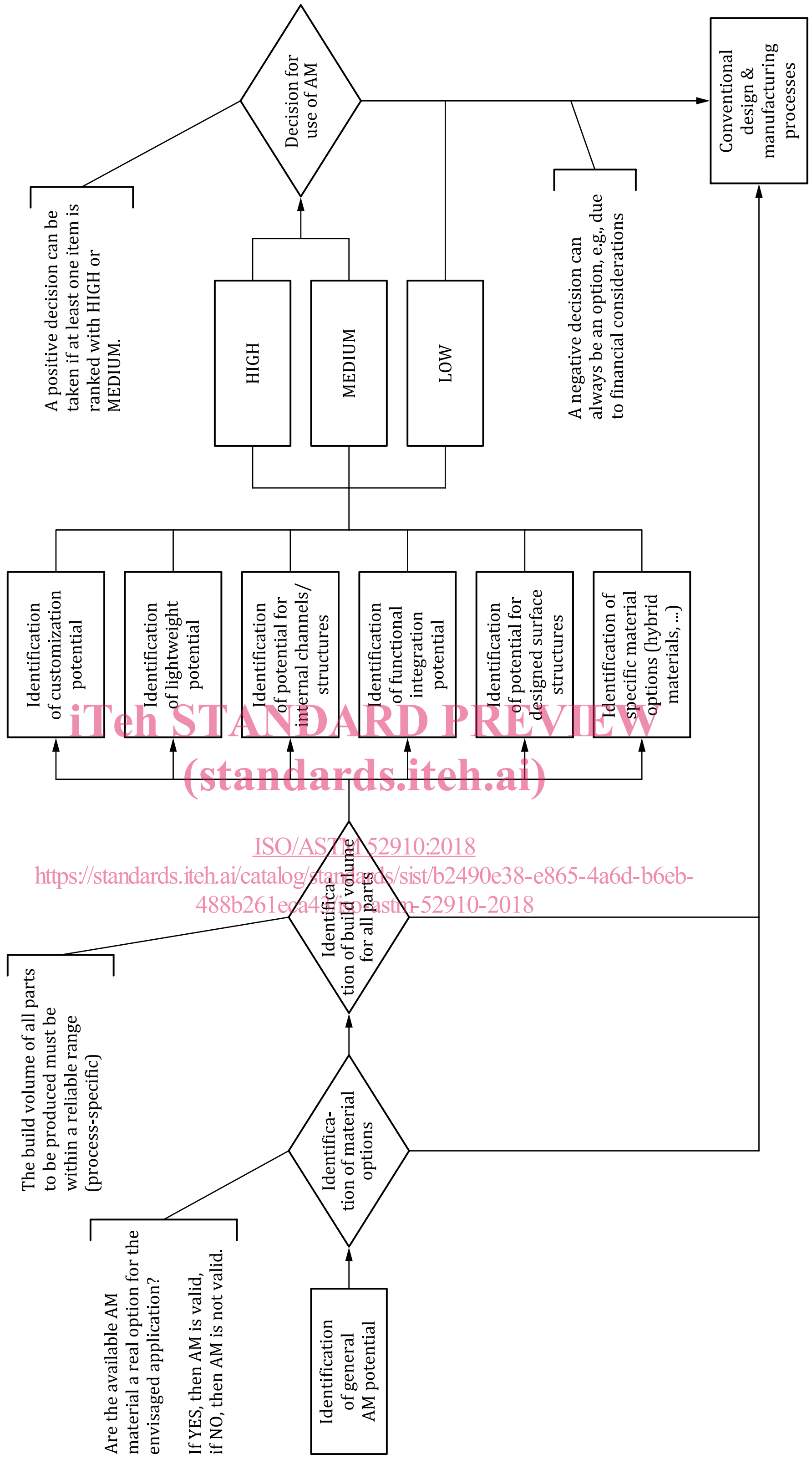
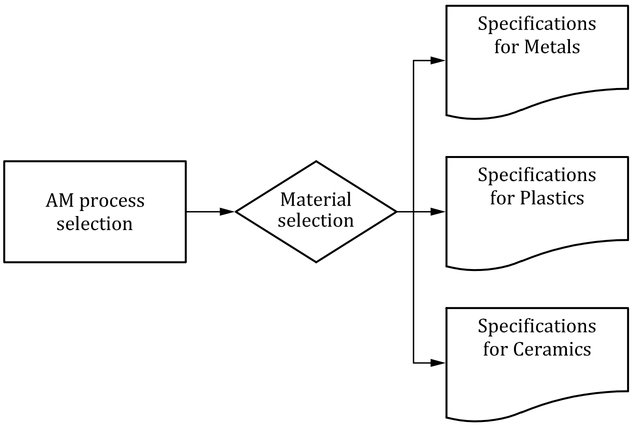


Figure 2 — Procedure for identification of AM potential



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				

Figure 3 — Parameters for the AM process selection

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 moulds, dies or fixtures. Geometries that are customized to individuals (customers or patients) can be economically fabricated. Very sophisticated geometric constructions are possible using cellular structures (honeycombs, lattices, foams) or more general structures. Often, multiple parts that were conventionally manufactured can be replaced with a single part, or smaller number of parts, that is geometrically more complex than the parts being replaced. This can lead to the development of parts that are lighter and perform better than the assemblies they replace. Furthermore, such part count reduction (called part consolidation) has numerous benefits for downstream activities. Assembly time, repair time, shop floor complexity, replacement part inventory and tooling can be reduced, leading to cost savings throughout the life of the product. An additional consideration is that geometrically complex medical models can be fabricated easily from medical image data.

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