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TOLERANCE SPECIFICATION AND RELATED ISSUES FOR ADDITIVELY MANUFACTURED PRODUCTS

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Abstract: Additive manufacturing (AM) has gained increased attention in the last decade as a versatile manufacturing process for customized products. AM processes can create complex free-form shapes, introducing features such as internal cavities and lattices. These complex geometries are either not feasible or very costly with traditional manufacturing processes. This creates new challenges in maintaining and communicating dimensional and geometric accuracy of parts produced. In order to manufacture a product that meets functional needs, the specification of those needs through geometry, material and tolerances is necessary. This paper surveys the current state and needs of geometry related accuracy specification mechanisms for AM, including a review of specification standards such as ASME Y14.5 and ISO 1101. Emerging AM-related tolerancing challenges are identified, and a potential plan of action is put forth for addressing those challenges.

Various issues highlighted in this paper are classified as (a) AM-driven specification issues and (b) specification issues highlighted by the versatility of AM processes. AM-driven specification issues include build direction, layer thickness, support structure related specification, and scan/track direction. Specification issues highlighted by the versatility of AM processes include, region-based tolerances for complex free-form surfaces, tolerancing internal functional features, tolerancing lattice and infills. Basic methods of solving these specification issues are also highlighted.

1 INTRODUCTION

Additive manufacturing (AM) has gained increased attention and user base in the last several years. One of the main driver for increased adoption is the advent of low cost AM machines since the expiration of original patents that were issued in 1980s [1]. According the ASTM F2792 [2], "Additive Manufacturing is defined as – the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies". The 3D model data used to manufacture parts is generated using a CAD system and then provided as a triangulated geometry model to be further processed for AM. In manufacturing a part by adding material layer by layer, AM gains certain advantages in producing complex shapes over traditional manufacturing (§2). There are, on the other hand, accuracy related disadvantages in AM processes.

In traditional manufacturing practice, a product is designed and then 3D model data or drawings are generated. These models and drawings include specification of geometry, material, tolerances, surface finish and any other additional requirements for proper functioning of the product. Each of these specifications has well established standards that govern and ensure non-ambiguous interpretation of the specifications by various stakeholders. For example, the ISO 10303 [3,4] series of standards govern geometry specification and the ISO 1101 [5] and ASME Y14.5 [6] series of standards govern tolerance specification. Proper functioning of a product relies on manufacturing the product within the specification, including allowable variations (tolerances).

These existing standards, although rigorous, have been developed based on the capabilities of traditional manufacturing processes. The aim of this paper is to highlight the need in current tolerancing standards and to suggest possible means of specifying tolerances to parts that are manufactured using AM processes. The notion of specialized tolerance specification standards is not new. There are existing standards for tolerance specification related to parts produced using casting, forging and molding [7]. In the following sections a brief summary of AM capabilities and the role and status of tolerance specification are presented.

2 ADDITIVE MANUFACTURING CAPABILITIES

There are many different variations of AM processes. These are well classified and studied in the literature [2,8,9]. AM processes have been able to use a large variety of materials, especially plastics [10–13], metals [14–17], ceramics [18,19] and biomaterials [20–23]. With these different materials and processes, AM technology is capable of producing complex free-form surfaces and many different kinds of structural lattices. In the following sub-sections, these capabilities are discussed in brief.

2.1 Free-from complex surfaces:

The main thrust for utilizing AM for manufacturing products is the superior/equivalent strength from lower weight/mass components than the ones produced through traditional manufacturing. This is achieved by applying topology optimization methods to obtain shapes that can be relatively easily produced using AM process and shapes that cannot be made at all or are not cost effective. A few industrial examples of these types of components with their traditionally produced counterparts are shown in Figure 1 (a) [24] (b) [25], (c) [26] and (d) [27]. The parts with various ribs and bars are the ones produced using AM process. These AM produced parts have superior or equal strength with less material while saving assembly costs. Such components are usually infeasible using traditional manufacturing process.

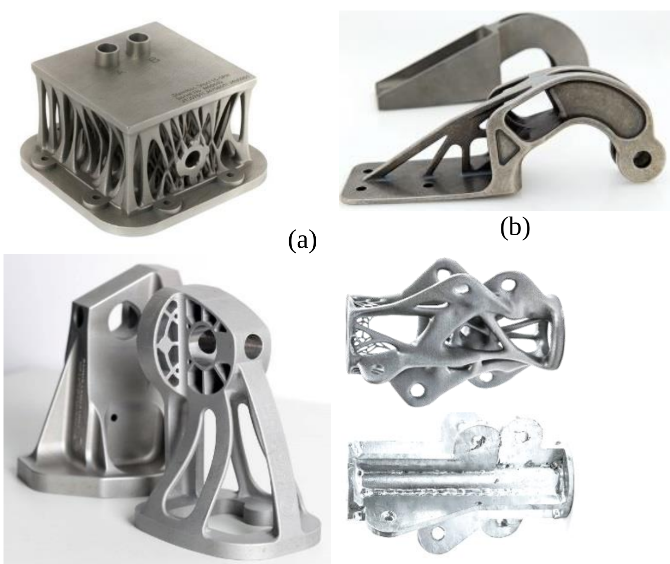
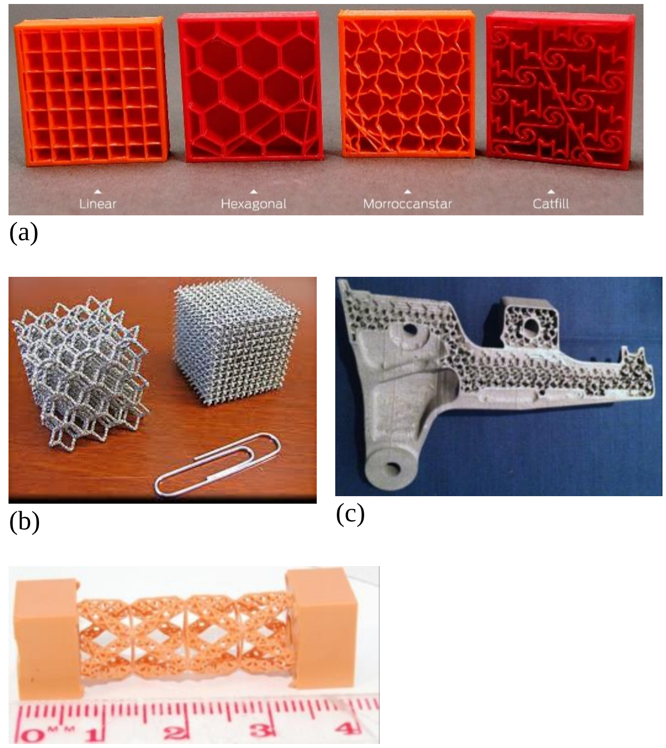

(a) (b) (c) (d)

Figure 1: Examples of topology optimized shapes that were produced using metal based AM technologies (a) figure from [24] that represents a load bearing part with ducts within that mate in curves for better fluid flow (b) figure from [25] showing traditionally produced and AM produced hinge for jet-engine cover, (c) figure from [26] showing traditionally produced and AM produced bracket for Airbus A380. and (d) figure from [27] showing traditional produced and AM produced complex structural building part.

2.2 Internal features:

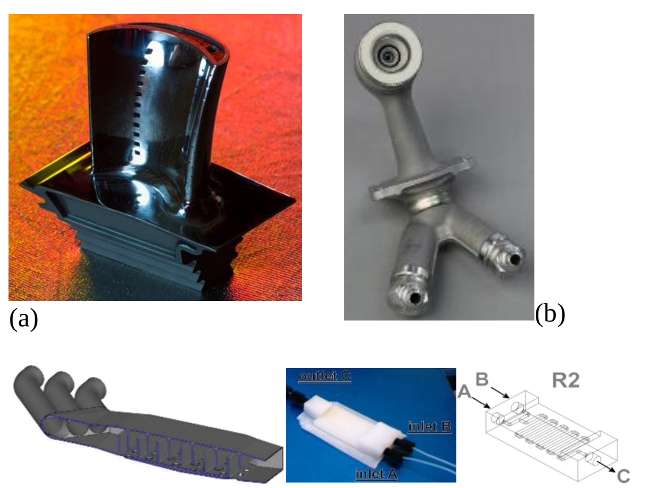
Another advantage of some AM processes is that they can easily produce internal channels and features. These features might just be used to reduce material in a component by creating internal patterns of material. Internal patterns can be a 2D extruded pattern or a 3D pattern. 2D extruded patterns are known as infill Figure 2 (a) while 3D patterns are known as lattices Figure 2 (b), (c) and (d).



(a) (b) (c) (d)

Figure 2: Various forms of infill shown in (a) and lattice structures shown in (b) [28], (c) and (d) [29] that have been produced using AM processes.

Examples of functional features are shown in Figure 3. Functional features are usually intricate internal channels that serve a functional purpose such as cooling ducts, or mixing channels and nozzles. Traditionally these parts would be produced as an assembly of multiple components. With AM, they can be manufactured as one component, thereby saving time, materials and cost.



(a) (b) (c) (d)

Figure 3 Examples of internal functional (channels) features that are produced using AM processes. Figures (a) and (b) from [30] showing complex channels in turbine blade and fuel injector. Figure (c) shows complex channels that create a cyclonic effect to remove water and dirt from air entering the engine compartment of “The Areion”, first 3D printed car [31]. Figure (d) shows complex internal channels for appropriate mixing of 2 chemicals.

3 TOLERANCE SPECIFICATION

Tolerance specification is the specification of the type and value of tolerances based on the Geometric Dimensioning and Tolerancing (GD&T) standard (ASME Y14.5 [6] or ISO 1101 [5]). GD&T is a language to communicate 3-dimensional variations of geometric elements in a part from design to manufacturing and inspection. GD&T is based on mathematical representations of variation of geometric elements and manufacturing knowledgebase [32,33]. It is also a way of specifying design intent to prevent misrepresentation. The final tolerance assignment to each feature is a tradeoff between tight tolerances, which usually result in better performance of the assembly, and loose tolerances, which result in lower cost to manufacture the individual parts but also in a lower probability of proper assembly and/or function. Different tolerancing activities that are part of the production process are shown in Figure *4*.

A designer can arrive at a satisfactory set of tolerances by using one of two approaches: tolerance analysis or tolerance synthesis [34]. With tolerance analysis, the designer estimates values for individual part tolerances and then uses a software analysis tool to determine the range of variations that they, when accumulated together, cause at one or more target features of the assembly.

With tolerance synthesis, often called tolerance allocation, the desired control at the target features (e.g. a maximum clearance to ensure proper lubrication or control of noise) is chosen and then tolerances are generated from a mathematically-based tolerance model to meet that choice. The manufacturing and inspection stages of the product life cycle very often utilize different datum featuress than those desirable for design and function. Therefore, tolerances suitable for design must be transferred, i.e. related, to tolerances on different dimensions with different datum features in such a manner that the product’s desired function is not compromised. This transformation of tolerances is called tolerance transfer. During the inspection stage, tolerance evaluation deals with the analysis of the data obtained from the inspection systems (e.g. coordinate measuring machines (CMM)) and conformance of analyzed data with the specified design tolerances. Figure *4* shows different tolerancing activities that deal with the design stage of production.

The ASME Y14.5 standard [6], classifies manufacturing variations into different tolerance classes with a specific tolerance type associated with each class. The classes relate to a feature’s dimension or size, form, orientation, position, runout, and profile. Of these classes, size; e.g. the diameter of a hole, is controlled with a conventional dimensional tolerance. The other five tolerance classes are geometric tolerances. Form tolerances are further classified as straightness, flatness, circularity and cylindricity. Orientation tolerances are parallelism, perpendicularity or angularity. Location and concentricity are the types of position tolerances. Runout includes circular and total runout while a profile tolerance can be for a line or a surface. Each of the tolerance types is specified with a feature control frame that is attached to a feature (see feature control frame ⌖ ⌀0.5Ⓜ A B in Figure 5(a)). A feature control frame consists of a symbol (cross-hair symbol for position tolerance in the example above) , a value of the tolerances (0.5 in the example above) and datum reference or references (A, B in the example above), if required

The ASME Y14.5 Standard [6] includes methods for stating and interpreting various design parameters, dimensions, datum features, and tolerances. GD&T represents each tolerance with a three-dimensional closed boundary within which the toleranced feature can lie. The enclosed region is called a tolerance zone. The shape of the tolerance zone depends on the type of tolerance and the geometry of the feature toleranced. The size of the tolerance zone depends on the value of the tolerance.

Since multiple tolerances can be applied to the same feature, certain tolerance zones, such as those for form or orientation, lie or float within others. Thus, geometric tolerances permit a more elaborate array of controls on manufacturing variations so that design requirements can be met. They give increased flexibility to designers to meet functional requirements.

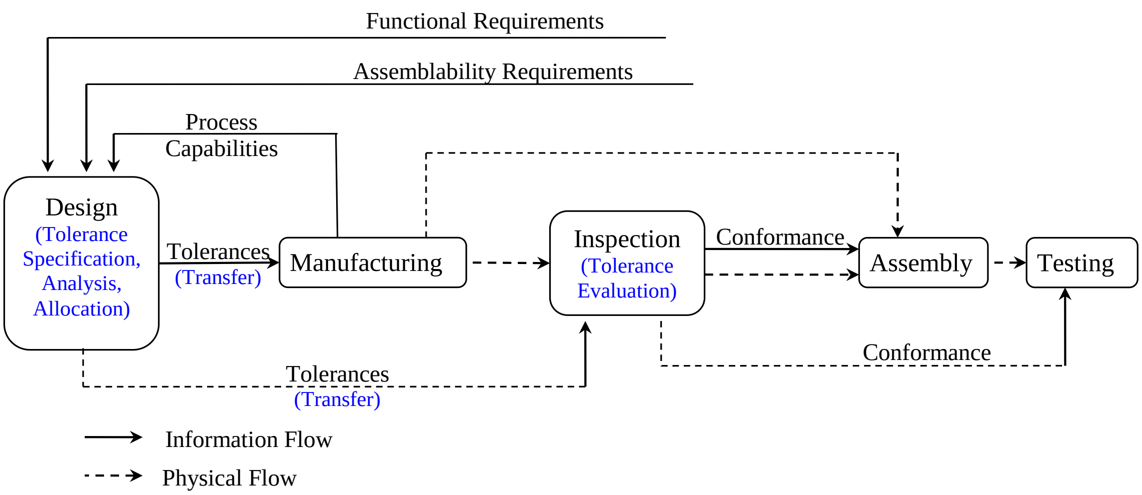


Figure 4: Modified figure from *[35]*, showing the ubiquitous role of tolerances in product life cycle.

AM processes have the capability to produce intricate and complex shapes that were not feasible using traditional manufacturing processes. The impact of these additional capabilities on tolerance specifications and related parameters will be discussed in the following sections. Section 4 will compare other process related specification standards. Section 5 highlights issues in tolerance and related specifications including potential ways of mitigating these issues followed by future outlook in section 6.

4 COMPARISON TO EXISTING PROCESS–DRIVEN SPECIFICATION STANDARDS

It is critical to demonstrate that the need for having process-driven specification standards is not unique to AM. Process-driven specification exists for parts made using composite processes and parts made using castings, forgings and molding processes. A summary of process-driven parameters that are included in ASME Y14.8 standard [7] on casting, forgings and molding is shown in Table 1. Process-driven parameters are shown non-italicized while process related tolerances are italicized in Table 1.

Table 1: Parameters and tolerances described in ASME Y14.8 standard on castings, forgings and moldings [7].

S. No.	Parameters considered
1	Markings
2	Parting line/Plane
3	Mold line
4	Flash extension
5	Forging Plane
6	Grain Direction
7	Grain Flow
8	Match Draft
9	Mismatch
10	*Draft angle and tolerance*
11	*Die closure tolerance*
12	*Fillet radii and tolerances*
13	*Corner radii and tolerance*
14	*All around and all over tolerances on different side of parting plane*

In the composite part drawing specification standard (ASME Y14.37[36]), the most important specification is related to ply. A ply is a "layer of laminated material". Other than ply, three process-driven considerations and descriptions are given in the standard. The composite processes are filament winding, multi-stage bonding (pre-cured, layup and procured with additional layup) and pultrusion (material roll cross-section) process. These are indicated in Table 2.

Table 2: Parameters and topics covered in ASME Y14.37 standard covering composite part drawings [36]

S. No.	Parameters considered
1	Composite part related requirements
1.1	Ply
1.2	Ply orientation
1.3	Ply Table
2	Composite manufacturing process requirements
2.1	Filament winding part
2.2	Multistage bonded Part – Precured, Precured with additional layup and only layup
2.3	Pultruded Part (Material Roll Cross-section)

Tables 1 and 2 show that there are specification standards that are driven by tolerancing needs of specific processes. These standards include process related parameters, their specification and applicable differences from ASME Y14.5 specification on tolerances. AM processes, as discussed in §1.1, have unique capabilities and require development of a similar process-specific standard. The specific issues that arise due to the capabilities of AM processes and their proposed solutions are discussed in the next section.

5 SPECIFICATION ISSUES IN ADDITIVE MANUFACTURING

In this section, specification issues will be presented in two categories. Specification issues that are AM process driven and specification issues that are highlighted by the capabilities of AM processes. This categorization serves the purpose of differentiating specification issues that should be handled in specification standard related to AM process (similar to tolerancing standard for casting, forging [7]) from those best handled in the GD&T standard. The purpose of the first section is to present specification issues and means that are useful for communication *within a manufacturing enterprise*. The purpose of the second section is to present specification issues and means that are useful for *communication between design and manufacturing teams*.

5.1 Process-Driven Issues

Process-driven specification issues play a crucial role in communication during concurrent engineering and manufacturing process planning. Similar process-driven specification standards exists for casting and forging processes [7] and for composite structural products [36] .

<u>(a) Build Direction and location:</u> Additive manufacturing is accomplished by producing a given component or assembly layer by layer. In many AM processes, each layer is produced by creating individual line segments. The direction of piling up these layers (called build orientation) is very critical for the functionality of the product. For example, part materials laid down in the same layer (xy-directions) have superior fatigue strength than those created across the layers (z-direction or build direction)[37,38]. Build direction also affects production time and geometric quality of the features [39,40]. Since all AM processes have a build direction, it is critical to specify the build direction/orientation in the model or drawing with acceptable. Since, build direction is a vector, a tolerance zone (either cylindrical or other shapes) can be used to indicate tolerance on the build direction. Such a tolerance might account for machine errors and allow designers to account for the errors in part design.

For example, consider the part shown in Figure 5(a). Due to the large flat surface for datum A and the geometry of the part, it is quite obvious that build direction should be along the axis of datum B and datum A should lie flat on the build plate. For clarification purposes, the support structures (using Fused Desposition Modelling - FDM techniques) needed for producing the part with other build directions are in shown in Figure 5(b) and (c).

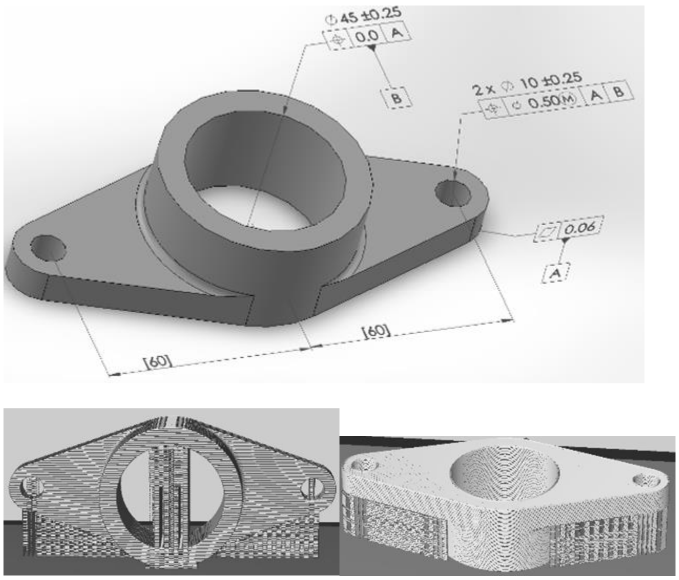


Figure 5: (a) A simple part with GD&T, (b), (c) support structures when the part is built along different build directions

In products where there are no large flat surfaces and the geometry of the part is such that the build direction is not obvious, then the designer needs a mechanism by which the build direction can be specified. Various researchers have proposed algorithms for optimizing the build-direction for reducing the production time, having better geometric precision and part strength [39,40]. The function of the primary datum (datum A) might not be served properly, if datum A is used to identify the build direction. In these situations, designer must specify the build direction and possibly associated acceptable variations in build direction.

Since build direction is an AM associated parameter, there is no existing mechanism to specify it. However, in ASME 14.5-2009 [6], an explicit means of identifying coordinates systems on the drawing is provided. A similar method can be used to specify build direction. One way could be indicating +z direction is the build direction for the part shown in Figure 6. For non-trivial build direction a notation ‘b’ with an arrow to indicate build direction could be included in the standard.

Furthermore, in AM, multiple parts can be produced in a single build. Therefore, it will be necessary to specify each parts’ build location on a build platform. The build-location specification indirectly determines the gap that should be maintained between multiple components being produced in a single build.

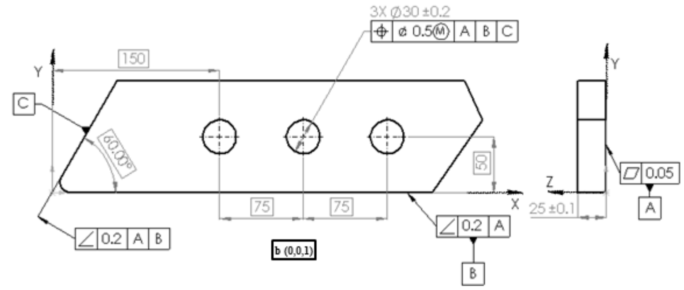


Figure 6: Figure from ASME Y14.5 [6] showing the use of coordinate system indicators in a drawing.

(b) Layer thickness: Since AM parts are built layer by layer, the thickness of a layer is an important criteria that will impact the quality of the product. Based on the product quality requirements, a product can have layers at different locations with different thicknesses.

Since layer thickness is an AM associated parameter, there are no existing mechanisms to specify it. In Composite Specification standard [36] there is a notion of ply table, which contains fiber orientations in each ply (layer). A similar method with a table showing layer thickness transitions can be used to specify layer thickness for each individual layer. A simpler method, appropriate when all layers have same layer thickness, is to provide an annotation in the drawing specification indicating layer thickness.

(c) Support structure shape, size, location and other parameters: Support structures are used in AM to provide support to overhanging structures and to keep parts from deforming. Support structures are process, material, and geometry specific. They also affect subsequent post-processing steps to finish the part. If the support structures’ size, shape, orientation, location, and number are not chosen appropriately, the part might not be produced to the requirements. Therefore, nominal parameters and acceptable variations for the support structures should be communicated in a process-related specifications.

The means of communicating nominal size, shape, orientation, location, number of features, and variation from these nominal parameters exist in the current drawing and tolerance specification standards. The issue with support structures is that, in a non-ideal scenario, each support structure might have different shape and other parameters. Furthermore, support structures are usually very large in number and might not be in any kind of repeating patterns [41,42]. These issues lead to cumbersome use of current methods for large number of geometry and related data. Therefore, better tools are needed to specify and manage specifications related to support structures.

(d) Other considerations: Various other considerations related to specifications in AM include boundary specification for (i) parts with heterogeneous material and (ii) scan/track direction for AM processes that are dependent on these parameters.

Parts with heterogeneous materials are usually manufactured for certain functional purposes [43–47]. For a part with two different materials there can be a distinct boundary between the materials or a graded transition between the materials. Specification of an explicit boundary with acceptable variations or the transition between materials with acceptable variations is not feasible with current specification standards. Since, graded materials based parts are unique to AM processes, new ways of specifying material boundaries, or grades and variations from the nominal specification needs to be developed.

Scan/track directions represent the path in which a Fused Deposition Modeling (FDM) extruder or an Selective Laser Sintering (SLS) laser moves in each layer. Scan/track directions are similar to tool path direction on a machined surface. The difference is that each layer and the shape of different features in each layer might have different scan/track directions. Scan/track directions not only affects the shape of the feature profiles in the layer, but also aid in binding of subsequent layers while serving part strength requirements.

In the current ASME Y14.8 standard on casting and forgings, there is a means for specifying grain direction for a part (Figure 7). Although a similar method can be used for scan/track direction, this method could be adapted to represent different scan/track directions in the same layer (creating feature shapes) and different layers.

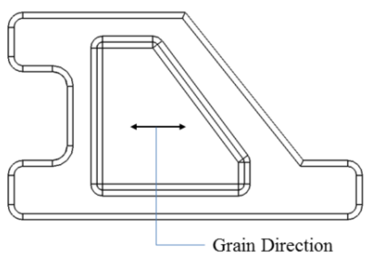


Figure 7. Example of grain direction specification from ASME Y14.8 [7] standard for casting and forgings.

5.2 Issues Highlighted by the Capabilities of AM

(a) <u>Tolerancing free-form complex surfaces</u>: Additive manufactured products typically can have a large number of surfaces that are free-form in nature. Contiguous, free-form surfaces can be toleranced using profile tolerances in GD&T standards (Figure 8). Specific surface equations and related parameters of the surface profile are typically embedded in the CAD model and are not considered part of GD&T. In certain cases, there might be different areas on the free-form surface that do not have a decipherable and clear boundary and are governed by different, surface profile equations and different tolerances. This implies that the surfaces will be C2 continuous [48] at their intersection edge.

The ASME Y14.5 -2009 standard includes special modifiers for surface profile tolerances such as "non-uniform" and "un-equally disposed" tolerance zone. The Un-equally disposed modifier specifies whether the tolerance zone indicates greater tolerance in surface normal direction than the opposite direction. Such an indicator might not be very useful when tolerancing contiguous free-form surfaces with different tolerances. The non-uniform tolerance zone modifier can potentially be useful; but, it currently only specifies a continuous tolerance zone with different tolerances along the surface. It is also not clear in the standard how to specify such a tolerance zone and its parameters.

It might be necessary in many situations to mark the surface boundaries that need different sets of tolerances or have discontinuous tolerance zones. Such boundary markers could potentially be created using target-area indicators.

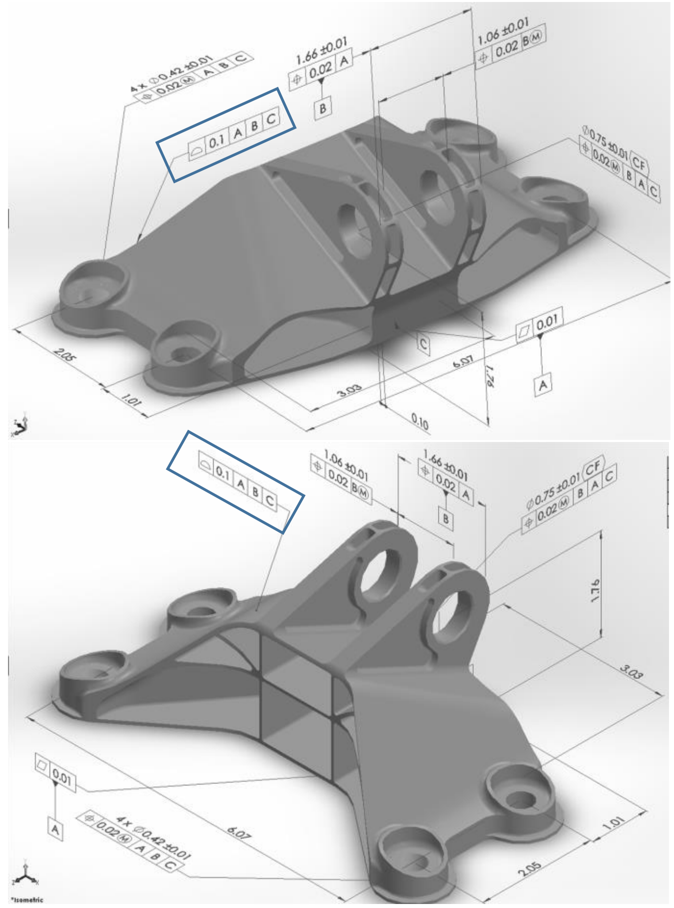


Figure 8: Modified part from the GE bracket design competition [49] winner [42]with GD&T tolerancing.

(b) <u>Tolerancing topology-optimized shapes/features:</u> Topology-optimized shapes as shown in Figure 1 are created to meet certain functional needs. Topology optimization is a method by which the connectivity of different elements in a model can be optimized for given objectives and constraints [51]. Usually, the direct results from topology-optimization in design are designs with many holes and thin bars. These designs are then modified to generate parts that can be produced traditionally. With the capabilities of AM, the shapes that can be produced become closer to the results obtained from topology optimization (as seen in the comparison of parts in Figure 1).

Deviations from the prescribed shape, size, orientation, and position may potentially have a large influence on the performance. The shapes connecting one end of the part with another can be complex and may have varying cross-sections.

These kinds of shapes are frequently used for AM parts and the current specification schemes make it cumbersome to assign geometric tolerances when required for functional purposes. For aesthetic purposes, general surface profile without datum (indicating form variations) can be specified.

(c) <u>Tolerancing internal features:</u> As was discussed in §2.1, AM parts are not always solid, and often use an infill pattern, lattice, or internal structures (such as cooling channels, etc). Typically, choices regarding infill pattern are left to the discretion of the manufacturer. Since, the infill pattern, lattice, or internal structures have functional bearing on product performance, these choices should be governed by the function of the product.

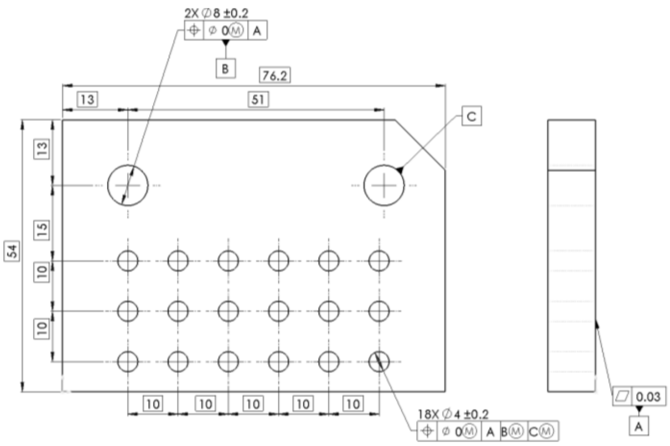


Figure 9: Figure from ASME Y14.5 [6] showing application of tolerancing a pattern of holes.

Fittingly, these choices should, when possible, be specified by the designers in the model or drawing of the product. Infill patterns are typically 2-dimensional patterns extruded along the build direction. For example, consider a typical, hexagonal, infill pattern with a particular % specified for infill. In the ASME Y14.5 standard [6], tolerances on patterns of features can be specified as shown in Figure 9 (pattern on holes). The holes position, orientation, shape, size, and relative position are governed by the specification. Similarly, specifications of a hexagonal infill pattern could be adapted from pattern tolerance rules in the ASME Y14.5 standard [6]. The infill-pattern specification could include, shape, size, wall thickness of the unit pattern, pattern origin and general position tolerances.

Lattice usually consists of a 3-dimensional unit cell that is replicated and/or conformal to the internal shape of the part. These internal structures could include specifically designed support structures from topology optimization. Typically, internal structures are used in combination with an infill pattern or lattice. Since, internal structures are specific for a particular function of a product, they should be specified by the designer. Therefore, in GD&T standards, methods to specify infill pattern (shape, size, wall thickness of unit pattern and parametric origin, directions and general tolerances of the entire pattern) and lattice (shape and size of unit cell [Figure 10], conformal or fill type and general tolerances for the entire lattice) are needed.

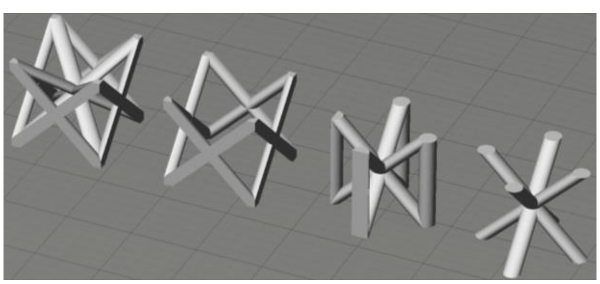


Figure 10: Unit lattice cells that are used to create lattices in AM.

For functional features, as shown in Figure 3, general surface profile tolerance might be sufficient for the needs of these features. The issue with these geometric elements is in the quality-assurance process. Although, CT-scans [52,53] are being used for inspecting internal features, the reliability for geometric quality is still being explored.

6 SUMMARY AND FUTURE OUTLOOK

This paper has presented a need for additional AM-driven specification standards and additions to current tolerancing standards. The AM-driven specification issues discussed were (a) build direction and location, (b) layer thickness (c) support structures and (d) other considerations including grades or boundaries of multi-material parts, scan/track directions etc. The specifications issues highlighted by AM process as discussed in the paper were related to tolerancing (a) free-form complex surfaces, (b) topology-optimized features and (c) internal features including infills, lattices, and functional features.

Recently a new committee, ASME Y14.46 [54], has been formed in order to address the specification issues that have been highlighted by AM. In other standards communities such as ASTM F42 [55] and ISO TC261 [56], AM-specific sub-groups have started to investigate and propose new AM related standards.

AM processes brings together the specification issues of material and geometry. The standards in material specification and geometry specification will have to work together in order to address the standard related challenges posed by AM processes.

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