Investigating the Role of Geometric Dimensioning and Tolerancing in Additive Manufacturing

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Additive manufacturing (AM) has increasingly gained attention in the last decade as a versatile manufacturing process for customized products. AM processes can create complex, freeform shapes while also introducing features, such as internal cavities and lattices. These complex geometries are either not feasible or very costly with traditional manufacturing processes. The geometric freedoms associated with AM create new challenges in maintaining and communicating dimensional and geometric accuracy of parts produced. This paper reviews the implications of AM processes on current geometric dimensioning and tolerancing (GD&T) practices, including specification standards, such as ASME Y14.5 and ISO 1101, and discusses challenges and possible solutions that lie ahead. Various issues highlighted in this paper are classified as (a) AM-driven specification issues and (b) specification issues highlighted by the capabilities of AM processes. AM-driven specification issues may include build direction, layer thickness, support structure related specification, and scan/track direction. Specification issues highlighted by the capabilities of AM processes may include region-based tolerances for complex freeform surfaces, tolerancing internal functional features, and tolerancing lattice and infills. We introduce methods to address these potential specification issues. Finally, we summarize potential impacts to upstream and downstream tolerancing steps, including tolerance analysis, tolerance transfer, and tolerance evaluation.
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1 Introduction

AM has gained increased attention and user population in the last several years [1]. According to 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 are generated using a computer-aided design (CAD) system and then provided as a tessellated geometry model to be further processed for AM. In manufacturing a part by adding material layer by layer, AM gains certain advantages over traditional manufacturing when producing complex shapes (Sec. 1.1). However, on the other hand, these geometric freedoms may come at a cost, as most AM processes face accuracy-related disadvantages.

In traditional manufacturing practices, a product is designed and then 3D model data or drawings are generated. These models and drawings may include specification of geometry, material, tolerances, surface finish, and any other additional requirements for proper functioning of the product. These requirements have well-established standards that govern and ensure nonambiguous interpretation of the specifications by various stakeholders. For example, the ISO 10303 [3,4] series of standards govern geometry specification while 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 specifications, including allowable variations (tolerances). Existing GD&T standards, although rigorous, have been developed based on the capabilities of traditional manufacturing processes.

Precedents have been set on establishing requirements on how geometry is represented and communicated in AM versus traditional manufacturing. Early work investigated the specifics of AM data transfer [7]. More recently, standards effort in AM have been led by ASTM Committee F42 on AM Technologies [8] and ISO TC 261 on AM [9]. ASTM has published standards on geometry specification (Additive Manufacturing file format (AMF)) for AM (ISO/ASTM 52915: 2013 [10]) and definition of terms used in AM (ASTM F2792-12a [2]). Here, we explore how GD&T efforts may be expanded to better suit the nuances of AM. In Sec. 1.1, a brief summary of AM capabilities is presented.

1.1 AM Capabilities. There are many different variations of AM processes. These are well classified and studied in the literature [2,11,12]. AM processes employ a large variety of materials, especially plastics [13–16], metals [17–20], ceramics [21,22], and biomaterials [23–26]. With these different materials and processes, AM technology is capable of producing complex freeform surfaces and many different kinds of structural lattices. In Secs. 1.1.1, 1.1.2 and 1.1.3, these capabilities are discussed in brief.

1.1.1 Freeform Complex Surfaces. One of the primary thrusts for utilizing AM for manufacturing products is the promise of superior/equivalent strength from lower weight/mass components than the shapes produced through traditional manufacturing. This goal is possible by using topology optimization and other methods to obtain complex shapes that can be relatively easily produced using AM processes. A few industrial examples of these types of components (some with applying their traditionally produced counterparts) are available at Refs. [27–30]. The parts with various ribs and bars are the ones produced using AM process. These

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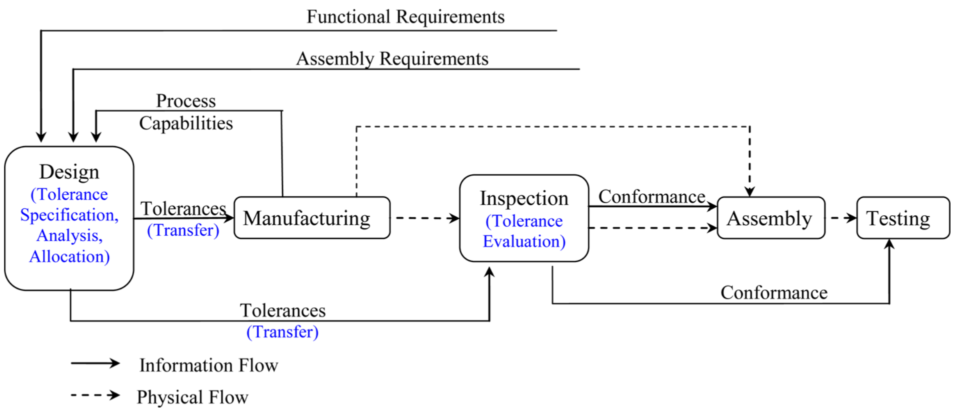


Fig. 1 Modified figure from Ref. [42], showing the ubiquitous role of tolerances in product life cycle

AM produced parts claim superior or equal strength with less material, potentially also saving on assembly costs.

1.1.2 Internal Features. Another advantage of AM processes is that many of them can easily produce internal channels and features. In some instances, internal geometry may be functional, in other instances the geometry may simply reduce material in a component by creating internal patterns of material. Internal patterns can be a two-dimensional (2D) extruded pattern or a three-dimensional (3D) pattern. Two-dimensional extruded patterns are commonly referred to as infill while 3D patterns are known as lattices [31,32]. Functional [33,34] are usually complex internal channels that serve functional purposes (e.g., cooling ducts, or mixing channels and nozzles). Traditionally, these features might be produced using individual components that are joined to form an assembly. With AM, these features can be manufactured into a single component, thereby potentially saving time, materials, and cost.

1.1.3 Assemblies. AM has the ability to produce working assemblies in a single build. This ability eliminates the need to assemble components for a functioning product, allowing for intricate assemblies and potentially saving cost. However, the specified clearance between two moving components needs to exceed certain AM process limitations, such as powder size or layer thickness. In addition, part cleaning may be required to eliminate rigid contacts that may form between moving components. Refs. [35–38] have demonstrated several as-built assemblies using AM processes.

1.2 Tolerance-Related Activities in Production. In this section, we provide a brief overview of GD&T applications. This overview will serve to provide a base context to discussions around AM-driven and AM-highlighted GD&T opportunities.

Tolerance specification is the specification of the type and value of tolerances based on the GD&T standards (ASME Y14.5 [6] or ISO 1101 [5]). GD&T is a language to communicate acceptable 3D variations of geometric elements in a part from design to manufacturing and inspection. GD&T is based on mathematical representations of the variation of geometric elements and manufacturing knowledge bases [39,40]. GD&T is also a way of specifying design intent to prevent misrepresentation during production processes. The final tolerance assignment to each geometric 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.

1.2.1 Tolerancing Activities. A designer can arrive at a satisfactory set of tolerances by using one of two approaches: tolerance analysis or tolerance synthesis [41]. 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 the tolerances, when accumulated together, cause at one or more target features of the assembly. With tolerance synthesis, often called tolerance allocation, the desired control at target features (e.g., a maximum clearance to ensure proper lubrication or control of noise) is chosen. Then, the tolerances are generated from a mathematically based tolerance model, also in an automated way, to meet that choice.

The manufacturing and inspection stages of the product life cycle very often utilize different datum features than those desirable for establishing design and function. Therefore, tolerances suitable for the design function must be transferred, i.e., related to manufacturing-based tolerances on different dimensions with different datum features. This transfer must occur in such a manner that the product's desired function is not compromised. This transformation of tolerances is called tolerance transfer.

Tolerance evaluation addresses the analysis of the data obtained from dimensional measurements and conformance of the part with the specified design tolerances. Figure 1 shows different tolerancing activities for the design stage of production.

1.2.2 Geometric Tolerances. The ASME Y14.5 standard [6] divides manufacturing variations into different tolerance classes, with a specific tolerance type associated with each class. These are classified as 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 in Fig. 2(*a*)).

A feature control frame consists of a symbol that represents the type of the tolerance (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 and B in the example above), if required.

The ASME Y14.5 standard [6] includes methods for specifying and interpreting various design parameters, dimensions, datum features, and tolerances. GD&T represents each tolerance with a 3D 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

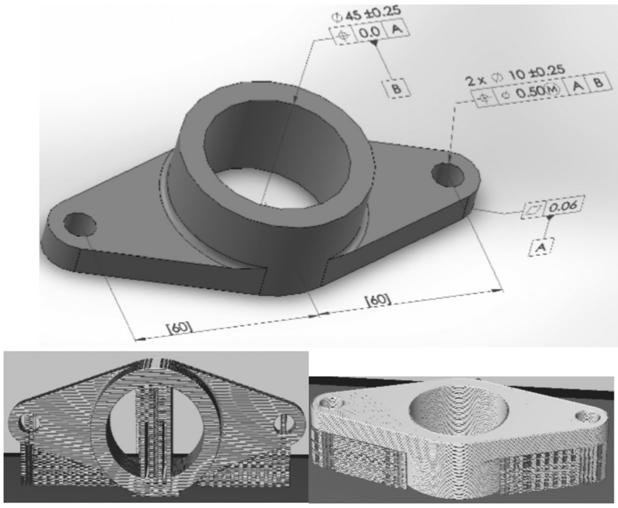


Fig. 2 (*a*) A simple part with GD&T and (*b*) support structures when the part is built along different build directions

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.

AM processes have the capability to produce intricate and complex shapes that are not feasible with traditional manufacturing processes. The impact of these additional capabilities on tolerance specifications and related parameters is discussed in this paper. Section 2 will compare other process-related specification standards. Section 3 highlights potential issues in tolerance and related specifications, including discussion on possible ways of mitigating these issues. Section 4 presents other relevant tolerancing issues, followed by future outlook in Sec. 5.

Table 1 Parameters and tolerances described in ASME Y14.8 standard on castings, forgings, and moldings [43] and ISO/DIS 8062-4 [44]. Items with asterisk are only part of ISO/DIS 8062 and not part of ASME Y14.8.

S.No.	Parameters considered
Cast, forged, and mold part-related requirements	
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 sides of parting plane*
*15**	*Required machining allowances*
Cast, forged, and mold processes for which allowances or tolerances are provided	
16*	Sand cast hand molded
17*	Sand cast machine molded
18*	Permanent molded
19*	Pressure-die casting
20*	Investment casting

Table 2 Parameters and topics covered in ASME Y14.37 standard covering composite part drawings [45]

S.No.	Parameters considered
Composite part-related requirements	
1	Ply
2	Ply orientation
3	Ply table
Composite manufacturing processes for which drawing suggestions are provided	
4	Filament winding part
5	Multistage bonded part—precured, precured with additional layup and only layup
6	Pultruded part (material roll cross section)

2 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 specifications exist 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 [43] and ISO/DIS 8062 [44] on casting, forgings, and molding is shown in Table 1. Process-driven parameters are shown nonitalicized and the process-driven tolerances are italicized in Table 1. In ISO/DIS 8062 [44], additional guidance is provided for assigning draft angle and required machining tolerances based on the specific process, such as sand casting, permanent mold casting, pressure-die casting, and investment casting.

In the composite part drawing specification standard (ASME Y14.37 [45]), 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, multistage bonding (precured, layup, and procured with additional layup) and pultrusion (material roll cross section) process. These are indicated in Table 2.

Tables 1 and 2 show that there are specification standards that are driven by tolerancing needs of specific processes. These standards include process parameters, their specification, and applicable differences from ASME Y14.5 specification on tolerances. AM processes, as discussed in Sec. 1.1, have unique capabilities and require development of a similar process-specific standard.

3 Specification Issues in AM

In this section, we discuss specification issues 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 standards related to AM processes (similar to tolerancing standard for casting and forging [43]) and those that fall under traditional GD&T standards, ASME Y14.5, and ISO 1101. The purpose of Sec. 3.1 is to present specification issues and means that are useful for communication *within a manufacturing enterprise* (*conducting concurrent design and manufacturing*). The purpose of Sec. 3.2 is to present specification issues and means that are useful for communication *between design and manufacturing teams*. The directions taken in Secs. 3.1 and 3.2 are proposed by the authors as best suited ways for addressing potential AM-specific issues that may be encountered when using currently available GD&T solutions. The directions discussed are not the only way to solve the issues, and, as research to incorporate these moves forth, novel and better solutions might be developed in the future.

3.1 Process-Driven Issues and Proposed Directions. Process-driven specification issues play a crucial role in communication during concurrent engineering and manufacturing process planning. Such issues may include (1) build direction and location, (2) layer thickness, (3) support structures, (4) heterogeneous materials, and (5) scan/track direction.

3.1.1 Build Direction and Location. (a) *Issue—Build Direction:* In many AM processes, each layer is produced by creating individual line segments. The direction of building up these layers (called build orientation) is very critical for the functionality of the product. For example, it is common for AM parts to have superior fatigue life in the directions parallel to the layers (i.e., the machine *xy*-plane) than in the directions normal to the layers (i.e., the build direction or the machine *z*-direction) [46,47]. Furthermore, geometric and surface quality of AM parts are affected by the build direction due to the stepwise discretization of layer thickness (Fig. 3) [48,49]. Since build direction affects part performance, it is vital that the designer has the means to specify the direction.

Because build direction is a vector, a tolerance zone (either cylindrical or other shapes) could be used to indicate tolerances on the build direction. Such a tolerance on build direction might allow designers to account for the machine errors in a part design. For example, consider the part shown in Fig. 2(*a*). Due to the large flat surface for datum A and the geometry of the part, it is intuitive to make the build direction along the axis of datum B, and datum A should lie flat on the build plate. However, let us consider a design specification where a surface tolerance is critical. Without a specification, perhaps for nesting purposes, an AM operator could choose an orientation (e.g., Fig. 2(*b*)) that might save space on the build platform, but require support structures (and additional postprocessing) for building. This decision could result in a part with insufficient wear properties of the tolerance surface, perhaps the inner cylindrical surface. Automated orientations could also create challenges, as researchers have proposed algorithms for optimizing the build direction for reducing the production time, having better geometric precision and part strength [48,49].

Proposed Direction: As it is an AM-driven parameter, there is no existing mechanism to specify the build direction. In ASME 14.5-2009 [6], an explicit means of identifying coordinates systems on a drawing is provided. For specifying build direction, a notation "b" with unit vector indicating build direction could be included in the standard, as seen at the bottom of Fig. 4 within a rectangle. This vector notation could be based on the coordinate system specification indicated in ASME Y14.5-2009 or similar specifications under ASTM F42.

A vector notion based on a defined coordinate system will be very flexible and will be able to represent any direction as needed for the specification of build direction. For AM processes that are not based on 2.5*D* axis motion, build direction specification in this manner would not be relevant and a different solution would be needed.

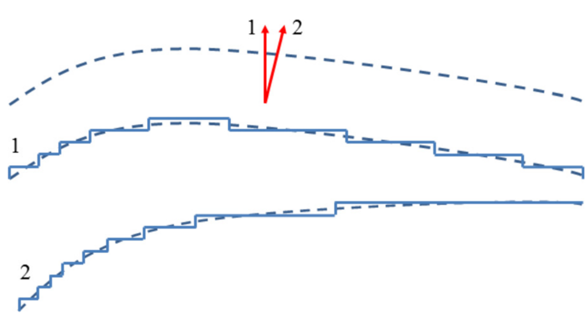


Fig. 3 Schematic depicting the effect of discrete layer thickness on the geometry of a freeform part based on a given build direction. Discretizations 1 and 2 are generated with build directions 1 and 2, respectively, for the same profile.

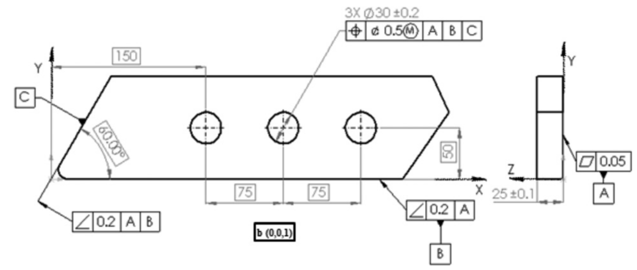


Fig. 4 Adopted figure from ASME Y14.5 [6] showing the use of coordinate system indicators (*x*, *y*, and *z* axes explicitly shown) in a drawing

(b) *Issue—Location:* In one single AM build, multiple parts can be produced, not only laterally but vertically too. For certain design requirements, particular AM process characteristics may influence part quality based on (i) location of the part on the build platform and (ii) how close other parts are in a single build. For many AM process, parts built in the center of the build plate have better geometric and mechanical properties than the ones built close to the edge of build plate. Furthermore, in powder bed fusion processes, if two part surfaces are close to one another, heat from a layer on one part may influence the properties of the other part. Therefore, it will be necessary to specify a minimum gap around a part within which no other parts' surfaces should lie. This issue may apply to assemblies as well. Specification of complete part boundary that limits other parts within that same boundary is not feasible with current specification standards.

Proposed Direction: Build location on the build plate can be specified using coordinates of part origin relative to the coordinates of the build plate. Axis alignment can also be indicated to specify in-plane orientation. To specify minimum build gap, a note can be included in the part specification. The note can limit another part's surface from being in close proximity.

These maybe considered as simple solutions to build location and part minimum gap on a build platform and intuitive to designers and manufacturers. However, when building assemblies or automating the nesting process, such specifications can quickly become critical, and communication is limited to the methods available.

3.1.2 Layer Thickness. Issue: In AM, the thickness of a layer is an important parameter that can impact the quality of the product. Based on the product quality requirements, a product design could specify layers at different locations with different thicknesses [50–52]. Layer thickness is an AM-driven parameter and there are no existing mechanisms to specify layer thickness.

Proposed Direction: In the composite specification standard [45], 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 the thickness of individual layers in AM (Table 3). An alternative method, when all layers have same layer thickness, is to provide an annotation in the drawing specification indicating layer thickness.

Table 3 A scheme showing specification of different layer thickness for AM

Layer number	Thickness (mm)
1–28 and 61–245	0.1
28–60	0.2
61	0.25

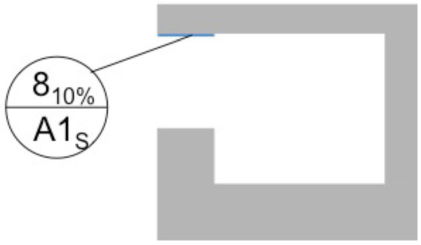


Fig. 5 Application of an area indicator showing the percentage of surface (10%) that can be covered by support structures. This will aid designers in limiting support structures at certain functionally critical locations.

The proposed direction borrows from existing methods used in composite standards and therefore will have a better chance of being adopted by the standards, design, and manufacturing communities. However, the layer thickness can vary to a much greater degree in AM, and representations that are more expressive may be preferred.

3.1.3 Support Structures. (a) *Issue for Limiting Support Structures:* Support structures are used by many AM processes to support overhang features or to limit part distortion. Placement of support structures also introduces additional postprocessing steps for removing and smoothening of part features where support structures contact the part. A designer may want to limit the application of support structures on critical features or at obscured locations in a part. Additionally, in parts with internal features (see Refs. [33,34]), it might not be feasible or be practical to remove support structures. Support structures within internal channels will lead to undesirable flow characteristics in these parts, mitigating the benefits of using AM processes. Specifications for limiting support structures are not feasible with current specification standards. Therefore, new ways of limiting applications of support structure at particular locations within a part are needed.

Proposed Direction for Controlling Support Structures: Two possible directions for addressing this issue are (1) use of an area indicator or (2) use of a feature control frame with a note or label that limits the application of support structures. Area indicators are readily available in ASME Y14.5 and ISO 1101 specification standards. The area indicators can only specify the ratio of surface area that can be covered by support structures. Figure 5 demonstrates the concept with area indicator A1. The subscript to A1 indicates the type of area. The subscript to "size of area" (8) specifies the percentage of the surface area that can be covered by support structures.

Different types of target areas can be included with different subscripts, such as c for circle, s for square, e for elliptical, and r for rectangular. The location of these target areas can be further elaborated in the drawings. The advantage of this method is that it builds upon existing elements in GD&T standards. Limitations of the proposed direction include cases where percentage of surface coverage may be too ambiguous.

(b) *Issue With Support Structure Shape, Size, and Other Parameters:* Support structures are process, material, and geometry specific. They also affect subsequent postprocessing steps required 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, the ability should exist to communicate nominal parameters and their acceptable variations of support structures in a process-related specification.

The means of communicating nominal size, shape, orientation, location, number of a feature, and variation from these nominal parameters exist in current GD&T standards. The issue with support structures is that in a nonideal scenario each support structure might have different shape or other parameters. Furthermore, support structures are usually very large in numbers and may not be in any kind of repeating patterns [53,54]. These issues would result in the cumbersome use of current methods. Therefore, better tools are needed to specify and manage specifications related to support structures.

Proposed Direction for Tolerancing Support Structures: Each support structure could be assigned a number or label. A table could be used to represent each support structures' shape profiles (including sizes) and tolerances. Although the proposed direction may be cumbersome, it promotes the inclusion of multiple variations of support structures.

3.1.4 Parts With Heterogeneous Material Considerations. Issues for Heterogeneous Material Boundaries: Parts with heterogeneous materials are usually manufactured for certain functional purposes [55–59]. Many researchers have proposed methods for modeling parts made from heterogeneous materials. A review of these methods and open problems in this area is presented in Ref. [60]. Hiller and Lipson in Ref. [61] proposed a multimaterial file format for AM in AMF.

For a part with two or more materials there can be a distinct boundary between the materials or a graded transition between the materials. Neither the specification of an explicit boundary with acceptable variations nor the transition between materials with acceptable variations is feasible with current specification standards. Since, producing parts with graded materials is unique to AM, new ways of specifying material boundaries or grades and variations from the nominal specification need to be developed, as indicated by the multimaterial representation issues discussed in Ref. [60].

Proposed Direction for Heterogeneous Material Boundaries: Since these boundaries or grades will be part of the geometry; material and geometry specifications should be aligned. Two directions are proposed here. The first direction would use functions to define a multimaterial distribution within a part coordinate system. The second, more elaborate, direction would be to specify multiple contour-based surfaces and volumes with specified materials or grades. Contour-based surfaces include the critical surfaces where the designer needs to control the variation of material distribution for functional needs.

As shown in Fig. 6, different contour surfaces/volumes can consist of different grades of materials. The contour surface and volume will need to be specified using geometry specification means. Grades can be further specified through a table. Surface and volume representations will allow surface profile and form tolerances to be utilized on these contour surfaces/volumes. The number of contour surface/volume specifications will depend on the number of specific locations with functional requirements within the part volume.

3.1.5 Scan/Track Direction for AM Processes That Are Dependent on These Parameters. Issue for Scan/Track Directions for AM Processes: Scan/track directions represent the path in which a material deposition head or an energy beam moves in each layer. Scan/track directions are similar to tool path direction on a machined surface. Each layer might have different scan/track directions. Scan/track direction not only affects the shape of the feature profiles in the layer but also aids in binding subsequent layers while serving part strength requirements. Further, scan direction has been shown to have a heavy influence on residual stresses present in metal AM parts [63]. Specifying a scan strategy when transitioning between layers could protect critical and highly detailed features from failure in complex parts.

Proposed Direction for Scan/Track Direction: The current ASME Y14.8 standard on casting and forgings provides a way to specify grain direction for a part (Fig. 7). A similar approach could be taken for specifying scan/track direction. The method could be adapted to represent different scan/track directions in the

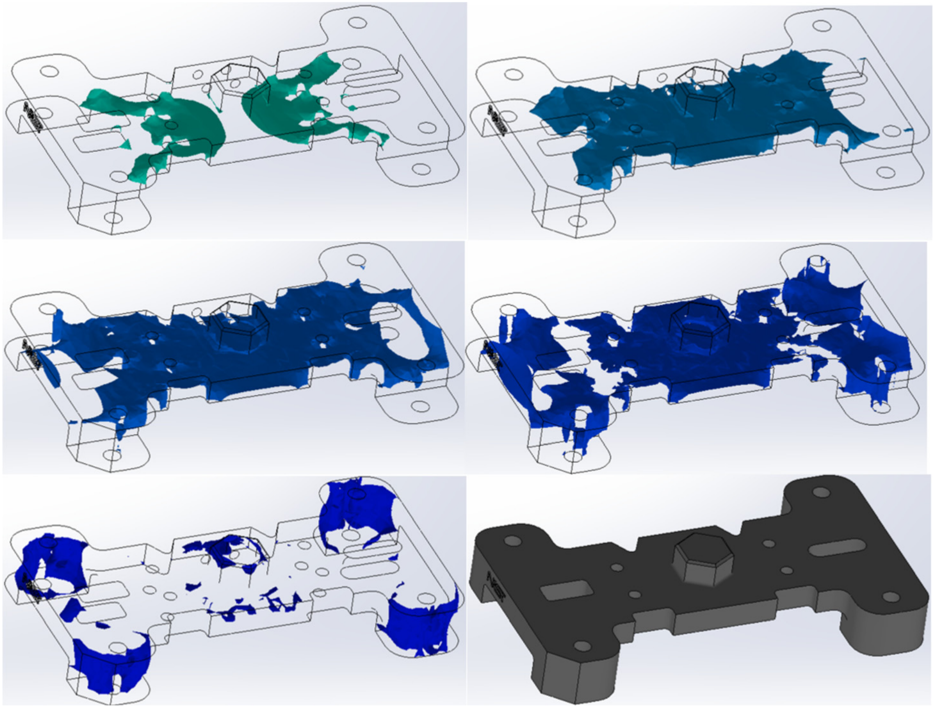


Fig. 6 Graded material distribution shown as grayscale color of surfaces and volumes in a part from Ref. [62]

same layer (creating feature shapes) or between different layers (Fig. 7) with an appended table.

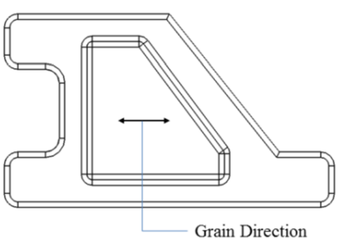
Issues Highlighted by the Capabilities of AM

3.2.1 Tolerancing Freeform Complex Surfaces. Issue: Though not unique to AM, the shapes generated by AM products often have surfaces that are freeform in nature. In general, contiguous freeform surfaces can be toleranced using profile tolerances in GD&T standards (Fig. 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, however, there may be multiple regions on a freeform surface that do not have a distinct boundary, but are governed by different surface profile equations and tolerances. This implies that the surfaces will be C2 continuous [65] at their intersection edge.

The ASME Y14.5-2009 standard includes special modifiers for surface profile tolerances such as "nonuniform" and "unequally disposed" tolerance zones. The unequally disposed modifier specifies if the tolerance zone indicates greater tolerance in surface normal direction (**v**) than the opposite direction (−**v**). Such an indicator might not be very useful in the situation described above. The nonuniform tolerance zone modifier can potentially be useful, but 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.

Proposed Direction: The application of nonuniform and unequally disposed tolerance zone modifiers can be expanded by coupling them with new boundary marker indicators. These boundary markers can be developed similar to the target area indicators in



Layer	Track direction
1,3,5..	0
2,4,6..	90
135	120
153	60
*around features track may follow feature profiles	

Fig. 7 Example of grain direction specification from ASME Y14.8 [43] standard for casting and forgings and proposed table to use grain direction specification as track specification for multiple layers. The angle in each layer is measured from the direction shown in the figure.

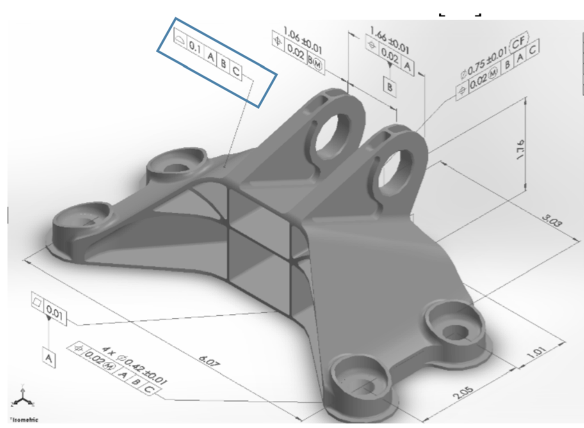


Fig. 8 Modified part from the GE bracket design competition [64] winner [42] with GD&T tolerancing

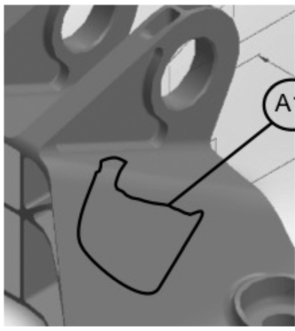


Fig. 9 A freeform target area indicator with subscript F. This area indicator can be coupled with feature control frame for profile tolerancing to specify tighter control of profile in this area for functional purposes.

the ASME Y14.5 standard [6]. Figure 9 shows an example of a freeform target area indicator. The projection of a freeform area can be specified to ascertain the shape of the area on the surface. Specifying basic dimensions on key edges of the area can provide location. A profile tolerance feature control frame can then be used to specify tighter control on a surface profile for functional purposes.

3.2.2 Tolerancing Topology-Optimized Shapes/Features. Issue: Topology optimization is a method by which the connectivity of different elements in a model can be optimized for given objectives and constraints [66,67]. Often the direct results from topology optimization are designs with many holes and thin struts (e.g., see Refs. [27–30]). In the past, these designs were modified to generate parts that could be produced by traditional processes. With the capabilities of AM, the shapes that can be produced become closer to the results obtained from topology optimization.

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.

Proposed Direction: For aesthetic purposes, a general surface profile without datum features (indicating form variations) can be specified. For specific functional purposes, each individual shape can be assigned a number or label. A table could communicate each individual shape's profile, including sizes and tolerances.

3.2.3 Tolerancing Internal Features. Issue With Infill Patterns: As was discussed in Sec. 2.1, AM parts are not always solid, and often use an infill pattern, lattice, or internal structures (such as cooling channels). Typically, choices regarding infill patterns are left to the discretion of the manufacturer. Since the infill pattern will have functional bearing on the product performance, these choices should be governed by the function of the product.

Proposed Direction: Infill patterns are typically 2D patterns extruded along the build direction. For example, consider a typical hexagonal infill pattern with a particular percentage specified for infill. In the ASME Y14.5 standard [6], tolerances on patterns of features can be specified as shown in Fig. 10 (pattern on holes). A hole's position, orientation, shape, size, and relative position are governed by the specification. Similarly, specifications of the hexagonal infill pattern can be adapted from pattern tolerance rules from the ASME Y14.5 standard [6]. The infill pattern specification may include, shape, size, wall thickness of unit pattern, origin of entire pattern, and general position tolerances.

Issue With Lattices: Lattices usually consist of a 3D unit cell that is replicated and/or conformal to the internal shape of a part. As lattices may be specific to the desired functionality of a part, they may need to be specified by a designer. Therefore, methods are needed to specify and communicate the shape and size of a unit cell (Fig. 11), conformal or fill type, and general tolerances for the entire lattice.

Proposed Direction for Lattices: For nonconformal type lattices, a unit cell's size, profile, and form can be separately toleranced. This toleranced unit cell can be used with a specification of pattern tolerance, as discussed, for infills. For conformal type lattices, a conformal function specifying the overall size variation and shape variation for a unit cell, based on the location within the part, can be used. An additional tolerance zone on the conformal function can also be specified.

For functional features [33,34], general surface profile tolerances might be sufficient for specifications. The issue with these geometric elements is in the quality assurance process. Currently, X-ray computed tomography scans [68,69] are being used for inspecting internal features. Their reliability for geometric quality is still being explored.

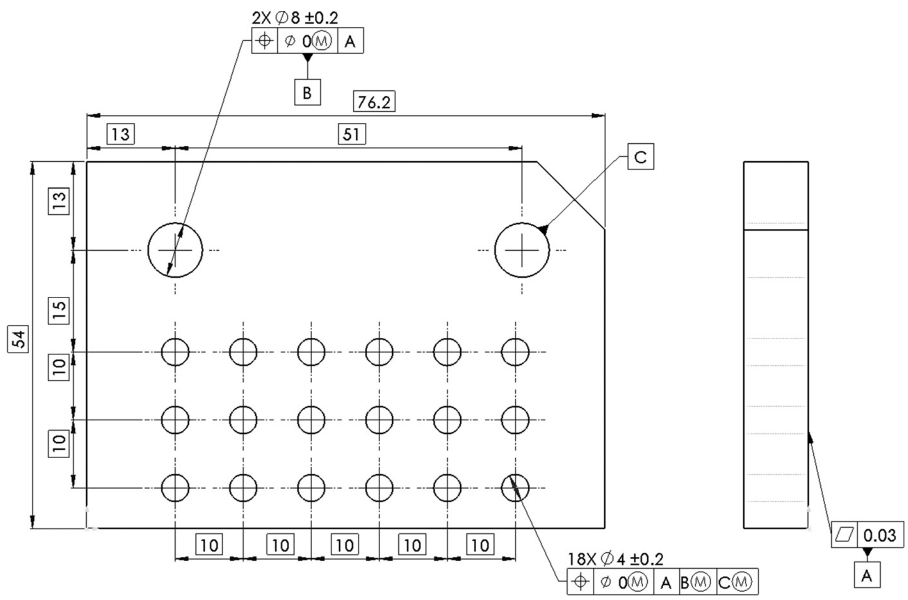


Fig. 10 Figure adopted from ASME Y14.5 [6] showing application of tolerancing a pattern of holes

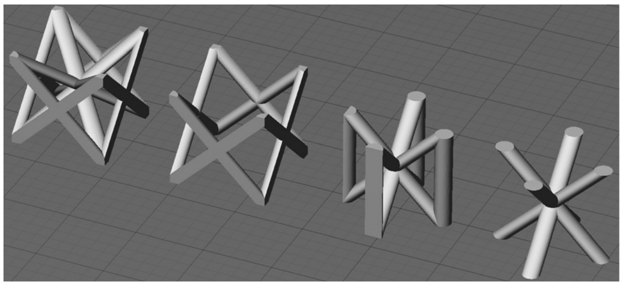


Fig. 11 Examples of lattice unit cells that are used to create lattices in AM

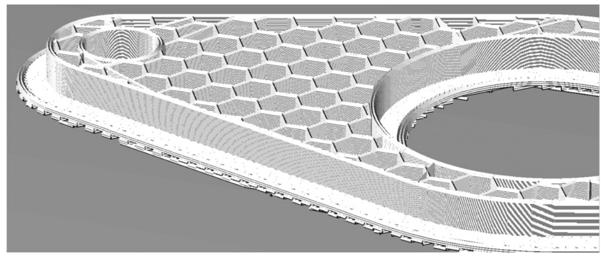


Fig. 12 Part from Fig. 2(*a*) being built. Smaller hole will be completed before the larger hole (a datum for smaller hole).

4 Other Relevant GD&T Issues

In Sec. 3, we explored specification issues that may arise when manufacturing a part using AM. Other relevant issues associated with GD&T include tolerance communication, tolerance analysis, tolerance transfer, and tolerance evaluation.

4.1 Tolerance Communication. In AM, all geometry is converted into a tessellation before processing for layers. During this process, all feature information, and tolerance information related to features, is lost. Therefore, tolerance communication must be performed via manual identification of features in the process planning software for specific processes. This approach defeats the purpose of GD&T as a means for unambiguous communication of tolerance and design intent.

4.2 Tolerance Analysis. Typically, tolerance analysis is conducted to verify that the accumulated effect of individual part variations is within the functional requirement of the assembly [70,71]. In AM, assemblies can be reduced to a single component [33,34], can be made as-built (made as assembled in the AM process [35–38] or individual parts can be built and then assembled in postprocessing.

When assemblies are built as a single component, traditional tolerance analysis does not apply. As-built assemblies may depend on the specification of clearances between moving components. Depending on resolution, these are typically in the range of 0.15 mm or more. In such situations, it will not be feasible to utilize traditional tolerance analysis methods to verify functional requirements of the assembly in the design stage. In as-built assemblies, due to larger clearances, greater rattle (undesired movement of rigid parts that would cause impact loading) leading to early part failure might be possible. In such scenarios, tolerance analysis in conjunction with impact, wear, and fatigue analysis might be needed.

Another issue is that, in AM, inaccuracies in each layer are accumulated to the next layer and lead to feature variations. Tolerance analysis in this case will be coupled with layer thickness, part geometry, and build direction for predicting feature variations.

4.3 Tolerance Transfer. From the design point of view, datum features are used to imply design intent of particular function of the part or sequence of assembly of components in a product [72]. Each feature in a part could potentially have a different datum reference based on the design intent. In traditional manufacturing, datum references are used to identify positions of machining features. In order to save time and cost, the number of datum references used in creating features is reduced in manufacturing. As the datum references are changed, validity of the tolerance specification is verified through a process called tolerance transfer or conversion [73,74]. In AM, parts and assemblies are built layer by layer, implying that all the features in the process will have a common datum reference. Different datum references could still be specified for postprocessing steps. Figure 12 shows the part from Fig. 2(*a*) being built. The larger hole in Fig. 2(*a*) is specified as the datum for the smaller hole. As is evident in Fig. 12, the smaller hole will be finished before the larger hole (datum reference for smaller hole) is completed. Therefore, tolerance transfer and process measurement for each layer [75] will be critical for achieving the geometric quality specified by the designer.

In AM processes, geometric errors in each layer will propagate and accumulate into feature errors. The impact of AM process datum references on the positions of part/assembly features will be greater than a design-specified datum reference.

4.4 Tolerance Evaluation. Tolerance evaluation or verification is often performed using Go–NoGo gages or functional gages. In products that require high precision, coordinate measuring machines (CMMs) that either use touch-based probes or optical methods, or combination of both, are used. Additionally, the data collected using CMMs is processed through algorithms (least squares [76] or Chebychev's [77]) for identifying nominal features and their variation zones. CMMs have been used for measuring external features that are produced using traditional manufacturing. For internal functional features, as discussed in Secs. 1.1.2 and 3.2.3, these methods will be infeasible.

Internal features are measured using ultrasonic testing [69], X-ray computed tomography [78,79], and neutron radiography [80,81] methods. These methods usually provide images as slices of the object. Therefore, standard algorithms and their efficacies (traceability, repeatability, etc.) using these new methods need to be developed.

5 Summary and Future Outlook

The goal of this paper was to review the implications of AM processes on current GD&T practices and discuss challenges, and possible solutions, that lie ahead. Among these challenges, this paper presented a perceived standard gap in GD&T that may be addressed by developing a process-specific specification standard or by enhancements to existing standards. Given the freeform nature of AM, and the process variability, addressing the unique challenges identified will require significant effort and direction beyond what is presented here.

The AM-driven specification issues discussed were (a) build direction and location, (b) layer thickness, (c) support structures, (d) heterogeneous materials, and (e) scan/track directions. The specifications issues highlighted by AM processes as discussed in the paper were related to tolerancing (a) freeform complex surfaces, (b) topology-optimized features, and (c) internal features including infills, lattices, and functional features.

As AM matures and part production becomes more viable, we believe the challenges described here will become increasingly significant. AM standards efforts, led by ASTM F42 [8] and ISO TC261 [9], have addressed AM-specific design needs through AM-specific file formats. Related to these efforts, we have used this paper as an opportunity to help identify where design-related challenges remain.

Future directions of tolerancing in AM may address the interactions between design, materials, and processes. Recently a new committee, ASME Y14.46 [82], has been formed to address the specification issues that have been highlighted by AM. As AM matures and designers become more comfortable with exploring AM design opportunities, new methods will be needed to communicate design intent to the manufacturing floor.

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