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Towards Annotations and Product Definitions for Additive Manufacturing

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Abstract

As Additive Manufacturing (AM) is viewed more and more as a production-capable technology, data and information needs have made the costs of AM complexity increasingly apparent. Techniques available in current GD&T practices do not fully support product definitions needs in additive manufacturing. The fully model-driven process introduces new intricacies and complexities that must be addressed to facilitate the reproducibility of AM parts. Machine-readability needs must trump human interpretation requirements. In this paper, we discuss the future directions of GD&T and semantic annotations as they relate to satisfying AM product definition requirements.

Keywords: Additive Manufacturing, Product Definition, PMI, GD&T

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1. Introduction

As a true digitally-based process, Additive Manufacturing (AM) continues to shape our understanding of how a part is manufactured. While manufacturing processes have long been considered inhibitors of design freedoms, AM contests this perception, as noted with the phrase “complexity is free [1].” However, as AM is viewed more and more as a production-capable technology, the costs of complexity become increasingly apparent, albeit in a new form. Newfound design flexibilities are accompanied by the need to describe and communicate complex designs. In AM, due to the intricacies of the processes, the communication of design intent must often include process, or even material, specifics. For these reasons, AM is compelling us to rethink how we package and communicate design requirements.

As a stand-alone production process, AM requires a 3D model for a machine to execute its instructions. 2D drawings and traditional annotations lack the capacity to be machine-interpreted for an AM-destined part [2]. New methods are needed to support appropriate definitions and communicate full design-intent in AM. As an example, the locations of the temporary support structures often used in AM processes may be critical to the strength and functionality of the final part. This manufacturing “process” detail begins to blur the line between design requirements and manufacturing plans, redefining how the mechanical hardware industry has typically provided design trait definition.

Geometric Dimensioning and Tolerancing (GD&T) practices are widely established as a means for conveying design intent for manufacture and inspection. However, until recently, GD&T practices have mostly been rooted in two-dimensional space. With the rise of Model-Based Engineering (MBE), the benefits of 3D product definition become increasingly apparent yet slow to evolve. AM has the potential to not only expedite, but also shape this evolution, as Model-Based Definition (MBD), a technique of communicating a product using the 3D model geometry and 3D annotations, is ideally suited for parts and assemblies built with AM methods.

A distinction critical to the conversation surrounding MBD methods is to understand the difference between annotations that are intended for human consumption (through presentation) versus those that are intended for computer consumption (through representation). Annotations (dimensions, notes, geometric tolerances, etc.) that are human destined are *presented* graphically. Annotations that are computer destined can be *represented* as data structures that can be interpreted by software. Elements of representation (or semantic) annotations are cautiously being introduced into GD&T practices through the ASME Y14 series committees[1] and ISO TC 213 committees[2]. To satisfy design definition for AM, these MBD elements must be both satisfied *and* extended. In this paper, we discuss annotation challenges created by AM, and the future of 3D product definitions and semantic annotations as they relate to overcoming these challenges.

2. Background

With traditional, subtractive manufacturing processes, the specifications provided by the GD&T community sufficiently support the verification and validation of manufactured parts. However, these same practices are insufficient for providing the unambiguous definitions necessary to guide how an AM part is manufactured and inspected. In [2], suggestions were made for how available techniques could be adapted to meet both the geometry and process-specific needs of AM. Comparisons were made on how AM needs compare with those seen in castings, forgings, and composites (Table 1). As the table indicates, several AM challenges are implementable using adaptations of available techniques; however, the question of practicality soon arises. A proper solution requires extending product definition to accommodate AM practices.

Table 1: Summary of parameters and tolerances described in ASME Y14.8 standard on castings, forgings and moldings [3]and ISO/DIS 8062-4 [4]that could be adapted and applied to AM. Table derived from [2].

Existing Technique	AM Counterpart
Cast, Forged, Mold part related requirements	
Parting line/plane	Build Plate
Mold line	Build Plate
Forging plane	Build Location
Grain direction	Build Direction
Grain flow	Inspection
Draft angle and tolerance	Build Direction
Die closure tolerance	Support Structures
All around and all over tolerances on different sides of parting plane	All around and all over tolerances
Required machining allowances	Post-processing allowances
Composite part related requirements	
Ply	Layer
Ply orientation	Scan Pattern
Ply Table	Scan Pattern by Layer

Similar to what has been encountered with castings, forgings, and composites [3, 5], how AM parts are processed will significantly impact whether or not the part is able to meet functional requirements. With AM processes, consistency in production is challenged by many possible variants. As a result, additional information related to AM processes may have to be conveyed by the designer at design time. In [2], AM challenges with process specifics such as build directions, support structures, and hatch plans were raised (Table 1). To achieve “as designed” functionality, “as processed” declarations must be made. If AM is to be treated as “just another process,” design requirements must hold and designers must have the ability to fully communicate process specifics.

As AM continues to emerge as a viable industry technology for the production of functional parts and assemblies, an accompanying need has emerged to ensure reproducibility in AM part design and functionality. As a purely model-driven manufacturing process, the role of drawings in the lifecycle of a product created with AM diminishes and, in many use cases, begins to have very little value. It is critical that the 3D model become the master data definition for a product produced with AM. Current GD&T annotation practices must evolve to a point where they are embedded within the modeling environment, allowing for “clickable” symbolics, and perhaps more importantly, semantic product definitions.

With Computer-aided technologies (CAx) and systems becoming, if not already, commonplace in industry, digital representations are increasingly used to supplement (and sometimes replace) drawings as a mechanism for communicating part geometry and specifications [6]. CAx systems provide a digital backbone on which information can be structured and stored. Accordingly, in what can be described as a transition to digital manufacturing, MBE requires users to create digital packages that can be interpreted by humans and computers[7, 8]. These digital packages are beginning to incorporate Product and Manufacturing Information (PMI), or annotations on a CAD model to precisely define product geometry and product specifications [8]. However, where product definition needs in traditional manufacturing can be satisfied by available annotation methods, including presentation methods, AM product definitions cannot.

3. Product Definitions: Transitioning from GD&T to PMI

In the traditional sense, GD&T is exactly as it states, a means for specifying dimensions on geometry and communicating allowable dimensional and geometric variations (tolerances) for which manufacturing can be planned and inspections can be made. Parts with tight tolerances may require precision machining methods, while loose tolerances may allow for greater flexibility. In the past, basic drawing annotations have been successful in telling manufactures how the final part should appear, entrusting the manufacturer with many, if not most of the process details to arrive at a desired state. Drawings and annotations have effectively enabled product end-users to validate their part against a design, ensuring that the part they were in possession of was indeed the part they were intended to have.

As designers learn to take advantage of the unique design opportunities provided by AM, they must also learn to plan and account how processing may affect their design intent. As some look to treat AM as “just another” manufacturing process [9-11], this is not be the case when communicating specific design requirements. When considering AM challenges, we must consider GD&T in the context of the service it provides, a means for the designer to communicate design requirements from the design through the manufacture to the part inspection (Figure 1).

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[1] https://cstools.asme.org/csconnect/CommitteePages.cfm?Committee=C64000000

[2] http://www.din.de/en/getting-involved/standards-committees/natg/international-committees/wdc-grem:din21:83875112

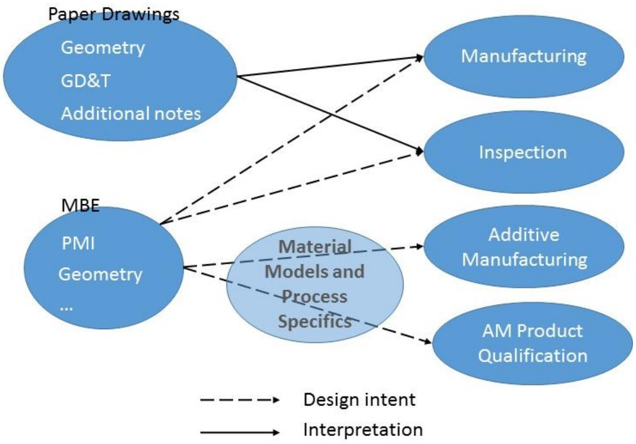

Fig. 1: MBE based communication has design intent embedded, mitigating misinterpretations.

It is crucial to avoid blindly transitioning 2D methods onto a 3D model, because the mathematical models and assumptions are different, and to take advantage of opportunities to improve any inefficiencies that exist with 2D drawing methods. The literal definition of GD&T falls short in meeting and communicating the design requirements from design through to part inspection for AM. In [12], the authors explore the role of traditional engineering drawings versus model-based definitions. They note that MBDs offer additional functionalities that can actively and proactively control product data.

In MBE practices, product definitions [13] have become the standard means for communicating requirements. With AM products, comprehensive product definitions are needed to facilitate (a) clarity in the communication, (b) efficiency in the as-built versus as-designed comparison, and (c) increased product quality. It is with these considerations that we discuss the need to transition from GD&T to PMI. Efforts to create a product definition in AM must support repeatability in a process in attempt to achieve reproducibility in parts. GD&T challenges with respect to AM will be discussed based on complex geometries, material-process interactions and internal features.

3.1 Complex geometries

Challenges in communicating AM design intent begin with complex geometries. In [2] the authors discuss geometries that are not necessarily specific to additive manufacturing, but are highlighted because of AM's unique capabilities. Many of these geometry types are currently unsupported by GD&T practices, and would be very difficult, if not impossible, to communicate through direct adaptations of these practices. Additionally, complex surfaces, created by methods such as topological optimization, may require numerous tolerance annotations at various locations. Such numerous tolerance annotations lead to ambiguity, hampering the purpose of GD&T. Therefore new methods of tolerancing complex surfaces may be required to address the presentation and representation of tolerancing requirements.

In the case of topological optimization, geometry is determined by the functional requirements of the part, so inconsistencies in geometry may directly relate to part failure. The top part in Figure 2, a hand structure, is an example of a freeform geometry where the shapes and surfaces may have specific functional implications. Note that that the provided annotations are insufficient for communicating tolerances on the geometry shown, as they correlate with only partial features of a very complex shape. The lower part demonstrated in Figure 2 was created to meet required strength and have minimum weight that can be produced using AM technology. The communication of allowable variations in these intricate geometries is not feasible through available GD&T techniques. Only the traditional surfaces can be toleranced using GD&T. Freeform surfaces with varying thickness or tolerances cannot be toleranced.

3.2 Material – process interaction

One of the most unique, and consequential, considerations that must be addressed in AM product definitions is how to account for material and process interactions. Though AM material specifications are in development[3], they are proving themselves to be highly dependent on process parameters (Most machine manufacturers will provide their own materials to be processed by predetermined and pre-set parameter sets to

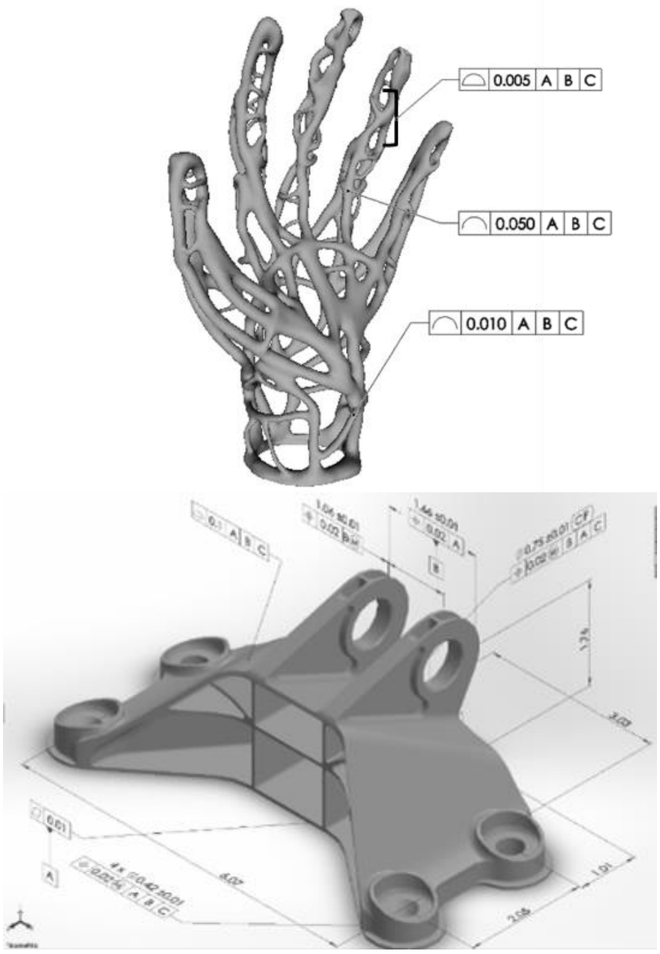

Fig. 2: Top: Example of applied tolerances on freeform geometry such as an organic structure[4]. Line and Surface profiles are allocated to demonstrate complexity. Bottom: Modified version of the topology optimized part from the GE bracket design competition [20] winner [21] with GD&T.

[3] http://www.astm.org/COMMIT/SUBCOMMIT/F4205, https://www.sae.org/works/committeeHome.do?comtID=TEAAMSAM

[4] Figure is derived from a model of a branched hand found on Makerbot Thingiverse
(http://www.thingiverse.com/thing:332451)

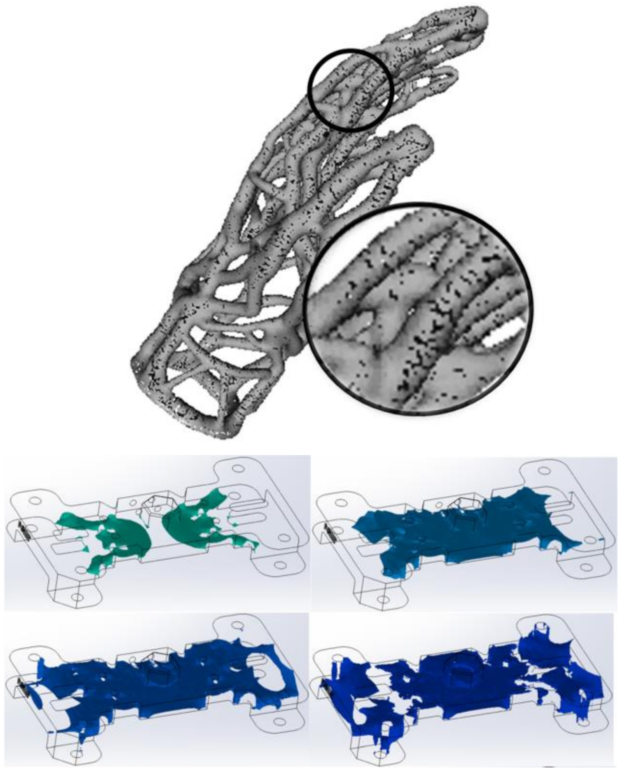

Fig. 3: Top: Example where voids may be engineered into a part to provide specific functionality. Bottom: Graded material distribution shown as surfaces and volumes in a part[5]. Various materials and processes metrics would be needed in order to semantically communicate this information.

mitigate material-process variability). AM, even more so than composites, is a process where the characteristics of the part cannot be determined until after the process is completed and the geometry has been formed. For this reason, how the material is processed must be accounted for in the product definition.

As AM technology matures, process communication challenges for a designer will be further compounded when engineering multi-material functionality into a design. AM is also unique in that part mechanics and performance can be digitally manufactured using multiple materials. Functionally graded materials are seen by many as a major breakthrough made possible by AM processes, and combine process and geometry characteristics.

When functional grades are designed into a part, to manufacture these grades metrics must be communicated about specific material locations in relation to process specifics (Figure 3). These multi-material parts epitomize the challenges AM can create with material processing. Testing for functionality will also create challenges, and additional information would have to be communicated about inspection as well (e.g., to communicate location-specific performance specifications). This again extends far beyond what is currently understood as GD&T. In [12], the authors conclude that the great majority of the MBD benefits will potentially be captured at the manufacturing and inspection levels, which happen to be the greatest areas of need in AM processing environments.

3.3 Internal Features

A unique trait of AM part production is the ability to create internal features that are not possible with other manufacturing methods. As such, specific inspection techniques may be required to ensure that the final parts meet design specifications. Non-Destructive Testing (NDT) is becoming an increasingly important instrument in qualifying parts against AM designs. Such methods are often necessary for measuring internal features or cavities without causing damage to a part. They also provide a means for studying potential variations between processed layers. For these reasons, it is conceivable that the designer may want to communicate to the inspector not only what needs to be measured within the part, but also what technique to use to measure it, and what acceptable tolerances are.

To treat AM as simply “another manufacturing process,” we must rethink how we communicate, interpret, and act upon information related to product definitions. Specifically, we must look past traditional GD&T annotations and explore what PMI and product definitions must convey in order to satisfy AM needs. To incorporate AM into production lines as an “alternative manufacturing process,” a large amount of additional geometry information, manufacturing information, and inspection information may need to be included in any data package associated with the part.

Until now, the discussion has focused on extending GD&T information as part of a larger set of PMI, why this extension of data is necessary in AM, and what some of this data may look like. What we have not discussed is the *how*, or how current practices can support the communication of this potentially vast amount of information. In the next section, we investigate the role semantics may play in communicating product definitions to support future AM MBE needs.

4. Product Definitions: Transitioning from Symbols to Semantics

As manufacturing has become an increasingly digital process, GD&T as a symbolic language for communication continues to be pressed. It is a common GD&T practice to require that all dimensions must have a tolerance [14]. With traditional GD&T and symbology, annotations are attached through notations. The number of dimensions necessary to define complex, organic shapes on a 2D drawing can quickly multiply, and in some cases are time limiting to create. Many organizations have turned to 3D model geometry as the master of the geometry, a tenet of MBD. However, a true transition from traditional GD&T practices to a 3D product definition (using appropriate PMI schemes) requires more than a superficial makeover. The fundamentals must be addressed as well.

From purely a GD&T standpoint, symbolic definitions are important to the human reader, to be able to comprehend the design, manufacturing or inspection intent, but are not necessarily ideal for computer consumption. A transition from human readable only symbolism to a greater reliance on semantics is a necessary step to bring AM nearer to full MBE [15] [16]. The differences between symbolism and semantics are recognisable when considering how PMI is communicated through presentation and representation, where:

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[5] http://www.nist.gov/el/msid/infotest/mbe-pmi-validation.cfm

Presentation (Graphic Annotation) is intended for visual consumption and human readability only (Figure 4), and[6]

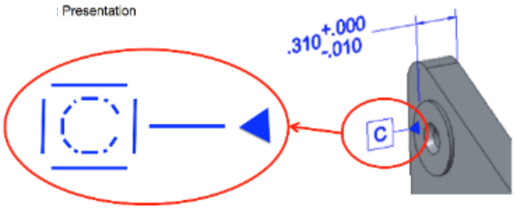

Fig. 4: Example depicting the concepts of presentation.

Representation (Semantic Annotation) is intended for software consumption. Data elements are encoded in the 3D digital model and associated to their product features and may also be human readable (Figure 5).[5]

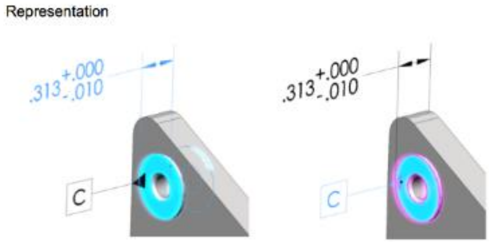

Fig. 5: Example depicting the concept of semantic annotations that represent digitally associated annotations.

Current practices using models and product definitions can be grouped into two categories: Model plus Drawing or Model-Only [17]. Using only 2D drawing graphics sheets and symbolic presentation to communicate an AM product into the CAM software required to drive the AM machine is inadequate, as AM processes are inherently model-driven. Therefore, Model-only product definitions are required for AM. These product definitions allow annotated 3D geometry to move from CAD (Computer-Aided Design) software into CAM (Computer-Aided Manufacturing) software without the need for a drawing or drawing graphics sheet [18].

Desired applications for AM include:

- Semantics to manage process-specifics across platforms while still maintaining the ability to communicate information so it can be interpreted reasonably
- Semantics to supplement visual aids/ semantics to guide visual interpretations based on interest (symbolic/semantic hybrid)
- Semantics to support automated inspection

A transition to representative, semantic annotations, attributes and metadata would not only reduce the amount of visual communication needed, but could also be used to template methods for communicating complex geometries and additional PMI.

The amount of information potentially communicated for an AM part also creates challenges specific to tolerancing methods, challenges that may be best addressed with semantic approaches. In discussing tolerancing with traditional GD&T methods, Wang notes that "tolerancing semantics such as logical dependency among variations and sequence of specifications is not maintained in these models" [19] [20]. Given the layer-by-layer nature of AM processes, it is immediately apparent that sequential tolerancing may be needed. Wang maintains a semantic tolerance modeling scheme based on general intervals is needed to improve interoperability of tolerance modeling. The author notes, "With the theoretical support of semantic tolerance modeling, a new dimension and tolerance specification scheme for semantic tolerancing is also proposed to better capture design intents and manufacturing implications, including flexible material selection, rigidity of specifications and constraints, component sorting in selective assembly, and assembly sequences." This list of benefits aligns well with complexities introduced by AM.

Beyond the layer-by-layer sequences, it is likely that distinguishing between several intermediate stages will be necessary to communicate different AM part requirements. For example, if trying to avoid process specifics, the argument may be made that support structures do not need to be addressed in the product definition. As noted in Section 2, however, process specifics such as the placement of support structures can directly influence both the shape and function of a part. In Selective Laser Melting (SLM) processes, for instance, support structures act as a heat sink during processing, relieving thermal stresses that are created during the build. These thermal stresses can create warping if not properly relieved. For this reason, the locations of support structures can greatly influence the quality of a build.

Accommodating for intermediate stages [21] (Figure 6) can create significant challenges when using symbolism to communicate product definition, especially in terms of presentation and consumption. Semantics can appropriately address such challenges by communicating through machine interpretable data calls as opposed to tables and graphs. In short, given the typically complex geometry of AM, in conjunction with the requirements of AM processing, it is imperative that new methods be developed for defining the "complete" AM product.

5. Product Definitions: Next Steps

As noted in Sections 3 and 4, AM pushes current GD&T practices to their limits, and, as the technology matures, these limits will be far exceeded. As AM technology matures, designers may look to intentionally engineer porosity into designs (Top, Figure 3), changing how a part may respond to particular loading conditions. Current design for AM is often restricted to a single material, though multiple material options are emerging, as noted in Section 3. As designers learn to introduce heterogeneity into part performance, the need to bridge design and process communication becomes increasingly important.

A finished AM part may be observed as two stages, one stage after the AM processing is completed, and one stage after the post processing is completed. New machines are now integrating these stages, where the build and the post processing are occurring in concert as a hybrid AM process. While this simplifies the process, it also highlights the necessities of machine-interpretable PMI (annotations, attributes and metadata). Hybrid machines would be enabled to process differences, where otherwise manual adjustments may have to be made.

[6] Action Engineering, Re-Use Your CAD MBE Workshop, http://www.action-engineering.com/pdf/CIC-2012_MBEWorkshop.pdf

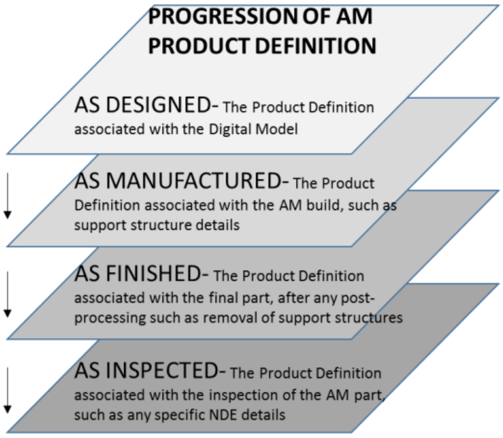

Fig. 6: Intermediate stages of AM product definition.

Also noted in Section 4 (and Figure 6) are the inspection challenges that AM may create. Internal features can not be readily inspected via traditional inspection CMM (Coordinate Measuring Machines). Additional non-destructive scanning technologies such as Computerized Axial Tomography (CAT) scans may be required to validate internal geometry. Still in their infancy (both in definition and technology to implement), automated 3D inspection capabilities have the potential to completely change the landscape of a “quality” product. Once we have design intent captured in semantic (digitally associated software readable) annotations, attributes and metadata, then the next steps of automated inspection can take place.

In summary, the challenges associated with communicating GD&T in AM are just beginning to emerge. As the technology matures, new methods will be necessary to communicate design intent, and these methods must rely heavily on PMI and representation techniques. The next steps necessary for support of AM product definitions include:

1) Developing methods to tolerance complex, freeform surfaces not currently supported,
2) Developing methods to communicate and tolerance heterogeneous materials and internal geometries,
3) Developing methods to communicate dimensioning and tolerancing requirements at multiple stages of a single product lifecycle,
4) Developing methods to facilitate machine-readable dimensioning and tolerancing from design to manufacture to conformance and verification.

Each of these conditions extend beyond current GD&T capabilities, yet must be satisfied to meet AM product definition requirements. As MBE continues to develop, current GD&T practices have been able to keep pace. To achieve the reproducibility required by a production alternative, an unprecedented amount of design information must be communicated for an AM product. To effectively meet these needs, AM, will *require* us to adapt what we currently understand to be GD&T and embrace the underlying principles of both PMI and semantic content. This thinking will change the landscape of manufacturing.

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