Exploring Model-Based Engineering Concepts for Additive Manufacturing

Robert R. Lipman, Jeremy S. McFarlane

Systems Integration Division, National Institute of Standards and Technology, Gaithersburg, MD 20899

Abstract

Robust geometry and tolerance representations are needed in additive manufacturing for precise part specification and interoperability with downstream activities such as manufacturing, inspection, and long-term archiving. A disconnection exists between process-independent part geometry and tolerances, and process-dependent information requirements for additive manufacturing. Existing and emerging standards for part geometry (ASTM AMF, 3MF, ISO 10303 STEP) and tolerances (ASME Y14) contain information related to the additive manufacturing process. Details of the standards will be discussed, how their use and improvement can benefit the additive manufacturing process, and their integration into the model-based engineering paradigm.

1 – Introduction

The trend for traditional, subtractive, manufacturing processes is towards a Model-Based Engineering (MBE) paradigm [1, 2]. The fundamental concept behind the adoption of MBE is to transition from communicating and exchanging part and manufacturing information in 2D drawings and documentation to using robust digital 3D product models and datasets. Traditionally, communicating part geometry and associated tolerances has been through drawings and associated documentation, methods that are well suited for human-consumption and interpretation. This is not compatible with increased part complexity and digital manufacturing processes. Interpretation of drawings is a potentially error-prone process, to be avoided, when developing a process plan to program machine tools for manufacturing or coordinate measuring machines for inspection. The use of 3D product models and associated data exchange formats are better suited than drawings for digital applications for manufacturing, inspection, maintenance, and operations [3]. This drives the fundamental characteristic of MBE, a single dataset containing the digital 3D product model and other associated product definitions that support downstream applications throughout the lifecycle of a product. Additive manufacturing (AM) processes are not compatible with 2D drawings. AM processes align with the use of digital 3D product models and MBE practices.

The U.S. defense industry has created a standard for MBE known as MIL-STD-31000A [4, 5]. The standard defines a Technical Data Package (TDP) used to describe the technical data used during the lifecycle of a product including "models, drawings, associated lists, specifications, standards, performance requirements, quality assurance provisions, software

documentation, and packaging details." The core of a TDP includes the 3D product model of a part represented by a Computer-Aided Design (CAD) model and supplementary data exchange formats. Currently, there is nothing specific to additive manufacturing in a TDP; however, the concept of the TDP being used as a lifecycle description of product information would be very beneficial for additive manufacturing.

A fundamental characteristic of the MBE approach is to link part and product information across the stages of its lifecycle. An additive manufacturing process can be defined by eight phases of information [6]: (1) part design, (2) raw tessellated geometry, (3) final tessellated geometry, (4) build file, (5) machine data, (6) printed part, (7) finished part, and (8) validated part. Raw tessellated geometry (Phase 2), which approximates the precise geometry in the CAD model (Phase 1), is transferred to AM software. In the AM software, the tessellated geometry can be modified in a variety of ways to ensure manufacturability. The resulting tessellated geometry (Phase 3) is then sliced and prepared for printing (Phase 4). The slicing process can introduce further deviations from the original CAD geometry. Finally, the slices are interpreted by the machine (Phase 5) and the printed part can be inspected (Phase 8). There is also feedback between the phases. For example, results from the inspection can be used to modify the part design for a part that does not meet desired design specifications.

Figure 1 shows a simplified flowchart of the design, printing, and inspection phases. Inspection is based on the tolerances specified with the original geometry in the CAD model. However, a disconnection exists between the design and inspection phases, indicated by the dotted line. The geometry of the printed part is based on an approximate tessellated geometry and its slices and not on the original geometry and tolerances from the CAD software. Consequently, there are two parallel independent representations of geometry. The first representation is the process-independent CAD geometry and tolerances. The second is a temporary representation used for printing that has transformed the CAD geometry into tessellated geometry and slices. The dual geometric representations and the disconnection between the design and inspection process create a significant challenge for an MBE process. The manufacturing and inspection processes would benefit if they were driven by a single geometric and tolerancing representation.
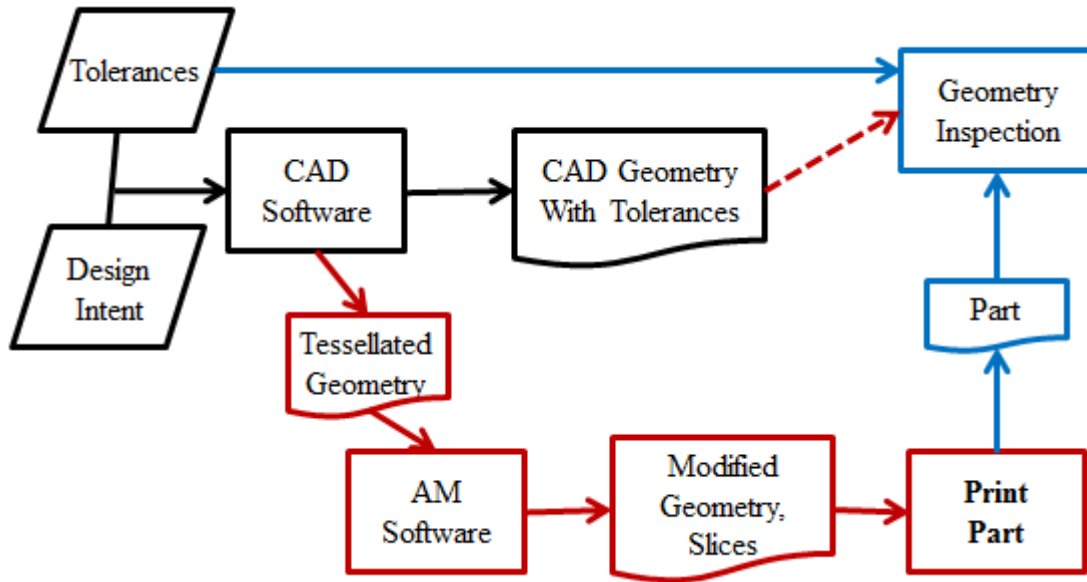
Figure 1: Flowchart of design, print, and inspection process

2 - Representations for MBE in Additive Manufacturing

Robust representations for geometry and tolerances are essential to the use of additive manufacturing information in MBE. Those representations generally serve two purposes (1) to exchange information between both CAD and additive manufacturing software with downstream planning, printing, and inspection processes and (2) to provide a repository for an additive manufacturing product model. Many of the data exchange formats used for these representations satisfy only some of the needs of MBE. In this section we describe the relevant formats and standards for both geometric and tolerance representations.

2.1 – Standards for Geometry Representations

Previous research from the 1990's and early 2000's [7-10] evaluated the data requirements for additive manufacturing, available data exchange formats for geometry and slices, and proposed new formats. Some of the evaluated geometry formats include STL (Stereo Lithography) [11], STEP (Standard for Exchange of Product Data) [12], STH (Surface Triangles Hinted), and CFL (Cubital Facet List). Two new data exchange formats were also proposed: RPI (Rensselaer Polytechnic Institute) [13] and LMI (Layer Manufacturing Interface) [14] formats. Some of these formats have survived, while others have not. Regardless, many of the data exchange requirements these formats were intended to meet still exist. More recently, two new formats have been proposed: AMF (Additive Manufacturing Format) [15] and 3MF (3D Manufacturing Format) [16]. STEP has been improved relative to data exchange requirements for additive manufacturing. These formats and their applicability to meeting MBE requirements

in the context of additive manufacturing are described below. A 2015 UK-funded project will also be assessing some of the same formats mentioned here, including AMF, STEP, and STEP-NC [17].

STL

The STL (Stereo Lithography) format is the commonly used, de-facto standard for exchanging tessellated geometry from CAD or additive manufacturing software with other AM-related processes such as geometry slicing, support generation, and printing [11]. An STL file contains unstructured planar triangular facets (tessellations) defined by three vertices and a facet normal. As a result, an STL tessellation only approximates the exact CAD model geometry using these discrete triangular elements. Parameters, such as chord height, deviation, and angle tolerance, in the CAD software control the deviations between the exact and the tessellated geometry. The tessellated geometry is unstructured in that every facet is defined completely independently of every other facet. There is no sharing of vertices between facets or defining edges and surfaces.

STL files usually need to be repaired to ensure that they can be sliced and printed [18]. This entails making sure there are no missing triangles, collapsed edges, unshared edges, inverted normals, overlapping or intersecting triangles, and that the tessellated geometry is watertight. The STL tessellation can also be modified in other ways to optimize the printing process such as filling small holes, hollowing out solids, and thickening thin-walled parts. The STL format is still widely used despite acknowledged shortcomings. These shortcomings, however, mean that STL does not satisfy the requirements for MBE.

AMF

The Additive Manufacturing File (AMF) format is a data exchange standard developed by ASTM F42 committee on Additive Manufacturing Technologies [19, 20]. The AMF format is co-branded with the ISO TC 261 standards committee on additive manufacturing [15]. AMF is an XML-based file format defined by an XSD schema [21].

The AMF format is intended as a replacement for STL. As such, it is a new means to transfer information between design software and additive manufacturing hardware. It has many features that are an improvement over the STL format. These features include support for curved patches, recursive subdivision, multiple materials, graded materials, internal structures, material properties, colors, graphics, build placements, and metadata.

Curved triangles are defined by normal vectors or edge tangents at each vertex of a planar triangle. Recursive subdivision further increases the tessellation accuracy by subdividing one triangle into four triangles. A highly accurate approximation of a sphere can be modeled starting with a coarse mesh of curved triangles and applying multiple levels of recursive subdivision.

This method generates a closer approximation of the precise geometry for a relatively coarse tessellation.

Multiple and graded materials allow new materials to be created by specifying a mixing ratio of materials or a variation of their distribution within an object. The ratios or distributions of materials are defined by mathematical functions. Multiple materials can have different mechanical properties and when printed, according to their distribution, create new mechanical properties in specific regions of a part to satisfy design specifications. Internal or external structures such as lattices or cooling fins can also be specified by a functional representation describing the distribution of material within a part.

AMF also has the capability to specify colors or texture maps in a region or at vertices, graphic images such as logos, print orientation and layout in a build volume (constellation), and metadata strings. The standards documentation also lists future potential provisions for dimensional and geometric tolerances, surface roughness, support structures, functional representations, voxel representations, and surface texture.

Although AMF is intended as a 'printing' format, the detailed model for additive manufacturing information satisfies only some of the needs of MBE. A single representation captures the intent of an additive manufacturing design. The AMF format also supports metadata that can be associated with, either the entire file or individual objects in the file. Metadata includes the name and description of the object, revision number, an associated URL, producer information, object volume for verification purposes, a single tolerance value for the entire part, and material strength. The AMF format has been developed to be independent of model resolution and layer thickness and contains no information specific to any one additive manufacturing process.

3MF

The 3MF Consortium introduced the 3D Manufacturing Format (3MF) in May 2015 as a new 3D printing format [16]. The consortium includes CAD and AM software vendors, 3D printer manufacturers, and 3D printing service bureaus. 3MF is designed to support interoperability between design software and 3D printing hardware. Documentation for 3MF includes two specifications and reference guides: (1) the 3MF core and (2) materials and properties. 3MF is defined by an XSD schema and 3MF files are written in XML [21].

The geometry representation for a 3MF object consists of a mesh defined by a list of vertices and triangles are defined by indices into the list of vertices. There can be multiple meshes in one object. Components and assemblies, such as a car body object and tire objects, can be defined each with its own transform to place the tires on the car body object. Objects can also reference a material name and color. The extension for materials and properties adds 2D texture coordinates, composite materials, and multi-properties to the 3MF core.

One of the primary purposes of 3MF is to send the required information to a 3D printer from design software directly. However, this purpose is not a concern for MBE. In addition to the features described above, the 3MF file format includes other information packaged with the object geometry. That information includes a thumbnail image of the object, a print ticket, metadata, and a digital signature. Metadata includes information about the designer, copyright, license terms, creation and modification date, and build instructions.

STEP

STEP (ISO 10303 –known informally as the STandard for Exchange of Product model data) [12, 22, 23] is a family of standards defining a methodology for describing product data throughout the life cycle of a product. Two STEP application protocols (AP) that have been widely implemented in CAD systems are AP203 known as '3D design of mechanical parts and assemblies' [24] and AP214 known as 'automotive mechanical design' [25]. AP242, a new application protocol approved by ISO in 2014, is known as 'managed model-based 3D engineering' [26]. AP242 covers the scopes of both AP203 and AP214. Additionally, it contains many new or improved capabilities such as tolerances, kinematics, data quality, and tessellated geometry [27]. Each of these APs is specified by a schema in the EXPRESS language [28]. A 'STEP file', also known as a 'Part 21 file', refers to a file that is exported by CAD software [29].

One purpose for STEP tessellated geometry [30] is to visualize large complex geometric models instead of rendering boundary representation geometry. In STEP, sets of triangulated faces are defined by a list of coordinates and indices referring to the coordinate list. Normal vectors are assigned to each triangle. Triangle strips or fans can be defined in addition to individual triangles. A coordinate list can contain all coordinates for an object or only those related to a set of triangulated faces. Multiple sets of triangulated faces can be grouped together to form a tessellated solid or shell. Multiple tessellated solids and shells can be grouped together to form a tessellated shape. Tessellated edges are defined by the two faces common to an edge and indices referring to the coordinate list for the endpoints of the edge. The definition of tessellated edges can be used to determine if the all of the triangles for an object define a watertight tessellation.

STEP AP242 is perhaps the best suited for addressing some MBE issues in the context of additive manufacturing. In particular, a single STEP file can contain precise model geometry, tolerances, multiple tessellated geometry representations, and associations between them. An important feature of STEP tessellated geometry is that a set of triangulated faces can refer to an exact geometric surface such as a plane, cylinder, or other boundary representations. Geometric and dimensional tolerances can also be associated with exact geometry and therefore with the tessellated geometry. Therefore, a set of triangulated faces can be directly inspected to ensure that they are within a tolerance value associated with them. This feature helps connect the disconnected processes shown in Figure 1.

Validation properties can be used to validate information in STEP files. For example, geometric validation properties are characteristics of solid and surface models, such as area, volume, and centroid that are written to a STEP file when it is exported from a CAD system. When the STEP file is imported to a receiving CAD system, that system can compute the same validation properties and compare them to the values from the originating system in the STEP file. If the computed validation properties are within an agreed tolerance to the original validation properties, then the exchange of geometric information has been validated. Validation properties have also been defined for tessellated geometry including the number of facets, surface area, and surface center point.

Another essential feature of geometric representations is their use for long-term archiving and retrieval. This is an important aspect of model-based engineering in the aerospace, automotive, and defense industries. Information about the design of manufactured parts might need to be retrieved, decades from when it was first manufactured, to create replacement parts or understand the design parameters and rationale for a part. There is no guarantee that CAD models in proprietary formats will work with future versions of CAD software or computer systems. LOTAR is a consortium that develops, tests, publishes, and maintains standards for archiving and retrieval of digital data [31]. STEP application protocols are the basis for the standards being developed by LOTAR. Some of the LOTAR standards relate to explicit 3D CAD data and tolerances associated with CAD models. A LOTAR standard for additive manufacturing product data is also being considered. The LOTAR consortium also tests STEP translators in CAD software for conformance to the standards.

The proposed scope of Edition 2 of AP242 includes higher-order curved triangles along with additive manufacturing specific information for the placement and orientation of parts in a build volume [32]. Past research also showed how additive manufacturing features such as heterogeneous materials [33, 34] and slices [35, 36] could be represented in STEP. As far back as 1995 STEP was being considered as a method to integrate design and solid freeform fabrication [37].

STEP-NC

STEP-NC (Numerical Control) is a machine tool control language that (1) extends the ISO 10303 STEP standards with the ISO 14649 machining model and (2) includes geometric dimensioning and tolerancing information similar to AP242 [38-40]. The application protocol for STEP-NC is AP238. An AP238 file includes part geometry, features, tool characteristics, work plans, and machining parameters; however, it does not include tessellated geometry. The intention of STEP-NC is to control a machine tool directly from an AP238 file rather than generate G-code [41] to program a machine tool.

Additive manufacturing is also being considered as an addition to STEP-NC. The control of the movement and operation of a laser for powder-bed fusion or the motion of an extruder

head is considered the same as the control of a machine tool used for traditional subtractive machining operations. This development would also be of interest to control hybrid subtractive-additive manufacturing machines. Some of the characteristics of additive manufacturing being considered for a future version of AP238 include supports, lattices, skins, cores, layer strategy, and machine processes. A proof-of-concept has also been developed for representing extruder motion paths from a Common Layer Interface (CLI) file in a STEP AP238 file [42].

STEP-NC supports use of machine tool control for MBE by having a single AP238 file that contains both geometry and a manufacturing process plan. In the future, it may also include additive manufacturing information and tolerances.

2.2 – Standards for Tolerance Representations

Equally important for MBE is the definition and communication of tolerances related to design geometry. Geometric dimensioning and tolerancing (GD&T) is a symbolic language for communicating engineering tolerances on manufactured parts. GD&T specifies the allowable deviation of features on a part so that the appropriate manufacturing and inspection processes can be used. The specification of GD&T on parts helps guarantee their operation in an assembly and controls how a part is measured to ensure that it meets the specified tolerances.

The ASME Y14.5 and Y14.41 standards [43, 44] and ISO 1101 and 16792 standards [45, 46] define how GD&T is specified on 2D drawings and 3D models. None of the tolerancing standards define anything specific to additive manufacturing. A new ASME committee Y14.46 was formed in 2015 to consider product definition practices for additive manufacturing, including tolerances. Research related to tolerances and additive manufacturing has considered part accuracy [47-49] and manufacturability of flatness and circularity tolerances [50-52].

Figure 2 shows a typical CAD model with geometric and dimensional tolerances applied to surfaces, slots, and holes [53]. The presentation of the annotations on the drawing, as line segments, is meant to be human readable. The representation of the tolerances in CAD systems or other standard file formats is intended for consumption by downstream applications such as manufacturing and inspection. The annotation representation does not contain any information regarding their visual appearance.

Figure 2: CAD model with typical GD&T annotations [53].

STEP AP242 contains information for the representation and presentation of ASME standards for tolerances. An AMF file can contain a single tolerance value related to the accuracy of the recursive subdivision. The AMF standard also lists dimensional and geometric tolerances as a possible future feature.

Recent research considers tolerance specification issues for additive manufacturing [54]. Those issues are either related to the additive manufacturing process or highlighted by the capabilities of additive manufacturing. For example, the build orientation used in an additive manufacturing process can affect the part strength, requirements for support structures, surface roughness, build time, and other characteristics [55-59]. A designer might want to specify the build direction and acceptable deviations from the build direction to ensure that requirements for strength, tolerances, and surface roughness are met. The ASME Y14.5 standard defines a way to identify coordinate systems on 2D drawings. The coordinate system could be extended to specify the build orientation for each part in a single build. Specifying the layer thickness and orientation of laser scanning or deposition patterns has some similarity to the process-specific ASME Y14.37 standard for 2D drawings of composite parts [60]. The composite standard contains a ply table of fiber orientations and layer thicknesses. The ply table concept could be

extended to specify layer thickness for printed parts and scan or deposition pattern directions. The definition of a grain direction in the process-specific ASME Y14.8 standard for casting, forgings, and molded parts [61] could also be adapted to represent scan or deposition pattern directions.

3 – Discussion

Table 1 summarizes the geometric representations presented in section 2.1. Empty cells indicate that a geometric representation does not support a particular feature. The first row shows a 'purpose' for each of the representations. Clearly, STL, AMF, and 3MF are printing formats intended to transfer information from CAD and AM software to printing hardware. Both AMF and 3MF are intended to be replacements for STL with improved tessellated geometry and other features. Being supported by a consortium of software and hardware vendors, the 3MF format aims for a seamless printing process.

The AMF format contains a lot more information to capture some of the unique features of additive manufacturing such as lattice structures and functionally graded materials. This positions the format as a 'printing' format with robust, additive-specific information. Some aspects of AMF put the burden of generating the final printed geometry on the slicing or printing software. Lattice structures are defined implicitly by a functional representation that has to be evaluated to generate the explicit geometry to be printed. In addition to the AMF file format, ASTM has developed a standard terminology for coordinate systems used in additive manufacturing [62]. The standard can be used to specify the position and orientation of a part relative to the build platform.

On the other hand, the STEP formats are product models and not printing formats. To 'print' a STEP file, the tessellated geometry can be converted to any of the 'printing' formats. The STEP file also maintains an association between precise geometry, tessellated geometry, and tolerances. In addition, STEP is the format used for long-term archiving and retrieval of product information. STEP validation properties can be used to verify geometry, precise and tessellated, and geometric and dimensional tolerances.

There might need to be some middle ground between the 'printing' file formats and the robust product models. However, instead of a middle ground, additive manufacturing information might only be represented in a product model. The temporary 'printing' file formats are only used to send information to a printer. Consideration needs to be given to the additive manufacturing data exchange process, in the context of MBE, to maintain the integrity of the design geometry as modeled in CAD software and what is eventually printed, finished, and inspected regardless of which format is used. This will help ensure additive manufacturing is a completely model-based process.

	STL	AMF	3MF	STEP	STEP-NC
Purpose	Printing	Printing, information model	Printing	Product model	Product model, manufacturing
Format, Schema		XML, XSD	XML, XSD	STEP Part 21, EXPRESS	STEP Part 21, EXPRESS
Tessellated Geometry	Unstructured triangles defined by vertices, normal vectors	Mesh defined by list of vertices and triangles indexed to the vertices, normal and edge vectors, curved triangles, recursive subdivision	Mesh defined by list of vertices and triangles indexed to the vertices	Mesh defined by list of vertices and triangles indexed to the vertices, normal vectors, groups of triangles, edges, multiple tessellations, association with exact geometry and tolerances	
Material		Composite materials, functional representation of heterogeneous materials	Composite, multi materials	Single material	Single material
Lattice Structures	Any geometry can be modeled	Functional representation of lattice geometry	Any geometry can be modeled	Any geometry can be modeled	Any geometry can be modeled
Build Orientation, Placement		Orientation and placement of objects in build volume	Arrangement of objects in build volume		
Color and Texture		2D and 3D texture maps, color defined at the material, object, volume, triangle, or vertex level, functional representation	2D texture maps, color defined at object and triangle level	Single color	Single color
Support Structures	Any geometry can be modeled	Explicitly not to be used for support structures	Mesh defined as support object	Any geometry can be modeled	Any geometry can be modeled
Validation Properties		Tessellation volume		Number of triangles, surface area, centroid	
Metadata		Object name, revision number, URL, producer, material strength, etc.	Designer, copyright, license terms, creation date, modification date, build instructions, etc.		
Tolerances		Single tolerance value entire part		Based on ASME Y14 standards	Based on ASME Y14 standards
Other		Many potential future features	Thumbnail image, digital signature, extension mechanism	Long-term archiving and retrieval, research related to heterogeneous materials and slices, future version considering curved triangles, build placement, texture maps	Machining operations, future version considering AM, proof-of-concept representing CLI in STEP-NC

Table 1: Summary of file format characteristics

Other characteristics of additive manufacturing will require new ways of thinking about how tolerances are applied and how features are inspected. Figure 3 shows a part with complex,

free-form surfaces and a part with multiple lattice structures and cooling fins. It is unlikely that traditionally specified tolerances or inspection methods can be applied to these and other features that are unique to additive manufacturing. For either part, even if a typical surface profile were applied to the entire part, it would be difficult to measure or inspect inaccessible surfaces. For the part on the left, a functional tolerance that measures the horizontal cross sectional area might be more appropriate. The area could be related to requirements for different loading conditions. For the part on the right, a tolerance might be applied to the outer boundary of each lattice section. New procedures will have to be developed to apply tolerances and inspect parts with inaccessible internal features such as cooling channels, embedded components, and transitions between heterogeneous materials. These unique geometric and tolerance characteristics will require new definitions of digital products models and MBE for additive manufacturing.
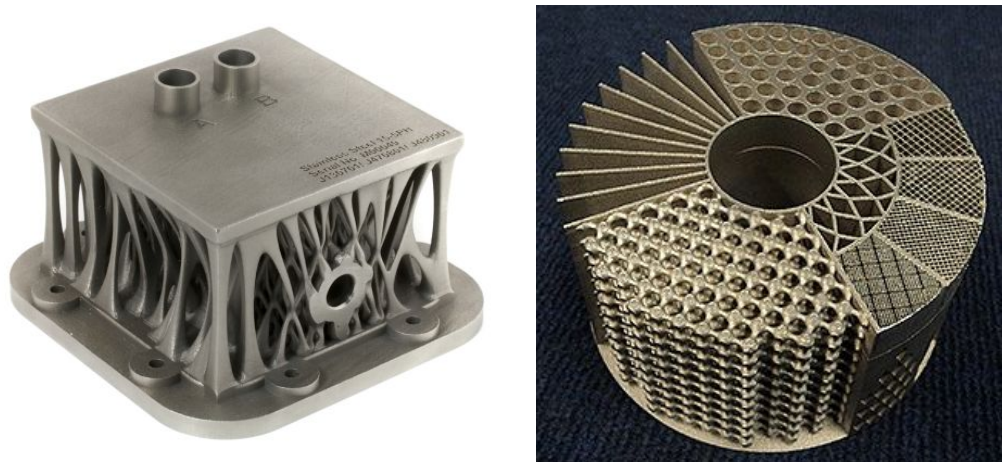

Figure 3: Examples of complex free-form surfaces [63], lattices structures, and cooling fins [64]

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