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Tolerancing and Verification of Additive Manufactured Lattice with Supplemental Surfaces

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Abstract

Additive manufacturing (AM) has enabled the production of complex geometries such as conformal lattices, topology optimized shapes, and organic structures. These complex geometric shapes must sometimes meet functional requirements, including (1) following specific curves or surfaces and (2) being bounded by specific surfaces. Mechanisms such as Theoretical Supplemental Surfaces (TSS) have been proposed for tolerancing of such geometric shapes, though challenges remain with inspection and validation requirements. A Theoretical Supplemental Geometry (TSG, including curves – TSC, surfaces – TSS and volumes – TSV) concept is introduced. To address these measurement and verification challenges, Derived Supplemental Surfaces (DSS) are introduced. The verification of a TSS specification using 3D scanning and DSS is demonstrated on a lattice surface using Chebyshev and Least Squares fitting.

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Keywords: Tolerancing Challenges; Additive Manufacturing; Lattices

1. Introduction

Additive manufacturing (AM) has opened avenues for manufacturing one-of-a-kind, highly complex organic geometries. These geometries can be designed using a variety of techniques including topology optimization, conformal lattice, bio mimicry, point-cloud editing, refinement and other traditional and emerging computational geometric techniques.

To benefit from the technological advantages underscored by new AM design tools, representation and specification schemes are rapidly being investigated [1–6]. The focus of this research is on the tolerancing and verification of lattice-based geometries across a defined surface and volume.

1.1. Lattices

Lattices generally aid in reducing the ratio of weight to function (e.g. strength to weight ratio) for AM parts. Once greatly subject to manufacturing constraints, the freedoms offered by AM are allowing lattices to be seamlessly incorporated into the manufacturing of a part. Researches continue to investigate new ways to design [7,8] and leverage [9–14] lattices in AM. Analysis software for lattice-based designs are available [15–18] to test designs against intended functionality. Lattices are most often represented as STL triangulations, voxels [7,19], and mathematical functions.

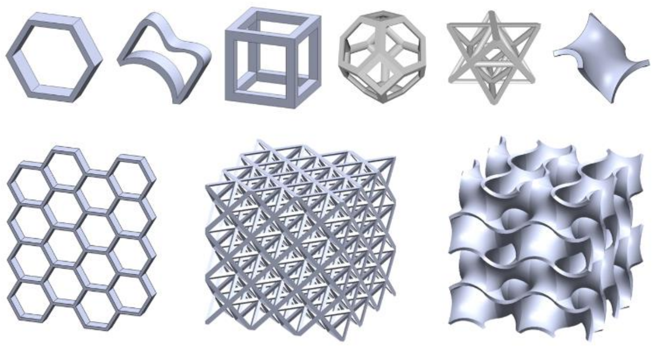

Figure 1: Examples of different unit cells (top row) and lattices (bottom row).

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1.2. Lattice at Meso and Macro scales

Lattices can be generally defined as a collection of repetitive geometric elements within an arbitrary area or volume (called a unit cell). These cells may form both two-dimensional and three-dimensional patterns to create lattice structures. Figure 1 shows several unit cells (in the top row) and lattice structures (in the bottom row) formed from the unit cells. We will refer to lattice structures that are not directly subject to part level requirements (e.g. geometric boundaries) as lattice structure at the meso-scale.

Incorporating lattice structures at meso-scales supports the creation of heterogenous volumes composed of both lattice and solid. Lattices can be used to fill a given volume in multiple ways, including variations such as: (a) trimmed with uniform thickness, (b) trimmed with non-uniform thickness and (c) conformal (Figure 2). Variations in unit cell types and in unit cell materials (Figure 2d) across different regions of a part are possible. Lattices can be unstructured (no distinct patterns but with basic cylindrical unit cells) and built using computational techniques, such as topology optimization, Voronoi diagrams, and Delaunay triangulations. When the volume of lattices is such that it must directly conform to part-specific requirements, we consider this lattice structure to be at the "macro-scale".

When discussing lattice structure in the context of geometric dimensioning and tolerancing (GD&T), lattices that are incorporated into geometric elements that directly meet functional needs are of particular interest. Figure 3 shows a part where lattice-based geometry is used as elastic compression bars. Given the absence of a continuous surface, these bars have lattices that lie within (not trimmed by) an a surface (shown with orange lines) of the bars. The focus of this paper will be on such lattices that must follow such supplemental curves or surfaces or are confined within supplemental volumes.

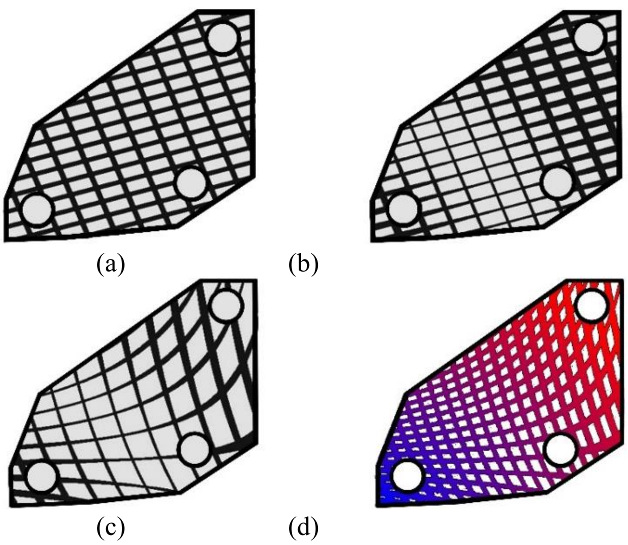


Figure 2: Four cases of simple unit cell filling a region in a part. (a) simple lattice, (b) non-uniform thickness lattice, (c) conformal lattice and (d) conformal lattice with multi- material.

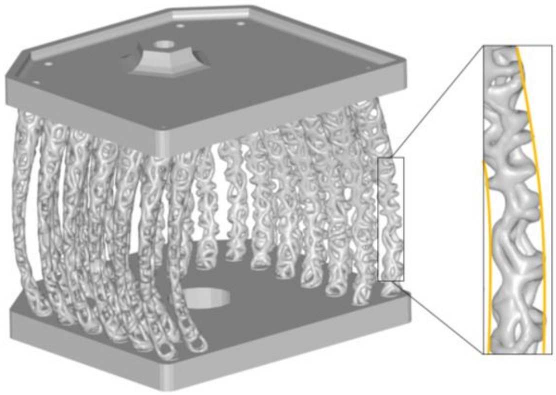


Figure 3: Lattice enclosed within an supplemental surface serving functional need for the part.

2. Tolerancing in AM

For the purpose of this discussion, we assume some process stability, as AM technology and specific machine-based process capability studies have been conducted for more than a decade. To discuss the tolerancing of lattices, we focus on mechanisms for communicating and measuring how well a manufactured part should and does fit to a specification. In surveying general tolerancing methods for use in AM [19–22], researchers have noted that traditional tolerancing techniques are not capable of addressing all tolerancing issues in AM parts. Among the many issues, lattice based structures pose critical challenges to both communication and verification of part geometry.

Challenges in tolerancing lattices arise from the multi-scale scaffolding often seen in their geometry. Elements that exist at meso-levels inform macro-level geometries. Tolerancing lattices at meso-level elements for a uniform thickness trimmed lattice would include (a) size tolerance for strut thickness and unit cell dimensions, (b) form tolerances for strut shape and unit cell shape, (c) orientation tolerances for individual strut and unit cell, and (d) position tolerance for unit cells and the lattice as a pattern. Furthermore, the trimming volume would also have size, form, orientation, and positional tolerances. The tolerancing of lattices has been restricted to relatively trivial mechanisms, such as tolerancing for minimum lattice strut thickness across multiple lattices. For non-uniform thickness lattices, conformal lattices, and unstructured lattices, it would be highly infeasible to utilize the techniques available in traditional tolerancing.

To address lattice tolerancing challenges at the macro-level, the ASME Y14.46 [23] standard introduces the concept of Theoretical Supplemental Surface (TSS), used with annotation "THEORETICAL SUPPLEMENTAL SURF". This supplemental surface can be toleranced using tolerancing tools available from ASME Y14.5 [24] or ISO 1101-2017 [25]. The surface is obtained and specified relative to a model geometry, thus the term "theoretical." When applied, the TSS supplemental geometry is able to specify the control of form, size, orientation, or location of a collection of geometric elements or lattices. The concept of TSS may be further extended to curves, Theoretical Supplemental Curve (TSC) and volumes, Theoretical Supplemental Volume (TSV), as needed

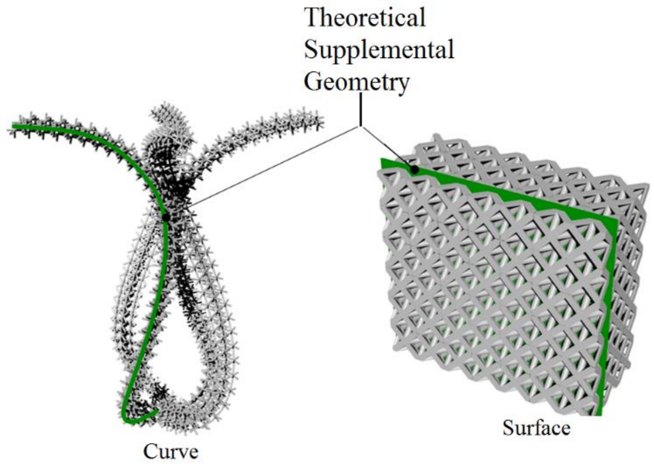


Figure 4: A curve as an extension of TSS that passes through the centroid of each unit cell and a plane as a TSS passing through the centroid of the first layer of unit cells in a lattice.

(Figure 3). As a group, these may be referred to as Theoretical Supplemental Geometry (TSG).

In application, tolerancing with a TSS is similar to tolerancing an axis of a hole. The axis does not physically exist but is inferred from the hole surface. Similarly, the TSS does not exist physically, but is inferred using geometric elements from the lattice. Therefore, the specification of geometric variation via TSS, and subsequent inspection, remains a challenge.

3. Verification of a TSS through a Derived Supplemental Surface (DSS)

While the TSS provides a means for controlling a surface of complex structures such as lattice structures, its definition is restricted to the virtual modeling space. Once a geometry is manufactured into a part, the virtual elements become a physical reality. Though the surface profile remains supplemental, the surface can now be derived from the physical manifestation of the part. We will call this measured profile a Derived Supplemental Surface, or DSS.

When calculating the DSS, the selection of both the measurement method and the control algorithm are integral to determining conformance. The measuring technique chosen will influence the selection of surface points on the physical part, a critical detail when deriving a supplemental surface from non-continuous surfaces. The control algorithm used to calculate the DSS will dictate the observed profiles. Different algorithms will use the measured points differently when fitting a surface. It is important to understand the different tradeoffs when deriving a DSS.

The ability to accurately measure a DSS is very much dependent on the resolution of the measuring equipment relative to the size of the lattice structures. In AM, and particularly with the most common metal machines, part sizes remain relatively small (e.g., 300mm x 300mm x 300mm). Thus, traditional (tactile and optical) verification is mostly suitable for external surface measurements, though lattice-based complex structures and internal features pose unique challenges.

The need for Non Destructive Evaluation (NDE) techniques in AM [26,27] has led to a multitude of measurement techniques to be researched on AM parts. For instance, X-ray Computed Tomography (XCT) and neutron imaging techniques are being employed to verify the sub-surface quality of parts in AM [28]. While XCT and other techniques are available for verification in AM, the intricate complexities of lattice based structures pose challenges. Full verification of the lattice may create challenges related to how raw data is processed, the amount of data to be processed, and the type and scale of verifications (size, form, orientation, position, etc.) to be conducted. When selecting a measurement technique, it is important to understand the context of the measurements and the limitations of the measurement equipment.

Once data points are obtained, how these points are processed will greatly influence how the results are interpreted. A point cloud is representative of a measured lattice surface, where the shape of the cloud may vary depending on the type of unit lattice. This shape variance creates challenges in the selection of fitting techniques, and requires alternatives to be considered before deciding on an optimal. As an example of algorithms affecting outcomes of verification, flatness is discussed here.

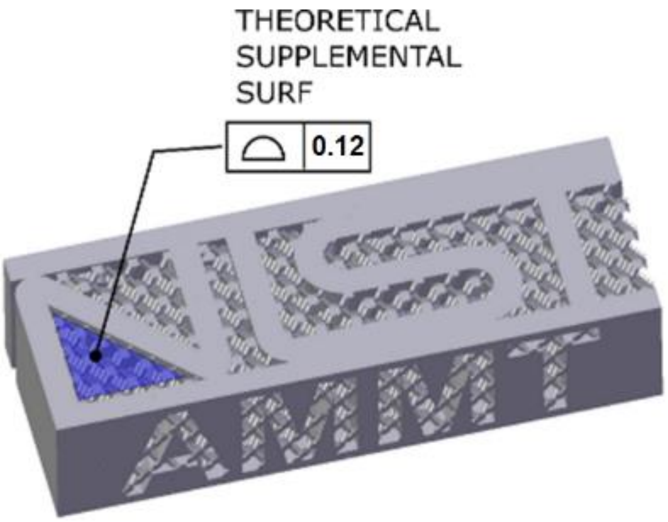
Two common techniques used in obtaining flatness are Chebyshev's fitting algorithm and the least squares algorithm. In this example, after filtering and trimming a point cloud, the point cloud is run through least square's and Chebyshev's fitting algorithm for flatness. Least squares flatness is computed using standard error minimization for fitting a plane on the point cloud, while Chebyshev's flatness is computed using min-max algorithm. The min-max algorithm computes the minimum of the maximum distances between the convex hull points and convex hull planes of the given point cloud. The least square's plane orientation and evaluated flatness zone is weighs the distribution of points based on the points' positions. The Chebyshev's plane orientation and evaluated flatness zone is based on global minimum for flatness zone value, thus attaining a different fit.

To showcase the use of TSS and DSS, and investigate the implications of different fitting algorithms, the next section presents a case study of specifying tolerances on a TSS from a lattice, followed by manufacturing the lattice and then inspecting the lattice to evaluate a DSS.

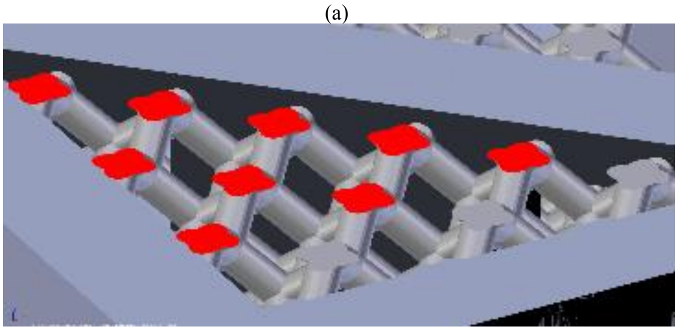
4. Case Study

In this case study, a logo part with diamond lattice (as shown in Figure 5(a)) is utilized. The thickness of each lattice strut is 0.42 mm and the dimensions of each unit cell are 2 mm X 2 mm X 2 mm. The dimensions of the entire part are 3.5 cm X 1.2 cm X 1.2 cm. A planar TSS lying on 9 flat lattice areas (colored red in Figure 5 (b)) is toleranced with a profile tolerance (without datum) by value 0.12 mm as per [23]. The part was built on an EOS M270* laser powder bed fusion

* Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.



(a)



(b)

Figure 5: (a) Part for the case study with TSS highlighted and toleranced. (b) The planar areas of 9 lattice regions within the TSS plane toleranced in (a).

machine using default settings, as defined by the manufacturer. The finished part is shown in Figure 6.

To simplify the TSS verification procedure in Section 5 we apply a profile tolerance without datum. Such a profile tolerance only requires form of the feature (in this case flatness) to be verified. The simplification advantage of using form (flatness) is that form (flatness) is independent of the orientation and the location of the TSS. Alternatively, if desired, a profile tolerance with datum may be used in conjunction with basic dimensions. Profile tolerance with datum would require the TSS form, orientation, and location all to be verified.

To take measurements in this case study, we use a laser confocal microscope to measure the part. This system was chosen for the initial study because of the high spatial resolution when compared to available XCT methods. Although, laser confocal microscope data may have noise, the data obtained is denser and is devoid of any mechanical filtering that may be imposed by stylus geometry in contact based inspection methods. Measurements were performed using a 10x objective and 0.5x tube lens, which resulted in a

Figure 6: Final produced part with lattice on EOS M270.

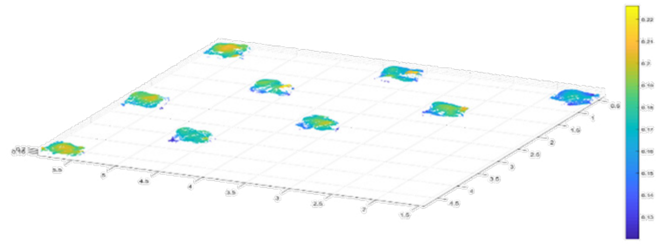
Table 1: Flatness values computed using various techniques on the point cloud of the 9 lattice regions from Figure 5(b).

Flatness (mm)	Chebyshev fit	Least Squares fit
Laser Confocal	0.1160	0.1215
Top 60% each	0.0507	0.0521
Top 30% each	0.0489	0.0504

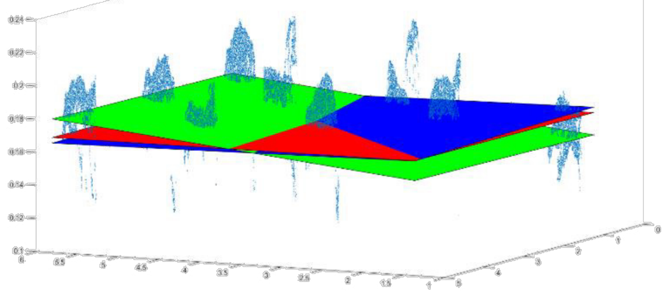
point spacing of 1.25 μm per pixel. The measured data was then filtered using the commercially available ConfoMap software to remove outliers. Before applying a flatness algorithm, the filtered dataset was again trimmed based on surface derivation needs. This trimming included removing some points that were measured outside of the zones of interest. The height map of the point cloud obtained after further height clipping is depicted in Figure 7(a). The DSS was fit to this data set.

The fitted DSS planes using Chebyshev's (blue) and Least squares (green) are displayed against the model TSS (red) in Figure 7(b). With only form (flatness) currently being considered, for demonstration the TSS is shown here as a horizontal plane passing through the mean of the point cloud. It does not indicate the location or orientation with respect to any Datum. It can be observed that the Chebyshev DSS is closer to the TSS than the Least Square's DSS.

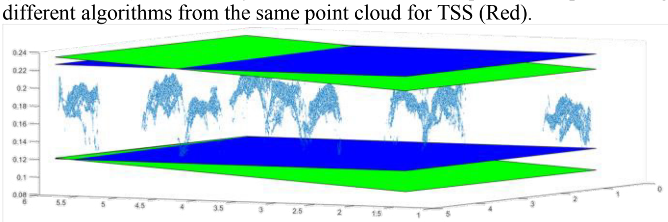
The fitted tolerance zones for the plane (flatness) using Chebyshev's and Least Square's fittings are shown in Figure 7 (c) in blue and green, respectively. The values of flatness using the two algorithms are 0.1160 mm and 0.1215 mm as shown in Table 1. Therefore, the flatness of the manufactured lattice is



(a) Height map of the point cloud of the 9 flat regions depicted in Figure 5(b).



(b) Two DSS (Blue – Chebyshev's; Green – Lease Squares) computed using different algorithms from the same point cloud for TSS (Red).



(c) Chebyshev and least squares flatness zones of the point cloud.. The z-axis is exaggerated.

Figure 7: Point cloud and fitting based on different algorithms.

in conformance to the specification if the Chebyshev's fitting algorithm is used. The flatness will be non- conforming to the specification if Least Square's fitting is used.

The results show that only the Chebyshev's fitting of point cloud from laser confocal falls within the specified tolerance of 0.12, while the least squares algorithms result in DSS calculations that do not meet the specification.

The case study results raise interesting questions about the "best" way to verify a TSS using a DSS. The methods used each returned different results, one in conformance and other not. It is clear that both the points used and the method selected impact the final outcome. Of course, the best algorithm choice depends on the design intent of the lattice to be toleranced, and the implications of falling outside a tolerance zone. Through this case study, it is evident that tools to specify and verify variations of TSS and DSS are incomplete and that further research is required.

5. Conclusion and Discussion

This paper introduced the concept of Derived Supplemental Surfaces and presented a case study for verification of tolerances specified on "Theoretical Supplemental Surface" (TSS) as proposed in ASME Y14.46 standard. Generalizations of TSS as geometry (Theoretical Supplemental Geometry – TSG) and specializations into curves (Theoretical Supplemental Curves – TSC) and (Theoretical Supplemental Volumes – TSV) are proposed. A plane was chosen as a TSS for a diamond lattice with a flatness tolerance (profile without datum on a plane) specification. The lattice is produced on an EOS M270 machine and a point cloud is obtained using measurements from a laser-confocal microscope. The point cloud is then used to infer a "Derived Supplemental Surface", the physical counterpart of a TSS. It was demonstrated that the choice of algorithms and related filtering of point cloud affects the resultant conformance to specification.

With the latest ISO 1101-2017 standard [25], the choice of filtering and algorithm for fitting can be specified with the tolerance specifications. Filtering choices include Gaussian, Spline, Complex, Opening Ball, Disc, Fourier, Hull, etc. Algorithm choices include Chebyshev (and its variants), Least Squares (and its variants), tangent feature, derived feature, etc. In the case study, two algorithm choices from ISO 1101 were compared – Chebyshev's and Least Squares. The Least Squares utilized parameter "T" for reporting peak to valley distance for flatness. Based on the discontinuous nature of point cloud from lattices, these two choices did not meet the requirements of verifying TSS by identifying appropriate DSS. In studying form (flatness), the case study results indicate that the "best" algorithm for obtaining flatness of a lattice may be one that does not yet exist. For instance, if not all points of each flat region are required to be within the tolerance zone for TSS, then the Chebyshev's and Least Square's algorithms need to be modified based on the requirement of how many or what points are to be within the tolerance zone.

The case study uses either top 60% or top 30% of measured points in calculating each DSS. Table 1 shows that the points selected influence the outcome of the fit. In this particular scenario, the top 30% point cloud and Chebyshev's algorithm have the best flatness. The correct selection of points is left undetermined, and is in need of further investigation based on relevant design intent.

A visual inspection of the individual point clouds of the 9 flat regions (Figure 7(a)) reveals that (i) some regions have most of the points with high z values, (ii) some regions have most of the points with low z values and (iii) some regions have z values distributed all over the z range. It is not evident from the specifications suggested for TSS in [23], whether all (some fraction) of the lattice points in the model used to define DSS should lie within the evaluated tolerance zone of the point cloud or not. This is specifically highlighted here because the lateral dimensions of the planes (in each flat region of lattice) is less than 10 times the z height difference among the points in the point cloud of individual "flat" regions. This situation is further exacerbated by the fact that the low z value filtering and boundary filtering begins to interfere in the accuracy of the fitting. Furthermore, the flat region shown in the lattice are dependent on the type of unit cell, position, orientation, size of lattice, and orientation of TSS. Moreover, in many conformal lattices, such flat regions may not exist at all.

Future work will introduce registration techniques [29–31] into the DSS placement. Bringing datum into consideration, which will introduce new verification constraints, perhaps influencing the measurement technique and algorithm selected. Such a verification would require first, to verify all datum from the specifications and then, to register the part's point cloud location and orientation relative to the datum. This registration would be followed by point cloud processing for verification of form, orientation, and location, in the specific order, using predefined algorithms. These new requirements will only add to current issues with tolerancing and verification of lattices as a whole, including a general lack of (a) tools to accurately specify designer's intent on a TSS and (b) research in the subsequent verification of a TSS.

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