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REVIEW ARTICLE

A review of geometric dimensioning and tolerancing (GD&T) of additive manufacturing and powder bed fusion lattices

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Abstract
To increase industrial adoption, part qualification and certification of the additive manufacturing (AM) process are crucial through geometric benchmarking as well as optimising the properties and process parameters. However, an extensive research gap remains concerning the geometric dimensioning and tolerancing (GD&T) of AM parts. This paper presents a review on the state-of-art GD&T benchmarking of powder bed fusion techniques enabling complex geometrical features like lattices. The study found a lack of design guidelines and standardised measurement techniques for lattice features and profiles.

Keywords Geometric dimensioning and tolerancing · Additive manufacturing · Powder bed fusion · Benchmarking test artefacts · Lattice structure

1 Introduction

In manufacturing and product design, geometric dimensioning and tolerancing (GD&T) plays an important role to describe the product and to facilitate communication between stakeholders involved in the process from conceptual development to manufacture. GD&T is a set of standardized symbols and rules used to communicate the design process and product description [1]. GD&T describes the nominal geometry of the product and the allowable variation of the geometric features. Realizing the functional nature of the geometrical measurements, Stanley Parker was credited being one of the first to develop the foundations of GD&T in 1938, at the beginning of World War II by developing the concept of "True Position" while working in a munition facility referring to the tolerances for the first time [2]. The first standard document related to GD&T was published by the British Standards Institution (BSI) as BS 308:1943, Engineering drawing office practice [3], followed by the US Army 30-1-7:1946, Mil-Std-8:1949 and American Society of Mechanical Engineers (ASME) Y14.5-1957. The latest version of ASME standards for general GD&T is Y14.5-2018 which includes stakeholder groups such as the American Standards Association (ASA), United States of America Standards Institute (USASI) and American National Standards Institute (ANSI) [2]. The International Organization for Standardization (ISO) also developed a set of standards including ISO 1101:2017, ISO 14405-1:2016, ISO/TS 17863:2013, and ISO 16792:2021 for GD&T and design specifications, covering conventional product design to Computer-Aided-Design (CAD) systems for additive manufacturing (AM) [4]. ISO 17296:2014 and ISO 52902:2019 refer to the test methods of geometrical characteristics and test artifacts of the parts made by AM. ASME published and updated Y14.41-2019 and Y14.46-2017 standards for digital product description data sets and drawing requirement in digital format for AM [5]. A list of existing standard documents for GD&T is presented in Table 1.

The ability to achieve predictable and repeatable shapes via AM is critical. To optimize the design of an additive manufactured product, tolerancing is a key issue [8] for defining, communicating, and assessing the dimensional and geometric accuracy of parts [9]. Although GD&T is a mature field in conventional manufacturing industries, digital and smart manufacturing processes have created a profound need for standardisation [10]. For this study, the underlined issues in GD&T benchmarking for PBF

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Table 1 Standards documents for GD&T [4–7]

Standardisation document	General GD&T process or guidelines	GD&T for AM processes	GD&T for artifacts
ASME Y14.5-2018-dimensioning and tolerancing	X	X	
ISO 7083:1983—technical drawings—symbols for geometrical tolerancing—proportions and dimensions	X		
ISO TC 1101:2017—geometrical product specifications (GPS)—geometrical tolerancing—tolerances of form, orientation, location and run-out	X		
ISO 5459:2011—geometrical tolerancing—datums and datum systems	X		
ISO 14405-3:2016—geometrical product specifications—dimensional tolerancing—Part 3: angular sizes	X		
ISO 2692:2014—geometrical product specifications (GPS)—geometrical tolerancing—maximum material requirement (MMR), least material requirement (LMR) and reciprocity requirement (RPR)	X		
ISO 5458:2018—geometrical product specifications (GPS)—geometrical tolerancing—pattern and combined geometrical specification	X		
ISO 8062:2007—geometrical product specifications (GPS)—dimensional and geometrical tolerances for moulded parts—Part 1: vocabulary	X		
ISO/TS 17863:2013—geometrical product specifications (GPS)—tolerancing of moveable assemblies	X		
ASME Y14.41-2019—digital product definition data practices		X	
ASME Y14.46-2017—product definition for additive manufacturing		X	
ISO 16792:2015—technical product documentation—digital product definition data practices		X	
ISO 17296-3:2014—additive manufacturing—general principles—Part 3: main characteristics and corresponding test methods		X	
ISO 52902—additive manufacturing—test artifacts—geometric capability assessment of additive manufacturing systems		X	X

techniques have been presented from a critical review of current literature of general GD&T for AM, and the GD&T benchmarking approach of using artifacts.

2 GD&T for additive manufacturing

The layer-by-layer bottom-up approach of AM causes rough surfaces known as stair-stepping that may potentially lead to geometrical inaccuracy. These geometrical errors also depend on factors such as part shrinkage, material properties, process parameters, support structures and surface approximation errors due to slicing techniques. Another important factor is the difference between the CAD and the toolpath model that creates a geometrical mismatch of the printed parts. The reason is that the printed part is not solely replicated from the original CAD model due to data adjustments made during the slicing stage to create a toolpath model that is dependent on various slicing parameters. Rupal et al. [11] addressed this issue and proposed a novel reverse CAD model algorithm that can convert the sliced file back to a CAD model. The reverse CAD model approach was able to assess the geometric and mechanical behaviours of the printed part while incorporating the effect of the slicing parameters. Some research works [12, 13] addressed the variation in printed part, especially for metal AM, that influences the part quality. Moges et al. [14] identified the sources of uncertainties of laser powder bed fusion (L-PBF) process chain that includes modelling uncertainty, parameter uncertainty, numerical uncertainty, and measurement uncertainty. They developed a methodology of quantifying uncertainties by case studies of semi-analytical and FEM-based L-PBF melt pool models. Another quantification approach using Isotherm Migration Method (IMM) model [15] by choosing melt pool width as the output quantity of interest was proposed by Lopez et al. [16], considering four sources of uncertainties corresponding to modelling, simulation, and measurement processes of L-PBF.

The isotropic layered structures, differential shrinkage of the parts, stair-stepping, and effect of support structure result into poor surface finish that cause non-conformance of the geometry. Many researchers and users of AM technologies realised that the GD&T of AM finished part does not fully comply with the existing ISO standardised GD&T process flow. AM yet not a standalone manufacturing option to produce higher precision surface finish of the printed part which still depends on the post-processing subtractive manufacturing technology such as CNC machining [17]. Rupal [18] mentioned that the two mostly adopted approaches for the geometric conformance or tolerance quantification for AM, (1) experimental methods based on geometric benchmark test artifacts (GBTA) and (2) predictive methods such as numerical analysis, are not in compliance with ISO 1101 standard. His work points that the limitations in GBTA design, guidelines in terms of geometric conformance, linkage of features to GD&T and their characterisation, parametric optimisation GD&T are yet to be addressed to fully realised the GD&T for AM assembled parts or moulds. Specifically in L-PBF, GD&T based datasets are crucial to consider the effect of removal of base plate. A Horizon 2020 project Computer Aided Technologies for Additive Manufacturing (2018) developed a metrology workflow including point cloud-based analysis that adds machining allowance to AM parts to achieve quality surface finish accomplished by post CNC machining [19].

In terms of GD&T for material extrusion (ME), Huang et al. [20] proposed a new method of identifying and predicting geometrical variation of ME parts using a “Skin Shape Model” to improve the geometrical quality of printed parts in the design phase, and validated by experiments with a Coordinate Measuring Machine (CMM) of a cylindrical test piece. Other researchers proposed steps to evaluate the geometrical accuracy based on conventional GD&T characteristics and test methods [21, 22], using Taguchi’s design of experiment (DOE) statistical approach to establish the relationship of the GD&T characteristics with 13 important process parameters of ME process which helped optimize the ideal parameters to improve the geometrical accuracy. The study extended a previous attempt [23] that proposing a design framework to build a test coupon with standard tolerance characteristics following ISO 1101:2005. They reported that four process parameters including component size, extruder temperature, print orientation and layer thickness are linked to the dimensional accuracy and geometrical tolerance. In terms of Vat Photopolymerisation (VP), a study was carried out to understand the effect of the slicing parameters on dimensional variation of a VP-printed part that could manipulate the horizontal dimensions of the unit printed-volume, known as a voxel [24]. The process resulted in printing with voxel dimensions below the size of the micromirrors in the VP process, thereby improving the GD&T of the printed parts. Powder bed fusion (PBF) has been widely used in tooling and biomedical sectors and the process uses a diverse range of materials especially metals, alloys, high strength polymers and ceramic. Based on the types of processing materials, fusion mechanism and heating source, PBF comprises a range of similar technologies including selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), and high speed sintering (HSS). However, one of the biggest constraints towards industrial adoption of the PBF family is limited knowledge of the GD&T processes, as well as the lack of understanding of the functional relationships between materials, process parameters, support structure, part size and geometry. In the GD&T research for metal AM, laser-based powder bed fusion (L-PBF) process, especially SLM, paid more attention possibly because, it is easy and comparatively affordable to improvise and well-adopted by the industries. Zongo et al. [25] conducted a comparative study of GD&T calculations carried out both experimentally by CMM and using micro-computed tomography (μ-CT) and theoretically using ANSYS Additive Print software for a L-PBF process. The geometrical distortion of a topologically optimized part printed with an EOSINT M280 printer and AlSi10Mg alloy powder was measured with different support structures. The results found that the AP software predicted similar trend of distortion gained experimentally and the CMM technique showed higher accuracy in data acquisition than CT scans. Importantly, higher density of support structures influenced global geometrical distortion but unaffected the local deviation of highly strained zones. Other studies of L-PBF focused on developing a design framework of suitable Geometric Benchmark Test Artifacts (GBTA) for evaluating the geometric behaviours and features. Rupal et al. proposed a methodology based on features, that is a classification system based on geometric reasoning for designing the printed part [26]. The study was further extended for complex metal parts including assemblies, known as an Assembly Benchmark Test Artefact (ABTA) that include mating features to identify the assembly capacity and dependencies of the geometric tolerancing quantifiers [27]. The framework was proposed to estimate geometric tolerances based on the Skin Shape Model considering material shrinkage and validated through a case study [28], shown in Fig. 1.

3 Geometric benchmark test artifacts

To measure AM capabilities and qualify machines for maintaining geometrical accuracy and tolerancing, a 3D CAD model comprising of different shapes and features, called a Geometric Benchmark Test Artifact (GBTA) is used. Several studies have focused on designing test artifacts for evaluating the geometrical performance of AM processes [21], proposing a framework, design criteria [29], manufacturing methodologies [30] and guidelines towards developing standardised test artifacts [31]. The first GBTA for evaluating accuracy of AM process performance was proposed by Kruth in 1991 [32]. Rebaioli et al. [21] reviewed almost 60 types of such artifacts utilised in geometric benchmarking process of AM techniques. The artifacts created mainly for PBF is listed in Table 2 with corresponding GD&T characteristics for specific processes and materials. Aspects of

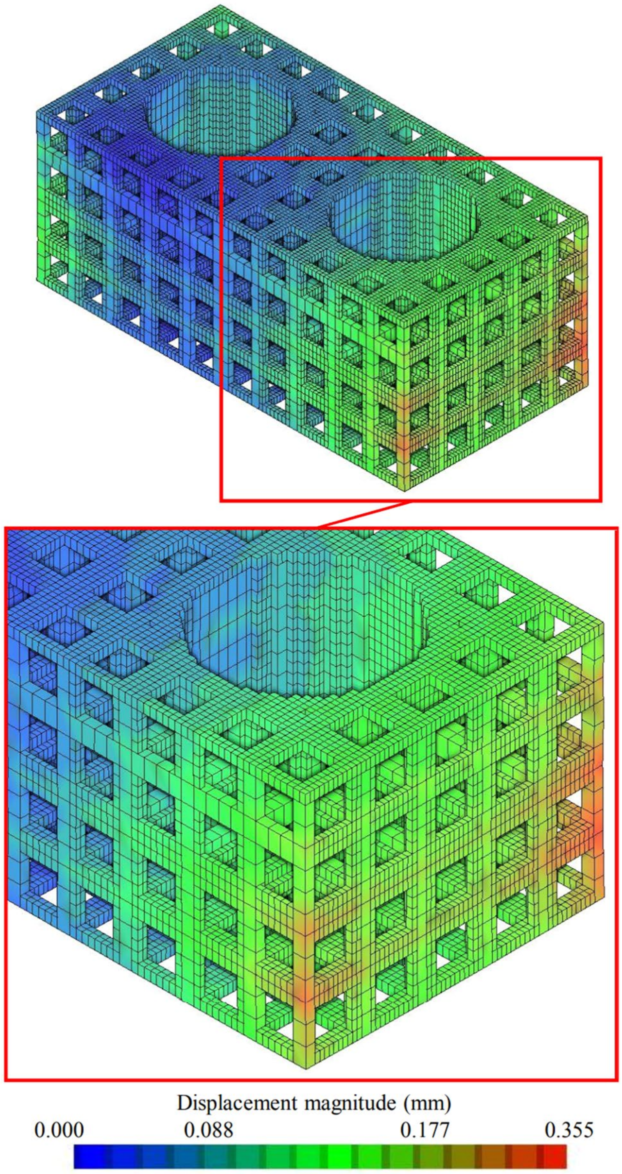

Fig. 1 The GBTA is simulated in Autodesk Netfabb Ultimate 2019 to observe the deviation caused by shrinkage to considered in the deviated point cloud of the skin shape model (repurposed from [28] with a copyright license no. 5247730280487)

linear accuracy, cylindricity and position were the most common features to be evaluated as compared to the level of assemblability and lattice structures that is not shown in a GBTA.

3.1 Lattice structures

The meaning of "Lattice" comes from a Germanic origin as a crossed-woven structure using metal or wooden strips with square or diamond-shape voids. Lattices can be found around us in nature, in various patterns with diverse shapes and sizes [33]. Lattice structures emerged in engineering applications from the late nineteenth century due to its extraordinary high strength-weight ratio. A remarkable example is the Bennerley Viaduct (see Fig. 2a) that is a railway bridge with a truss-like lattice structure in England used to carry trains between 1876–1877 [34]. In today's modern world, lattice structures, like shown in Fig. 2b, are used in biomedical, transportation, tooling and microelectronics due to the extreme lightweight nature with scalability and realised through use of AM [35, 36].

There are different taxonomies for lattice structures proposed in various studies. However, this paper will only focus on periodic lattices, rather than stochastic cellular structures such as foam or honeycomb cells, due to their comparatively superior structural integrity [37]. Following a review of current literature, we present a classification system of lattices, considering the periodicity, size, material, orientation, and geometric constituent of the unit cell that form the lattice. As shown in Fig. 3, the first class is based on the degree of order or periodicity, consisting of three variants including disordered/random lattices, periodic lattices and pseudoperiodic lattices. Both periodic and pseudoperiodic lattices can be further classified into homogeneous and heterogeneous lattices based on the strut thickness, cell density and material type in terms of functionality. The pseudoperiodic lattice is also known as a conformal lattice [37] in relation to the conformity of the lattice orientation and the surface normal of the boundary. For the same reason, periodic lattices are also known as non-conformal lattices as it is trimmed at the boundary edges. This classification is further elaborated for periodic, pseudoperiodic and random lattices in terms of topology or the geometric constituents of the unit cell including beam, shell-based elements, and Triply Periodic Minimal Surfaces (TPMS) cells that are created following 3D trigonometric functions. This classification will be used to help identify the fundamental design of lattices in terms of size, shapes, orientation, and geometric profiles and with a view of applying relevant GD&T approaches.

Nazir et al. [33] conducted an extensive review on the forms, designs and performance of lattice structures manufactured by AM, where the capabilities and issues of DfAM for lattices using existing CAD software was highlighted. They showed different approaches of designing and optimizing the cellular structure through analytical and digital modelling techniques. There are several CAD-FEM software packages commercially available for designing and optimizing beam or shell structures, such as Catia, Creo, Solidworks, Mimics, SpaceClaim and Netfabb listed in Table 3 and current capabilities of lattice design vary among commercially available software with some requiring different levels of programming and mathematical skills of users. For example, nTopology has a comprehensive library of various lattice design including volume, surface and conformal

Table 2 GD&T characteristics for different metallic materials using PBF [21]

Artifact	Processes	Materials	LA	C	Ps	P	SR	MS	R	A	LS
Kruth, 2005	SLS/SLM	Polymer coated SS (SLS), Tool steel, 316L SS, Bronze (SLM)	X	X	X			X			
Abdel Ghany and Moustafa, 2006	SLS/SLM	LaserForm A6 (Steel based), DuraForm (Glass-filled Polyamide), Direct steel DS20, Direct steel DSH20 (SLS), CL 20ES SS, CL 50 WS (Hot work steel), CL 40 Ti, Metals, Ceramic (SLM)	X	X	X			X			
Vandenbroucke and Kruth, 2007	SLM	Ti6Al4V, CoCrMo	X	X	X			X			
Pessard, 2008	SLS	DM20 (Cu-based powder), DS20 (Steel-based powder)					X				
Kotlinski, 2009	SLS	Nylon 12	X	X	X						
Cooke and Soons, 2010	EBM/SLM	Ti6Al4V (EBM), 17–4 SS, 15–5 SS (SLM)	X	X	X	X					
Campanelli, 2010	SLM	18 Ni Marage 300 steel	X	X	X			X			
Delgado, 2010	SLS	Direct Metal 20 (bronze-based powder with Ni)	X	X	X						
Fahad and Hopkinson, 2012	SLS	Nylon	X	X	X	X			X		
Moylan, 2014	SLS/SLM/EBM	Polymer, SS (SLS), SS (SLM), Ti (EBM)	X	X	X			X			
Yasa, 2014	SLM	Inconel 625									
Teeter, 2015	SLM	316L SS	X	X	X			X			X
Berger, 2016	SLM	AlSi10Mg	X	X	X	X		X			
Kniepkamp, 2016	SLM	316L SS		X				X			
Calignano, 2017	SLM	Al	X	X				X			
Toguem Tagne, 2019	SLM	Inconel 718	X	X	X	X	X	X	X		
Rupal, 2020	SLM	Inconel		X						X	X
Taylor, 2021	L-SLM	Ti6Al4V	X	X	X	X	X	X	X		X

SS stainless steel, *Al* aluminium, *Ti* titanium, *Ni* nickel, *Cu* copper, *LA* linear accuracy, *C* cylindricity, *Ps* position, *P* profile, *SR* surface roughness, *MS* minimum feasible size, *R* repeatability, *A* assemblability, *LS* lattice structure

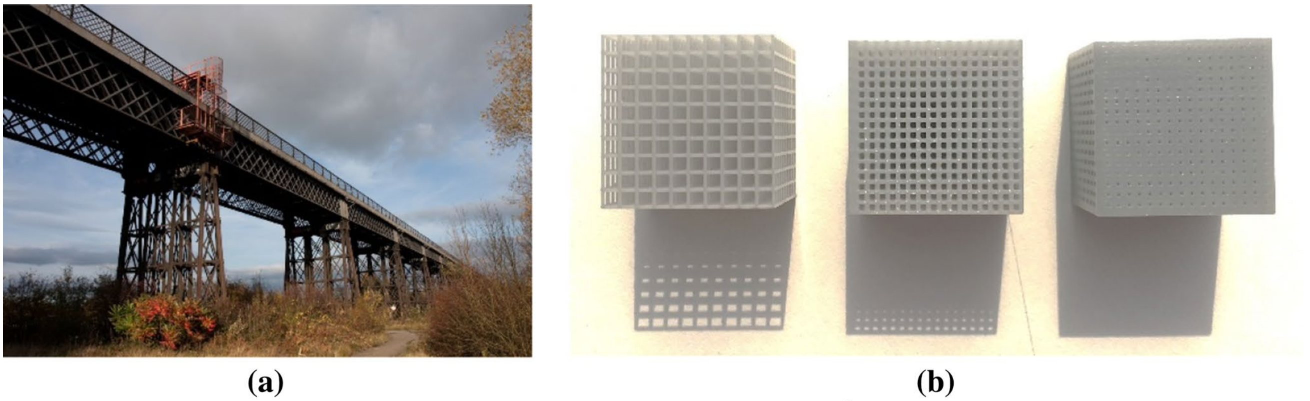

Fig. 2 **a** Large lattice structure used in transport engineering in late nineteenth century in the UK (repurposed from Adam Foster in Fickr.com with sharable licence [17]); **b** lattice cubes (2×2×2 cm^3) printed in Vat-photopolymerisation AM technique

lattices with beam, shell and TPMS unit cells. Autodesk Netfabb and Ansys SpaceClaim have limited options and mainly include common beam and shell elements. It was also found that the terms used to describe the lattices vary. For example, Netfabb describes the shell feature as a surface element. Moreover, almost all software do not have the capabilities of assessing the dimension and tolerance of the modelled part, especially for lattice structures. Creaform [39], GOM Inspect Suite [40], Hexagon PC-DMIS [41] are commonly used as quality inspection tools with GD&T capabilities.

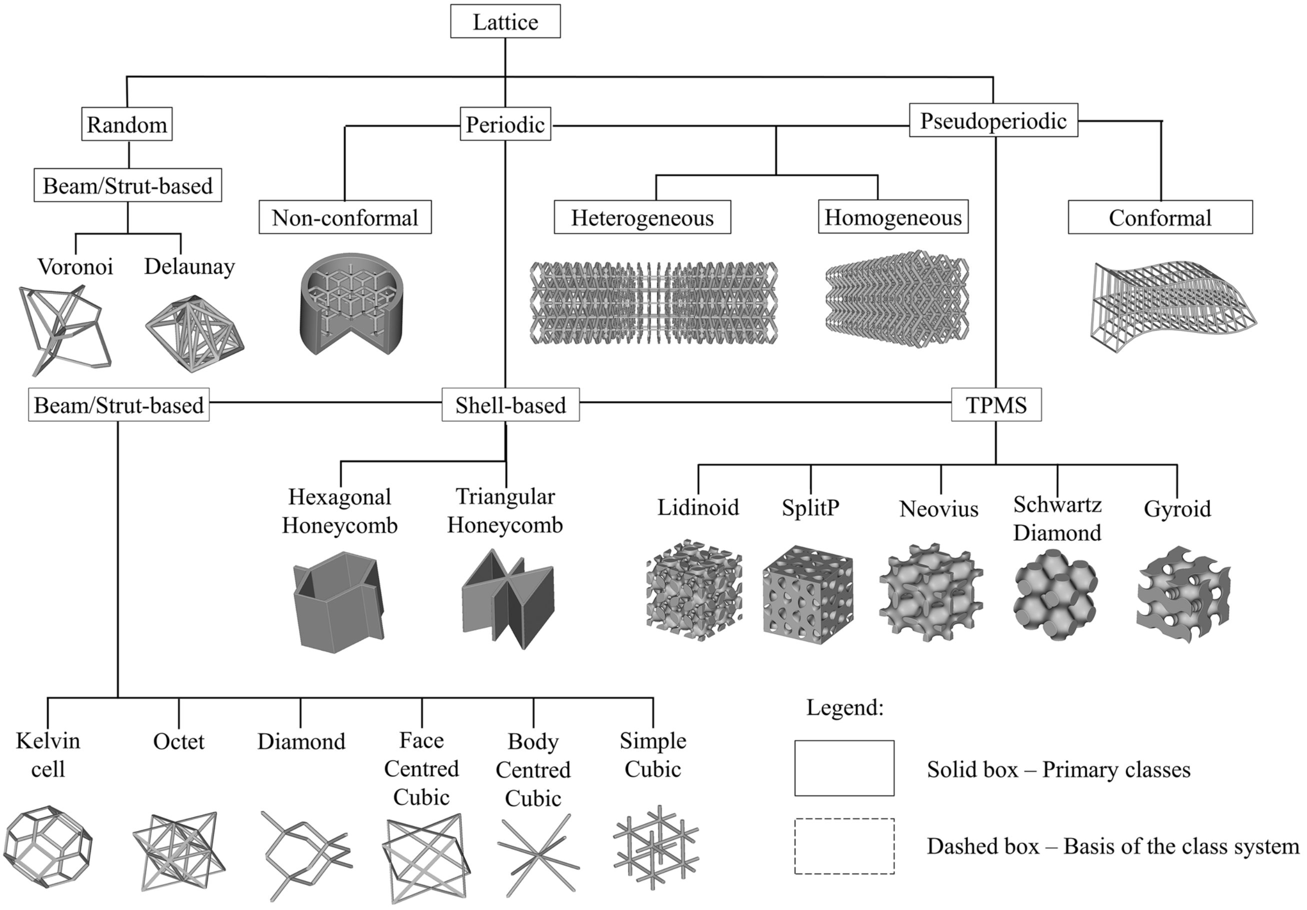

Fig. 3 Classification of lattice structure [33, 36–38] (images created using nTopology)

Table 3 CAD-FEM packages for designing cellular structures using AM [33, 42]

Company/software	Lattice structure modelling	FEM analysis	Topology optimisation
ANSYS SpaceClaim	X	X	X
Dassault Systems CATIA	X	X	X
PTC Creo	X	X	
Dassault Systems Solidworks	X	X	X
Materialise Mimics	X	X	
*MIT Abaqus	X	X	
nTopology	X	X	X
Autodesk Within	X		X
Altair Optistruct	X		X
Autodesk Netfabb	X	X	X
Materialise 3-matic STL	X		
Paramount Conformal lattice structure (CLS)	X		
ParaMatters CogniCAD	X		X

Massachusetts Institute of Technology (MIT)

3.2 GD&T methods for lattices

Ameta et al. [43, 44] claimed that conventional GD&T techniques are inadequate to tolerance lattice structures for AM including non-uniform thickness lattices, conformal lattices, and unstructured lattices and to verify the design against a functionality. The tolerancing of a lattice structure comprises of 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. To address this gap, they introduced a Total Supplemental Surface (TSS) concept for the ASME Y14.46 standard, mitigating the tolerancing challenges for lattice structures which is shown in Fig. 4. The successful outcome of the TSS process lies in the selection of the measurement techniques and control algorithms for the TSS profile. Rupal et al. [27] also utilised a similar TSS technique to tolerance their proposed artifact called an Assembly Benchmark Test Artifact (ABTA), including mating features and lattice structures to characterise fit to form of the features and geometric tolerance of the lattice feature. The deviation of the sample is predicted by a theoretical point cloud model called skin model shapes in MATLAB, verified using finite element analysis and experimental validation of the part.

4 Summary

GD&T is a mature field for the manufacturing sector. However, for companies utilising AM, the geometric quality and structural integrity of the built part not only depends on the machine set-up, process parameters, built environment, but also the quality of the CAD model and the slicing techniques to convert the digital model into a toolpath planning and printing. In addition, the built position, orientation, support structure and materials influence the geometric quality of the built part [25]. Previous studies focused on optimising the mechanical properties of the built part and corresponding process parameters [45–47]. Other studies [11, 21, 28, 48] only relate to geometric part qualification using common geometric features such as rectangles, squares, cylinders, holes, cubes, walls and slopes. They benchmarked GD&T characteristics of various artifacts produced from different AM technologies. The common GD&T characteristics such as flatness, cylindricity, parallelism, circularity were investigated, including the spatial repeatability of the features, surface finish and the minimum feature size [30]. Most GD&T work has focused on PBF techniques because of the excellent capability of the process to build various shapes, forms and complex features, including thin internal channels, infills, lattices and consolidated assembled parts [49]. However, there is a significant gap in the GD&T for complex features, especially for internal channels, lattice structures and consolidated parts. Handful studies developed tolerancing methods for lattice structures except for Ameta et al. [43, 44, 50], who proposed using a transition region known as TSS to represent the allowable variation in materials and geometry of a part with lattice structures and verifying the data using experimental metrology by CMM, XCT and FVM. However, their work is not fully applicable to different lattice structures shown in Fig. 3.

In summary, a literature review has been conducted on GD&T benchmarking for AM, and there is an extensive research gap requiring the need for GD&T benchmarking of PBF parts with complex features such as lattice structures. There is an urgent need for a standardised approach for

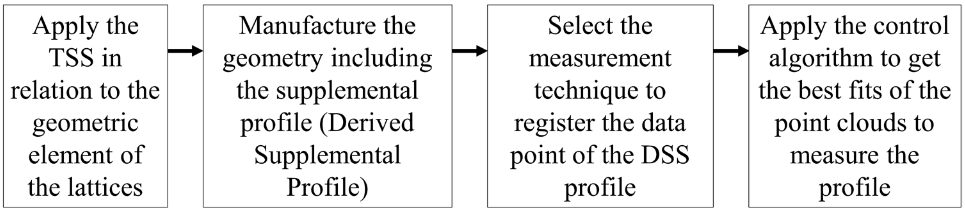

Fig. 4 The workflow of the TSS mechanism for tolerancing lattice structure [43, 44]

GD&T artifacts encompassing lattice features and other free-form structures. Future work should also propose a GD&T workflow for designing artifacts with lattices structures.

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References

1. GD&T 101: an introduction to geometric dimensioning and tolerancing. Available online: https://www.fictiv.com/articles/gdt-101-an-introduction-to-geometric-dimensioning-and-tolerancing
2. The Who and the history of geometric dimensioning and tolerancing. Available online: https://www.validate-3d.com/blog/the-who-and-the-history-of-geometric-dimensioning-tolerancing#:~:text=TheBeginning%3A. What we now, a torpedo factory in Scotland
3. MacMillan DM, Krandall R Bibliography for dimensioning and tolerancing. Available online: https://www.circuitousroot.com/artifice/drafting/drawing-studies/dt/bibliography-for-dt/index.html#parker-1956
4. Lu Y, Morris K, Frechette S (2016) Current standards landscape for smart manufacturing systems, vol 8107 (**ISBN 1069600690287**)
5. Digital Product Definition Data Practices-Y14.41:2019. Available online: https://www.asme.org/codes-standards/find-codes-standards/y14-41-digital-product-definition-data-practices. Accessed on 25 Mar 2021
6. ISO 17296-3:2014 Additive manufacturing—general principles—Part 3: main characteristics and corresponding test methods. Available online: https://www.iso.org/standard/61627.html. Accessed on 25 Mar 2021
7. ISO/ASTM 52902:2019 Additive manufacturing—test artifacts—geometric capability assessment of additive manufacturing systems. Available online: https://www.iso.org/standard/67287.html. Accessed on 25 Mar 2021
8. Dantan JY, Huang Z, Goka E, Homri L, Etienne A, Bonnet N, Rivette M (2017) Geometrical variations management for additive manufactured product. CIRP Ann Manuf Technol 66:161–164. https://doi.org/10.1016/j.cirp.2017.04.034
9. Moroni G, Petrò S, Polini W (2017) Geometrical product specification and verification in additive manufacturing. CIRP Ann Manuf Technol 66:157–160. https://doi.org/10.1016/j.cirp.2017.04.043
10. Morse E, Dantan JY, Anwer N, Söderberg R, Moroni G, Qureshi A, Jiang X, Mathieu L (2018) Tolerancing: managing uncertainty from conceptual design to final product. CIRP Ann 67:695–717. https://doi.org/10.1016/j.cirp.2018.05.009
11. Rupal BS, Mostafa KG, Wang Y, Qureshi AJ (2019) A reverse CAD approach for estimating geometric and mechanical behavior of FDM printed parts. Procedia Manuf 34:535–544. https://doi.org/10.1016/j.promfg.2019.06.217
12. Gradl PR, Tinker DC, Ivester J, Skinner SW, Teasley T, Bili JL (2021) Geometric feature reproducibility for laser powder bed fusion (L-PBF) additive manufacturing with Inconel 718. Addit Manuf 47:102305. https://doi.org/10.1016/j.addma.2021.102305
13. Santos VMR, Thompson A, Sims-Waterhouse D, Maskery I, Woolliams P, Leach R (2020) Design and characterisation of an additive manufacturing benchmarking artefact following a design-for-metrology approach. Addit Manuf 32:100964. https://doi.org/10.1016/j.addma.2019.100964
14. Moges T, Yan W, Lin S, Ameta G, Fox J, Witherell P (2020) Quantifying uncertainty in laser powder bed fusion additive manufacturing models and simulations. In: Solid free. fabr. 2018 proc. 29th annu. int. solid free. fabr. symp.—an addit. manuf. conf. SFF 2018, pp 1913–1928
15. Devesse W, De Baere D, Guillaume P (2014) The isotherm migration method in spherical coordinates with a moving heat source. Int J Heat Mass Transf 75:726–735. https://doi.org/10.1016/j.ijheatmasstransfer.2014.04.015
16. Lopez F, Witherell P, Lane B (2016) Identifying uncertainty in laser powder bed fusion additive manufacturing models. J Mech Des Trans ASME 138:1–4. https://doi.org/10.1115/1.4034103
17. Thompson A (2018) Surface texture measurement of metal additively manufactured parts by X-ray computed tomography. University of Nottingham, Nottingham
18. Rupal BS (2021) Geometric tolerance quantification and prediction framework for additive manufacturing processes. University of Alberta, Edmonton
19. de la Maza S, Ventura T (2018) Metrology workflow for AM workpieces, including WP6 task integrated into sub workflows targeting the different use cases, 2018
20. Huang Z, Dantan JY, Etienne A, Rivette M, Bonnet N (2018) Geometrical deviation identification and prediction method for additive manufacturing. Rapid Prototyp J 24:1524–1538. https://doi.org/10.1108/RPJ-07-2017-0137
21. Rebaioli L, Fassi I (2017) A review on benchmark artifacts for evaluating the geometrical performance of additive manufacturing processes. Int J Adv Manuf Technol 93:2571–2598. https://doi.org/10.1007/s00170-017-0570-0
22. Mahmood S, Qureshi AJ, Talamona D (2018) Taguchi based process optimization for dimension and tolerance control for fused deposition modelling. Addit Manuf 21:183–190. https://doi.org/10.1016/j.addma.2018.03.009
23. Mahmood S, Talamona D, Goh KL, Qureshi AJ (2016) Fast deviation simulation for "Fused Deposition Modeling" process. Procedia CIRP 43:327–332. https://doi.org/10.1016/j.procir.2016.02.004
24. Mostafa K, Qureshi AJ, Montemagno C (2017) Tolerance control using subvoxel gray-scale DLP 3D printing. In: ASME int. mech. eng. congr. expo. proc., vol 2, pp 1–7. https://doi.org/10.1115/IMECE2017-72232
25. Zongo F, Simoneau C, Timercan A, Tahan A, Brailovski V (2020) Geometric deviations of laser powder bed-fused AlSi10Mg components: numerical predictions versus experimental measurements. Int J Adv Manuf Technol 107:1411–1436. https://doi.org/10.1007/s00170-020-04987-7
26. Rupal BS, Ahmad R, Qureshi AJ (2018) Feature-based methodology for design of geometric benchmark test artifacts for additive manufacturing processes. Procedia CIRP 70:84–89. https://doi.org/10.1016/j.procir.2018.02.012

27. Rupal BS, Anwer N, Secanell M, Qureshi AJ (2020) Geometric tolerance and manufacturing assemblability estimation of metal additive manufacturing (AM) processes. Mater Des 194:108842. https://doi.org/10.1016/j.matdes.2020.108842
28. Rupal BS, Anwer N, Secanell M, Qureshi AJ (2020) Geometric tolerance characterization of laser powder bed fusion processes based on skin model shapes. Procedia CIRP 92:169–174. https://doi.org/10.1016/j.procir.2020.05.185
29. Toguem SCT, Rupal BS, Mehdi-Souzani C, Qureshi AJ, Anwer N (2018) A review of AM artifact design methods. In: Proc.—2018 ASPE euspen summer top. meet. adv. precis. addit. manuf., pp 132–137
30. de Pastre MA, Toguem Tagne SC, Anwer N (2020) Test artefacts for additive manufacturing: a design methodology review. CIRP J Manuf Sci Technol 31:14–24. https://doi.org/10.1016/j.cirpj.2020.09.008
31. Moylan S, Slotwinski J, Cooke A, Jurrens K, Donmez MA (2014) An additive manufacturing test artifact. J Res Natl Inst Stand Technol 119:429–459. https://doi.org/10.6028/jres.119.017
32. Kruth JP (1991) Material incress manufacturing by rapid prototyping techniques. CIRP Ann Manuf Technol 40:603–614. https://doi.org/10.1016/S0007-8506(07)61136-6
33. Nazir A, Abate KM, Kumar A, Jeng JY (2019) A state-of-the-art review on types, design, optimization, and additive manufacturing of cellular structures. Int J Adv Manuf Technol 104:3489–3510. https://doi.org/10.1007/s00170-019-04085-3
34. Martinez H Bennerley viaduct. Available online: https://www.erewashmuseum.co.uk/index.php/easyblog/entry/bennerley-viaduct.html. Accessed on 15 Mar 2021
35. Harris J 5 techniques for lightweighting: doing more with less. Available online: https://ntopology.com/blog/2019/10/18/5-techniques-for-lightweighting/. Accessed on 15 Mar 2021
36. Xiao Z, Yang Y, Xiao R, Bai Y, Song C, Wang D (2018) Evaluation of topology-optimized lattice structures manufactured via selective laser melting. Mater Des 143:27–37. https://doi.org/10.1016/j.matdes.2018.01.023
37. Dong G, Tang Y, Zhao YF (2017) A survey of modeling of lattice structures fabricated by additive manufacturing. J Mech Des Trans ASME 139:1–13. https://doi.org/10.1115/1.4037305
38. Maconachie T, Leary M, Lozanovski B, Zhang X, Qian M, Faruque O, Brandt M (2019) SLM lattice structures: properties, performance, applications and challenges. Mater Des 183:108137. https://doi.org/10.1016/j.matdes.2019.108137
39. Creaform mastering Gd&T and metrology helps you get the most out of your inspection software. Available online: https://www.creaform3d.com/blog/mastering-gdt-and-metrology-helps-you-get-the-most-out-of-your-inspection-software/. Accessed on 24 Mar 2021
40. Geometric dimensioning and tolerancing (GD&T) in GOM inspect suite. Available online: https://www.gom.com/en/products/gom-inspect-suite/gd-and-t. Accessed on 24 Mar 2021
41. Guenet A PMI for beginners: how to consume product manufacturing information in PC-DMIS. Available online: https://blog.hexagonmi.com/pmi-for-beginners-how-to-consume-product-manufacturing-information-in-pc-dmis/. Accessed on 24 Mar 2021
42. Taylor HC, Garibay EA, Wicker RB (2021) Toward a common laser powder bed fusion qualification test artifact. Addit Manuf 39:101803. https://doi.org/10.1016/j.addma.2020.101803
43. Ameta G, Fox J, Witherell P (2018) Tolerancing and verification of additive manufactured lattice with supplemental surfaces. Procedia CIRP 75:69–74. https://doi.org/10.1016/j.procir.2018.02.023
44. Praniewicz M, Fox J, Ameta G, Kim F, Witherell P, Saldana C (2020) Exploring registration of optical, CMM and XCT for verification of supplemental surfaces to define AM lattices: application to cylindrical and spherical surfaces. Procedia CIRP 92:181–186. https://doi.org/10.1016/j.procir.2020.05.182
45. Gurrala PK, Regalla SP (2014) Multi-objective optimisation of strength and volumetric shrinkage of FDM parts: a multi-objective optimization scheme is used to optimize the strength and volumetric shrinkage of FDM parts considering different process parameters. Virtual Phys Prototyp 9:127–138. https://doi.org/10.1080/17452759.2014.898851
46. Phan TQ, Strantza M, Hill MR, Gnaupel-Herold TH, Heigel J, D'Elia CR, DeWald AT, Clausen B, Pagan DC, Peter Ko JY, Brown DW, Levine LE (2019) Elastic residual strain and stress measurements and corresponding part deflections of 3D additive manufacturing builds of IN625 AM-Bench artifacts using neutron diffraction, synchrotron X-ray diffraction, and contour method. Integr Mater Manuf Innov 8:318–334. https://doi.org/10.1007/s40192-019-00149-0
47. Zhang F, Levine LE, Allen AJ, Young SW, Williams ME, Stoudt MR, Moon KW, Heigel JC, Ilavsky J (2019) Phase fraction and evolution of additively manufactured (AM) 15–5 stainless steel and Inconel 625 AM-Bench artifacts. Integr Mater Manuf Innov 8:362–377. https://doi.org/10.1007/s40192-019-00148-1
48. Zhu Z, Anwer N, Huang Q, Mathieu L (2018) Machine learning in tolerancing for additive manufacturing. CIRP Ann 67:157–160. https://doi.org/10.1016/j.cirp.2018.04.119
49. Ameta G, Lipman R, Moylan S, Witherell P (2015) Investigating the role of geometric dimensioning and tolerancing in additive manufacturing. J Mech Des Trans ASME. https://doi.org/10.1115/1.4031296
50. Ameta G, Witherell P (2019) Representation of graded materials and structures to support tolerance specification for additive manufacturing application. J Comput Inf Sci Eng 19:1–9. https://doi.org/10.1115/1.4042327