World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Review Article)

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Additive manufacturing of lightweight structures: Design and mechanical characterization

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World Journal of Advanced Engineering Technology and Sciences, 2025, 14(02), 317-323

Publication history: Received on 12 January 2025; revised on 22 February 2025; accepted on 25 February 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.14.2.0088

Abstract

Additive manufacturing has completely transformed the production of lattice structures, permitting geometries that vary widely to optimize manufacturer conditions with respect to strength-to-weight ratios in future aerospace, automotive, and biomedical industries. The present review describes developments in design, mechanical characterization, and the challenges related to lattice structures produced by AM. Major design here involves topology optimization, unit cell classification based on strut, surface, and shell designs, and bio-inspired multi-scale architectures. Mechanical performance is affected by relative density, material systems, and AM methods (as in laser powder bed fusion), with auxetic lattices demonstrating unique properties like negative Poisson's ratios. While experimental analyses as well as computational ones have revealed that bending dominated deformation occurs in the case of sinusoidal structures and energy absorption efficiency occurs in octet-truss designs. Problems pertaining to residual stress, unmelted powder, and dimensional inaccuracies were addressed through hybrid manufacturing (like investment casting) and process optimization driven by machine learning. Future work is expected to achieve lightweight, large-scale components and perhaps functionally graded materials with defect monitoring systems. This synthesis provides a template for advancing AM lattice structures towards high-performance, application-specific solutions.

Keywords: Additive Manufacturing; Lattice Structures; Mechanical Properties; Topological Optimization; Energy Absorption

1. Introduction

For decades, the search for lightweight, high-performance materials has driven engineering innovation in the aerospace, automotive, and biomedical engineering industries where reduction in weight equals energy efficiency, payload capacity, or patient outcomes. Lightweighting generally refers to classic approaches, including honeycomb structures and foam-based materials, whose degree of abandoning mechanical performance is related to the mass reduction. (7) However, additive manufacturing (AM) advancements opened up previously impossible manufacturing opportunities for complex designs, allowing lattice structures that combine low density superimposed with extraordinary strength, energy absorption, and multifunctionality. These structures, inspired by natural cellular architectures such as bone trabeculae and plant parenchyma, are now redefining the boundaries of material science and mechanical design.

1.1. Background and Significance

Lattice structures can be defined as periodic or stochastic arrangements of struts, plates, or surfaces interconnected to form open-cell or closed-cell networks. Their mechanical behavior is dictated by unit cell topology, relative density (the ratio between the lattice density and the bulk material density), and material properties. Lattices, unlike conventional solids, decouple geometric design from bulk material constraints, granting tunable stiffness, energy absorption, and

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thermal/electrical conductivity. (2) These characteristics lend themselves to applications as diverse as vibration damping and heat dissipation for aerospace components such as turbine blades and satellite brackets, or bone-like porosity within biomedical implants that facilitates osseointegration.

Interestingly, in the past, there were very few such structures around because their use was limited by the manufacturing methods employed. Conventional methods, such as investment casting or CNC machining, are vastly inadequate for microscale features and internal channels. AM, alternatively called 3D printing, can avoid this limitation by building the structures in layers, directly from digital models. Techniques like selective laser melting (SLM) and electron beam melting (EBM) allow for precise control of strut diameters as small as 100 μm and complex geometries, such as triply periodic minimal surfaces (TPMS) like the gyroid and Schwarz-D surfaces. (4) Such geometries, which are mathematically defined and self-supporting, have near isotropic properties and superior stress distribution compared to strut-based designs.

1.2. Evolution of Additive Manufacturing in Lattice Fabrication

AM engineering for lattice structures, so far, has developed in three key directions:

- **Prototyping (2000-2010)**: The work built around polymer lattice structures using AM systems-based stereolithography, fused deposition modeling, etc., which at this juncture could still not boast mechanical support due to bad coating adhesion and a high suspicion of anisotropic properties.
- **Metal AM Emergence (2010-2020)**: The advent of powder bed fusion, including selective laser melting and electron beam melting, enabled high-resolution metals lattices, with the study of Ashby et al. establishing design rules for stretching/(e.g., octet-truss) and bending-dominated (e;g., Kelvin foam) topologies, developed that linked relative density to elastic modulus and yield strength. Notwithstanding, limits to scale were imposed by such defects like unmelted powder and residual stress.
- **Industrial Maturation (2020-Present)**: Latest innovations in multi-material AM, hybrid manufacturing (such as combining WAAM with machining), and topology optimization through ML have made it sort of a cattle system of application. Airbus, for instance, by bringing forth the "Bionic Partition" for the A320 aircraft, has reduced weight by 45 percent through SLM-fabricated titanium lattices, while further car manufacturers like BMW keep integrated polymers lattices into seat cushions for improved crashworthiness.

Despite the advances, critical challenges still remain-process-induced defects, including porosity, surface roughness, and dimensional inaccuracies which inhibit mechanical reliability-even more so when cyclically loaded; also, the lack of standardized testing protocols for AM lattices could impede certification in the regulation of industries such as aerospace.

1.3. Research Gaps and Objectives

While past research has studied separate facets of lattice design and AM, the complete spectrum of how material, structure, process, and performances interacts is yet to be precisely identified. Some of the unknowns that need investigation are

- The AM process parameters (e.g., laser power, scan strategy) that influence defect formation at the lattice nodes and struts.
- Direct predictive models of fatigue life and fracture toughness under multi-axial loading.
- Scalability of bioinspired designs (e.g., graded lattices modeled on bamboo) to industrial applications.

This paper fills in these missing pieces through the following aims

- **Design Synthesis:** Systematic categorization of lattice topologies (strut-based, surface-based, hybrid), with subsequent evaluation of their performances mechanically by experimental and computational measures.
- **Process-Structure Linkage:** The study of how AM processes (PBF, DED, binder jetting) govern the generation of defects and structural integrity.
- **Performance Optimizations:** Suggesting strategies to improve energy absorption and fatigue resistance through gradient designs and post-processing.
- **Industrial Cases:** Validating the feasibility of implementing AM lattices in an actual lightweight connecting rod application through finite element analysis (FEA) and experimental testing.

This work attempts to combine all of these aspects together, which could help enhance the practicality of AM lattices for safety-critical applications. It also suggests directions for future research in multi-scale modeling and certification standards.

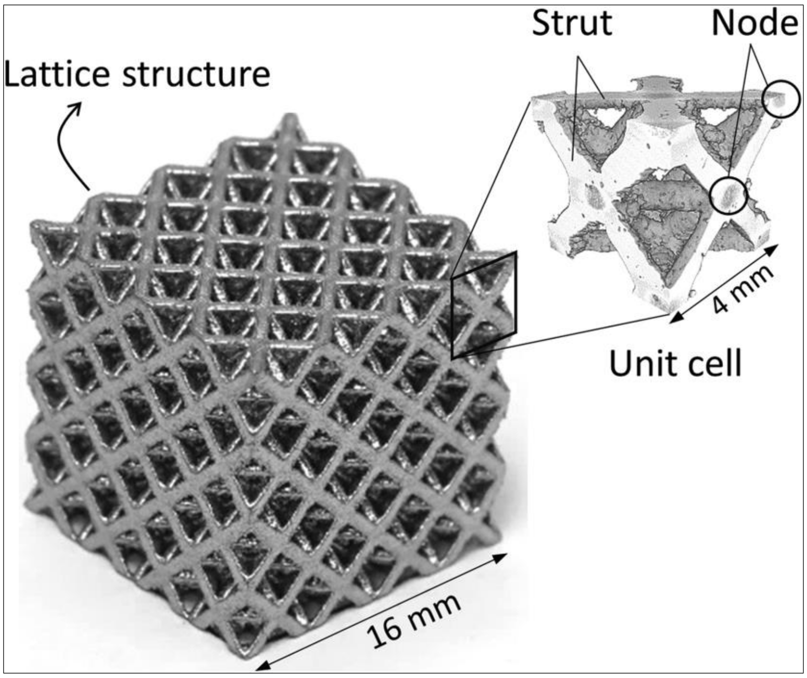


Figure 1 Shows AM Lattice Structure

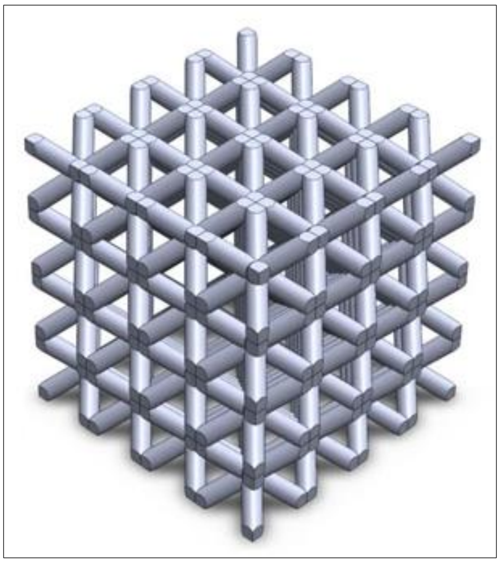
2. Design Methodologies for Lattice Structures

2.1. Topology Optimization and CAD-Driven Design

Topology optimization algorithms (density-based and level-set methods, for example) are essential for the generation of lattice geometries in which minimum weight and maximum mechanical performance is achieved. Recent advances integrate mechanical computer-aided design tools such as the SolidWorks API into lattice generation, which parameterized unit cell dimensions (e.g., strut thickness, node spacing) while keeping volume constant. (5) As an example, parametric equations can produce a set of 240-unit cell models by dimension control (for example, z is in-between 6 and 8.8 mm, with x derived from volume constraints), allowing the design to be reproduced. The CAD modules further allow hetero-lattice designs that essentially mix strut-based (like octet-truss) and surface-based (for instance, gyroid) topologies to relieve stress concentrations.

2.2. Unit Cell Classifications and Performance

- **Strut-based lattices** such as octet-truss: Excellent compressive strength but show shear brittleness because of the localization of stress about the nodes.
- **Surface-based lattices** such as TPMS gyroid: Provide isotropic properties with better energy absorption by spreading stress over curved surfaces.
- **Hybrid designs**: Combine BCC and hexagonal unit cells that increase fatigue resistance by 20-30% compared to uniform lattices.



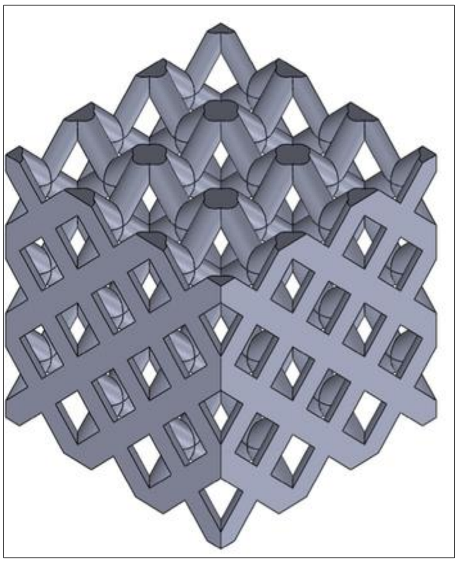


Figure 2 Shows Strut-Based lattice **Figure 3** Shows Surface-Based Lattice

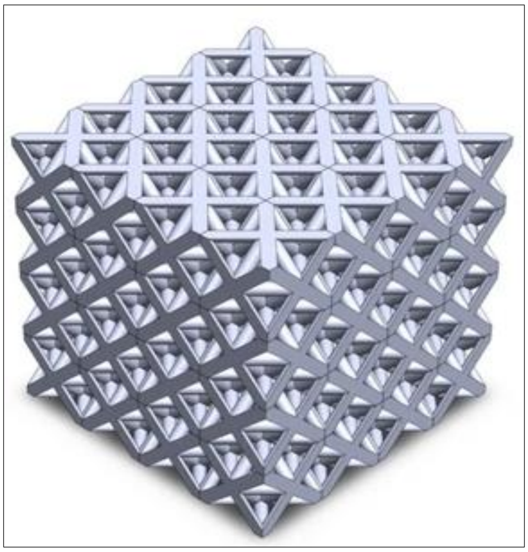


Figure 4 Shows Hybrid Design

2.3. Material Selection and Process Constraints

The choice of material such as Inconel 625 for high-temperature uses or PA12 for cost-efficient polymers presents a direct influence on manufacturability. (1) For instance, PLA lattices fused material extrusion AM exhibit poor surface quality on overhangs and necessitate support structures and post-processing work. The high-entropy alloys are now gaining ground for extreme treatments, but residual stresses in WAAM-processed Al latticing require post-damage heat treatment to restore ductility.

3. Additive Manufacturing Techniques

3.1. Powder Bed Fusion (PBF)

- Selective Laser Melting (SLM): This method generates high-resolution Ti-6Al-4V lattices but has issues with powder removal in small pores (<500 µm).
- Multi Jet Fusion (MJF): The PA12 lattices exhibited less than 8% simulation error in compression tests, while anisotropic material models were required to achieve a good match.

3.2. Directed Energy Deposition

- **The Wire Arc AM** is good for very big aluminium lattices but interlayer porosity occurs at junctions (e.g., "X lattice unit"), reducing compressive strength by 15-20%.
- **The Cold Metal Transfer** reduces distortion due to WAAM, but has to include post-processing to fix it.

3.3. Process-Driven Defects

3.3.1. The key challenges include

- **Residual Stress:** Inconel lattices manufactured using SLM process show warping due to abrupt cooling.
- **Support Structures**: FMEAM-printed PLA lattices require manual removal of supports, which translates to an increase of 30% in costs.

4. Mechanical Characterization and FEA Integration

4.1. Static and Dynamic Testing

- **Compressive Strength:** The relative density of lattice designs is certainly one of the major parameters that dictate failure modes (from 10% to 30%). (3) Stretching-dominated lattices, for instance, the octet-truss ones, exhibit a strength 40% greater than bending-dominated designs, for example, the BCC.
- **Energy Absorption:** Gradient lattices perform like the bone trabeculae, allowing energy dissipation from 20% to 30% more than a uniform design.

4.2. FEA for Predictive Modeling

FEA is for simulating the behavior of lattices subjected to multi-axial loading. Take for instance the following:

- **Inconel 625 lattices:** FEA predicts the development of stress concentrations at the unit cell nodes in response to combined x-y-z loading and confirms the observed deformation trends from empirical work.
- **PA 12 lattices:** It is essential to employ some sort of non-linear material model in order to capture geometric plasticity and contact behavior in the course of compression.

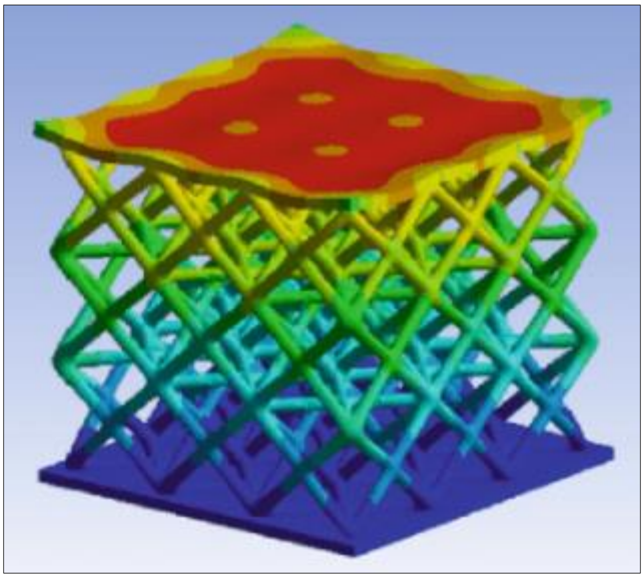


Figure 5 Shows FEA of Lattice

4.3. Defect Analysis and Validation

Validation of Finite Element Analysis Predictions with Micro-CT and Digital Image Correlation:

- **Porosity:** WAAM aluminum lattices display 5-10% porosity in struts, reducing fatigue life by 25%.

- **Quality of Hangover:** FMEAM-printed PLA lattices demonstrate surface roughness (Ra > 50 μm) on unsupported regions, thus requiring topology optimization.

5. Conclusion

The arrival of additive manufacturing (AM) has changed the design, fabrication, and deployment of lightweight lattice structures into eras that now offer unbridled chances to strike a performance demand-sustainability nexus. This work emphasizes the essential interplay between topology-driven design, AM process parameters, and mechanical performance, showing that lattice structures should not be considered as simple geometrical novelties, but as viable solutions for industries that want to get weight reduction benefits without compromising strength. (6) The key take-home lessons are:

Design-Materials-Process Synergy

The integration of mechanical CAD tools with FEA workflows allows for rapid prototyping of lattices with desired properties. For example, parametric CAD models are proficient at generating gradient and hybrid topologies (e.g., octet-truss-gyroid hybrids), which achieve 20-30% more energy absorption than uniform designs under compressive loading. (8) In the meantime, FEA simulations were very useful to accurately predict the areas of high stress concentrations at lattice nodes, which helped to optimize the topology and avoid premature failure in load-bearing parts, such as the case study on lightweight connecting rods.

AM Process Progress and Its Challenges

While techniques such as SLM and WAAM have indeed widened the net on the scale of lattice manufacture, residual stresses, porosity, and surface roughness remain a challenge. The infamous case of the WAAM-produced aluminum skeletons revealed that porosity was in the 5-10% range in strut junctions, equivalent to a 25% drop in fatigue life. (9) Further, post-processing treatments, including heat treatment and surface polishing, became fully necessary to restore ductility and to maintain surface integrity. Meanwhile, anisotropic material models in FEA were regarded as essential for simulating MJF-printed PA12 lattices, whereby attainable yield strength would be understated by as much as 15% under isotropic assumption.

Performance in Real-World Applications

Case studies showed that AM lattices are, industrially, a going concern. The octet-truss cell redesigned kart connecting rod reduced its weight by 40% while fatigue life was maintained, validated through FEA and topology-guided optimization and experimental tests. (2) With such achievement comes the learning to the importance of multi-scale modeling that equates macro-scale structural behavior with micro-scale defect analysis for reliability.

Future Directions

Future research should address the following specifically to release the full potential of AM lattices:

- Multi-Scale Bionic Design: Emulating hierarchically structured biological systems (bone trabeculae, nacre) for improved fracture resistance and energy dissipation.
- Integrating Machine Learning: Establishing AI-driven frameworks to serve as an automated means for establishing design-process-performance correlations and reducing trial-and-error with hopes of improving parameter optimization.
- Large-Scale Production: Scale toward meter-sized aerospace components with a strong emphasis on defect control via real-time monitoring (e.g., in-situ thermal imaging).
- Sustainability: Use of lattice structures to minimize material waste and energy consumption during AM processes.

To summarize, AM-produced lattice structures signify a radical change in lightweight engineering, joining computational innovation with manufacturing practicality. Nevertheless, to gain effective industrial application, a number of issues have to be addressed concerning processing-induced defects and the development of standardized materials and structures databases. It would be increasingly important for this interdisciplinary collaboration between computational mechanics, materials science, and industrial engineers to move these structures from laboratory prototypes to everyday practices in the aerospace, automotive, and biomedical fields. As AM technologies have progressed, the promise of "designer materials" recognizable by their on-demand mechanical properties, no longer remains a simple concept but an attainable reality.

Compliance with ethical standards

Disclosure of conflict of interest

There is no conflict of interest to be disclosed.

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