aerospace

Review

Compressive Behaviour of Additively Manufactured Lattice Structures: A Review

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Abstract: Additive manufacturing (AM) technology has undergone an evolutionary process from fabricating test products and prototypes to fabricating end-user products—a major contributing factor to this is the continuing research and development in this area. AM offers the unique opportunity to fabricate complex structures with intricate geometry such as the lattice structures. These structures are made up of struts, unit cells, and nodes, and are being used not only in the aerospace industry, but also in the sports technology industry, owing to their superior mechanical properties and performance. This paper provides a comprehensive review of the mechanical properties and performance of both metallic and non-metallic lattice structures, focusing on compressive behaviour. In particular, optimisation techniques utilised to optimise their mechanical performance are examined, as well the primary factors influencing mechanical properties of lattices, and their failure mechanisms/modes. Important AM limitations regarding lattice structure fabrication are identified from this review, while the paucity of literature regarding material extruded metal-based lattice structures is discussed.

Keywords: additive manufacturing; 3D printing; lattice structures; metals; polymers

Citation: Obadimu, S.O.; Kourousis, K.I. Compressive Behaviour of Additively Manufactured Lattice Structures: A Review. *Aerospace* **2021**, *8*, 207. https://doi.org/10.3390/aerospace8080207

Academic Editor: Khamis Essa

Received: 3 July 2021
Accepted: 27 July 2021
Published: 30 July 2021

1. Introduction

First introduced in the 1980s [1], additive manufacturing (AM) adopts the layer by layer and bottom-up approach for the fabrication of parts compared to the conventional subtractive fabrication process [2]. AM offers several advantages over conventional manufacturing. For example, it provides the opportunity to manufacture structures with complex topology (e.g., lattice structures), and it does not require auxiliary tools (e.g., jigs and fixtures) for support, making the AM process efficient and optimal in terms of material utilisation [1,3–7]. However, despite all these advantages, there are still some drawbacks such as cost, product or part imperfections, and size limitations—for instance, print bed size limitation, which results in limiting the maximum size of specimen being designed for fabrication [1,5]. The American Society for Testing and Materials (ASTM) F42 have categorised AM into Powder Bed Fusion (PBF), Material Extrusion (ME), Binder Jetting (BJ), VAT Photopolymerization (VATP), Directed Energy Deposition (DED), Material Jetting (MJ), and Sheet Lamination (SL). Table 1 highlights the aforementioned AM categories, as well as their subcategories based on the ASTM F42 guidelines.

Further advancements of AM technologies have opened doors for designers to design and fabricate complex structures with intricate geometries; thus, exploring the freedoms of design offered by AM [4,8]. An example of such a structure is the lattice structure. A lattice can be broadly defined as a structure made of long pieces of metal, wood, or plastic crossed and fastened together with diamond or square-shaped spaces between them [9]. Additionally, lattice structure offers superior properties such as lightweight, high energy absorption, and improved strength to weight ratio [1,6,10] compared to other forms of cellular structures such as foams [4,8]. Hence, in recent years, there has been an increasing interest in lattice structure fabrication for aerospace applications [5,11] and other applications, such as in biomedical engineering [12,13], sports technology [14], and personal protective equipment (PPE) manufacturing [15,16].

Lattices are open-celled structures composed of repeating unit cells defined by their dimensions and connectivity in a three-dimensional space [17]. In addition, a lattice consists of struts and nodes; a strut connects/links the nodes, while a node is a joint where struts connect [18]. Dong et al. [4] and Tang et al. [19] classify lattice structures into three categories according to their degree of order of the lattice frame:

- Periodic lattice structures: lattices unit cells with the same shape, size, and topology, arranged periodically in a 3D Euclidean space;
- Pseudo-periodic lattice structures: lattice cells with different shapes and sizes but share the same topology;
- Randomised or disordered lattice structures: lattice structure with randomly distributed unit cells with different cell sizes and topologies.

Pseudo-periodic and periodic lattice structures are the most commonly used in engineering applications, including aerospace, due to their tailorable properties—they can be further subdivided into heterogeneous and homogenous based on the uniformity of strut's width/thickness [4,19]. Homogenous lattice structures are those with the same strut thickness/width, while heterogeneous structures have varying strut thickness/width [4,19]. Figure 1 depicts the differences between the aforementioned categories of lattice structures.

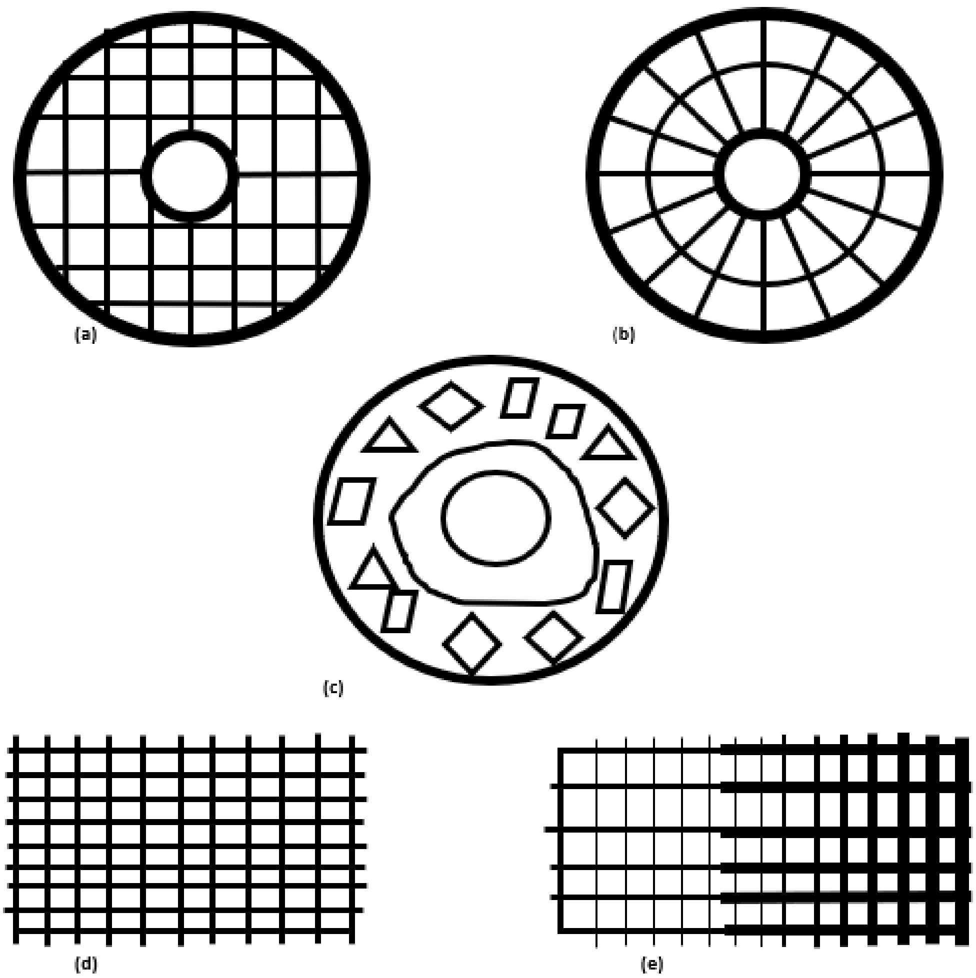

Figure 1. Different categories of lattice structure. Redrawn from Tang et al. [8,19]. (**a**) Periodic lattice structure; (**b**) pseudo-periodic lattice structure; (**c**) randomised or disordered lattice structure; (**d**) homogenous periodic lattice structure; and (**e**) heterogeneous periodic structure.

Although lattice structures have been successfully fabricated for engineering applications via the Powder Bed Fusion (PDF), Material Jetting (MJ), Material Extrusion (ME), Binder Jetting (BJ), and Vat Photopolymerization (VATP) processes [2,20–22], it is important for researchers/designers to consider the AM process to use for fabrication based on budget, manufacturability, and application requirements when designing lattice structures [1].

Furthermore, in terms of lattice unit cells, several studies have been conducted by researchers to design unit cells with unique properties. Some of the most commonly employed lattice models are body-centred cubic (BCC), face-centred cubic (FCC), simple cubic, and Kelvin unit cell [23–25]. Substantial research efforts have been undertaken to improve and optimise the mechanical properties and performance of lattice structures using the aforementioned lattice models. Figure 2 depicts these lattices. However, to the best of our knowledge, there is still paucity in lattice structure related literature, even though a large number of AM related reviews exist [26–28].

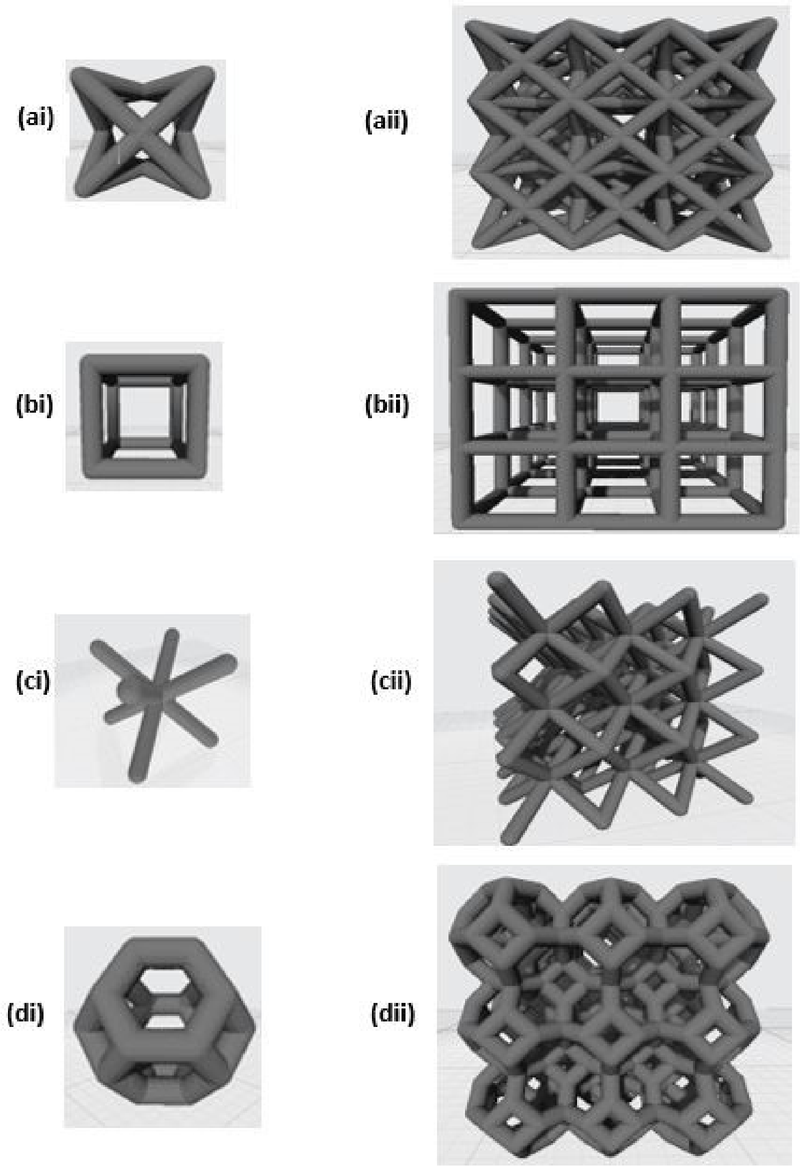

Figure 2. Commonly used lattice structures' geometry: (**ai**) FCC unit cell and (**aii**) FCC lattice structure; (**bi**) simple cubic unit cell and (**bii**) simple cubic lattice structure; (**ci**) BCC unit cell and (**cii**) BCC lattice structure; and (**di**) Kelvin unit cell and (**dii**) Kelvin lattice Structure.

Table 1. Summary of Additive manufacturing (AM) categories and techniques from reviewed literature [29–32].

AM Category: Metal and Non-Metallic (M&NM)	Printing Techniques/Technologies	Materials
Powder Bed Fusion (PBF): (M&NM) Mostly metallic, but can also fabricate non-metallic materials, e.g., use of polymer powder (SLS)	Selective Laser Melting (SLM), Electron Beam Melting (EBM), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), and Selective Heat Sintering (SHS).	Nylon, stainless steel (SS), titanium, aluminium, nickel alloys, etc.
Sheet Lamination (SL): (M&NM) For metallic, uses ribbons of metal then bound together by ultrasonic welding and for non-metallic, uses paper and adhesive for binding	Laminated object manufacturing and Ultrasonic additive manufacturing	Sheets, e.g., paper, or ribbons of metal, e.g., copper and stainless steel.
Material Extrusion (ME): (M&NM) Mostly non-metallic, can now print metallic materials, e.g., ultrafuse 316LX	Fused deposition modelling (FDM) and Fused filament fabrication (FFF)	Nylon, Acrylonitrile Butadiene Styrene (ABS), PLA, PEEK, Polyetherimide (PEI), etc.
Vat Photopolymerization (VATP): (NM) Non-metallic	Direct Light Processing (DLP) and Stereolithography (SLA)	Photopolymers or Resins and Ceramics
Material Jetting (MJ): (M&NM) Mostly non-metallic, but can also print metal parts by utilising the NPJ technology	Drop on Demand (DOD), Material Jetting (MJ) PolyJet (PJ), and Nano particle jetting (NPJ)	Ceramics, Stainless Steel (SS), ABS-like, Wax, etc.
Binder Jetting (BJ): (M&NM) Uses binder as an adhesive for powder-based materials. Can fabricate both metallic and non-metallic materials	Binder Jetting	Stainless steel, Silica sand, Inconel alloy, etc.
Directed Energy Deposition (DED): (M) Metal-based AM which cannot be used for polymer or ceramic materials	Electron Beam Additive Manufacture (EBAM) and Laser Engineered Net Shape (LENS)	Stainless steel, Titanium, copper, etc.

Considering this gap in the published body of knowledge, this paper aims to review the current literature on the mechanical performance of metallic and non-metallic lattice structures, with a focus on compressive behaviour. The techniques currently being employed for mechanical performance optimization are investigated and presented. The review also examines the failure modes/mechanisms of lattices under compression, as well as the impact of lattice geometry (cell size and strut diameter) on their compressive performance, in an attempt to identify current AM lattice fabrication issues and gaps.

2. Mechanical Performance Optimisation of Lattice Structures

2.1. Metallic Lattice Structures

Researchers have explored different optimisation techniques to improve the mechanical performance of AM metallic lattice structures, mainly produced via powder bed fusion (PBF) methods. In an attempt to optimise 3D printed lattice structures and improve mechanical properties whilst considering strength to weight ratio, Bai et al. [33] developed and proposed an optimised face-centred cubic (called AFCC) lattice structure comprising six faces and eight vertices. For comparison, BCC and AFCC lattice structures were fabricated via selective laser melting with the same manufacturing parameters. While maintaining a low weight, the AFCC lattice configuration showed significant advantages in terms of mechanical performance compared to the BCC structures.

Gümrük et al. [34] utilised the BCC, BCCZ, and F2BCC lattice topologies to investigate the mechanical performance of micro-lattice structures of stainless steel 316L (SS316L) fabricated via PBF under different boundary and loading conditions. BCC structures with a node at the centre were fabricated. A stiffened version of BCC with vertical struts is BCCZ, and F2BCC is the combination of two BCC unit-cells. Overall, BCC structures exhibited the lowest mechanical performance, compared to BCCZ with superior mechanical performance in terms of collapse stresses and modulus of elasticity. The high performance was attributed to the presence of vertical struts. Similarly, Shen et al. [35] studied the mechanical properties of SS316L BCC lattices. Four lattice structures were fabricated and compared (BCCZ, BCC, BCC with woven carbon-fibre reinforced epoxy skins and BCCZ-H with horizontal strut). Following experimental analysis amongst other lattices, it was observed that lattice structures designed and fabricated with vertical struts offered better mechanical properties. Campanelli et al. [12], who investigated the effect of vertical reinforcements on the load-carrying capacity of DMLS Ti6Al4V lattice structures, confirmed the same observation. Interestingly, two years later, similar findings were reported by Leary et al. [23] whose report on the compressive performance of lattices restated the positive effects of vertical struts/reinforcements with a focus on BCCZ, FCCZ, and FBCCZ lattice structures exhibiting higher compressive strengths than BCC and FCC structures. Furthermore, Leary et al. [23] observed that Young's Modulus "is always lower than the Moduli at 1% and 2% strain", stressing that it is particularly important for researchers and designers to note that "as reported Young's modulus may underestimate stiffness for actual in-service loading" during compression tests. Similarly, Alghamdi et al. [36], who recently compared, experimentally and via finite element analysis, the mechanical properties of FCC Ti6Al4V lattice structures, confirmed underestimation of the mechanical response of as-built structures.

In an attempt to improve the poor mechanical performance of BCC lattice structures and reduce the impact of stress concentration at the nodes, Bai et al. [37] proposed an improved version of the BCC lattice called the graded-strut body-centred cubic (GBCC) with increased radii corner of the BCC nodes. They compared PBF fabricated Ti6AI4V BCC and GBCC structures. Following quasi-static uniaxial compression tests and numerical analysis, BCC structures were observed to experience failure along the nodes, while GBCC structures experienced failure away from the nodes, thus showing an improved stress concentration and mechanical performance. Based on the same premise as Bai et al. [37] and Ding et al. [38] proposed the 'ARCH' strut lattice, so named "because the centre line of the arch strut is arched compared to other structures" [38]. According to Ding et al. [38], this new design will optimise lattices' mechanical performance, including energy absorption and load-bearing capacity. Numerical and quasi-static compression tests of PBF fabricated SS316L ARCH lattice specimens with different relative densities and strut diameters confirmed this [38].

Further lattice improvement methods have been achieved by Cao et al. [39] and Xiao et al. [40]. Cao et al. [39] proposed a modified rhombic dodecahedron (RD) lattice structure. Their experimental and numerical results showed that modified RD SS316L structures outperformed original RD structures. Similarly, superior mechanical performance of SS316L lattice structure was achieved by Xiao et al. [40], who utilised the topology optimisation (TOP) technique for the design of lattice structures. The TOP technique is used to optimise the thickness, length, and diameter of lattice unit-cell struts and geometries, effectively obtaining an optimised lattice structure. In addition, the TOP technique assists designers in determining materials required for a lattice structure based on design requirements and performance criteria, thereby removing redundant materials and optimising material distribution without compromising structural integrity [40,41]. This approach offers the opportunity to fabricate complex geometrical shapes via AM. The TOP technique has been explored further by Xiao et al. [42] and Challis et al. [10,43].

The fabrication of TOP lattice structures via the PBF AM process has also been found to yield good results for biomedical applications. For example, Xiao et al. [42] explored the TOP technique to obtain optimised cellular bone scaffolds using the PBF process. Experimental results showed that a balance between biological performance and mechanical properties can be achieved by utilising the TOP approach. Consequently, Xiao et al. [42] recommended the PBF AM process as suitable for the fabrication of metallic biomaterial scaffolds, and recommended further research into the fabrication of TOP lattice structures via the PBF AM process. On this premise, Challis et al. [10] showed, experimentally and numerically, that these techniques produce not only optimised lattice structures, but also parts with superior strength and stiffness to weight ratio. Moreover, Challis et al. [43] utilised the TOP technique to solve scaffold design and biocompatibility issues. Experimental and theoretical results showed excellent agreement, thus confirming the viability of fabricating TOP lattice structure via the PBF AM process. Recently, Yang and Li [44] showed that the TOP technique can indeed optimise the compressive performance of lattice structures. In their study via finite element analysis modelling, they enhanced the energy absorption, relative elasticity modulus, and collapse strength of a cuttlebone-like lattice by 174.06%, 203.01%, and 141.96%, respectively when compared to octet and BCC lattice structures.

Another lattice structure optimisation method gaining prominence is the triply periodic minimal surface (TPMS) method. Compared to the TOP approach, the TPMS method is based on a mathematical algorithm used to design and optimise unit cells using, amongst others, the Weistreass formulation. TPMS method allows designers to alter computationally; volume fractions and the structural features of lattice structures, including the unit cell size [45]. Utilising this method, Yan et al. [45] investigated the mechanical performance of diamond and gyroid TPMS lattice scaffolds and found that their mechanical properties correlate well with their relative density. As a result, they recommended utilising the TPMS method for customising the elasticity modulus and porosity of lattice structures. Similarly, Zhao et al. [16] compared TPMS optimised BCC lattice structures with unoptimised BCC structures. Following compressive tests, TPMS lattice structures exhibited superior mechanical performance, owing to their unique stress and volume distributions, in addition to their higher energy absorption capacity, compressive strength, and elasticity modulus compared to unoptimised lattices.

Regarding the characterisation and quantification of the effects manufacturing defects on the mechanical properties of lattices, Alghamdi et al. [36] recently introduced the 'automated analysis of microscope images' method. This method utilises transmitted light microscope images of as-built lattices to generate 2D models for finite element analysis, and was considered suitable for the prediction and optimisation of the mechanical properties of as-built AM fabricated metal lattices. In a similar vein, Zhou et al. [46] proposed a quicker means of measuring and obtaining the Young's modulus of lattice structures—the use of the Instrumented Indention Testing (IIT) system. The IIT utilises a probe tip specially designed to press against a sample's surface whilst measuring applied force and displacement. Young's modulus was evaluated for binder jetted SS316L 1 mm and 1.5 mm grid lattices via the IIT system and compared with compression and 3-point bending test results. Measured values via the IIT system were 1.50 GPa and 0.446 GPa, respectively, which were similar to the Young's modulus results obtained from the 3-point bending and compression tests, further verifying the reliability of the IIT system. Although the values were significantly less than 200 GPa for a conventionally fabricated SS316L [46], the authors attributed this to inhomogeneous material distribution and the complicated binder jetting AM process causing a weak interface between SS316L powder particles.

2.2. Non-Metallic Lattic Structures

Dong et al. [47] investigated the influence of process parameters on print quality in an attempt to optimise material extruded (ME) lattice structures. They compared the inclined and the horizontal struts whilst exploring different manufacturing parameters, including fan speed and layer height. For horizontal struts, three fan speeds were compared (0%, 50%, and 100%), while maintaining nozzle temperature and print speed at 245 °C and 600 mm/min, respectively. For inclined strut, layer heights of 0.1 mm and 0.2 mm were compared, keeping nozzle temperature constant at 255 °C and print speed at 1200 mm/min. Experimental results revealed that the 0.1 mm layer height produced the best print for inclined struts, while for horizontal struts, 0% fan speed produced the best print quality. Following analysis of variance (ANOVA) of their data set, layer height/thickness was identified as the most significant process parameter for horizontal struts and fan speed for inclined struts. Furthermore, considering their experimental and ANOVA results, Dong et al. [47] fabricated and tested additional lattice samples with optimised process parameters. As expected, they were found to exhibit superior mechanical properties/performance. The overall conclusion of Dong et al. [47] was that layer thickness is the most significant process parameter for lattice structure fabrication via the ME process, and high nozzle temperature "will strengthen the bond between each layer".

Similarly, Mazlan et al. [48] investigated the effect of three manufacturing parameters—nozzle temperature, print speed, and layer thickness—on polylactic acid (PLA) printed lattice structures. Following experiments and ANOVA analysis, layer thickness was found to have the most significant effect (at 67%) on the mechanical performance of the fabricated lattices, while print speed and nozzle temperature showed less significance (at 13% and 3.3%, respectively). Furthermore, the impact of ME manufacturing parameters on the mechanical properties of lattice structures was also studied by Panda et al. [49]. Whilst keeping other manufacturing parameters (such as raster angle, layer thickness, and print orientation) constant, the effects of cell size and wall thickness were studied. Following experimental and numerical modelling, after finding that elastic modulus and yield strength decreases with an increase in cell size, the authors concluded that keeping cell size at a minimum of 4 mm and wall thickness around 3 mm would produce ME honeycomb lattices with good mechanical properties. However, Mason and Leu [50] argue otherwise; according to Mason and Leu, a decrease in cell size equals a decrease in the compressive properties attributed to "the decreasing uniformity and quality of the struts" during ME process.

In addition to layer thickness and wall thickness, strut shape/thickness, surface roughness, build orientation, and lattice structure porosity have also been confirmed to influence the mechanical behaviour and print time of ME lattices. This was confirmed by Iyibilgin and Yigit [51], Ravari et al. [21], and Gautam et al. [52]. Iyibilgin and Yigit [51] investigated the effect of cellular lattices, cell size, and porosity on build time and compressive properties. Amongst other observations, they found that increase in lattice porosity results in a decrease in yield strength and compressive modulus, and an increase in edge length results in a decrease in print time. Additionally, the authors observed that the honeycomb lattice with 0.76 cm edge length and 57% porosity exhibited the best mechanical properties (in terms of yield strength) and had the shortest print time. Ravari et al. [21] studied and confirmed the impact of strut diameter on the elastic modulus and collapse stress on BCCZ lattice structures. As part of the lattice structure optimisation process, they suggested modelling "the cross-section variations along the strut's length" in order to predict lattices' mechanical performance. Gautam et al. [52], on the other hand, found that an increase in strut diameter increases the elastic stiffness and peak strength of a lattice structure. Additionally, they observed that the dimensional accuracy of an ME component or part depends on the build orientation. This view was also affirmed by Garg et al. [53] who studied the effect of print orientation on ME parts. Moreover, Maharjan et al. [54] identified volume fraction as a major factor that influences the compressive properties of a lattice structure. The higher the volume fraction, the higher the compressive strength and vice versa [54].

Efforts are still being devoted to optimising the mechanical properties of ME lattice structures. Liu et al. [55] proposed a 'snap-fitting' method for the optimisation of material extruded BCC lattice structures. The snap-fitting technique allows the fabrication of lattice struts and panels separately, and then 'snap-fitting' and bonding them with super glue. Liu et al. [55] (2019) compared lattices fabricated by integrated ME method (i.e., the standard bottom-up approach) with snap-fitted fabricated ones (i.e., those printed separately). Amongst other findings, snap-fitted lattice structures were found to have higher energy absorption capacity and higher compressive strength than the integrated ME lattices. Kumar et al. [7] recently proposed a sea urchin (SU) lattice structure for the fabrication of supportless lattice structures during the ME fabrication process. For comparison, SU, ethylene vinyl acetate (EVA) foam and BCC lattice structure samples were fabricated. Following an experimental analysis, SU lattices were found to exhibit superior mechanical properties in terms of energy absorption capacity and stiffness property compared to both the EVA foam and BCC structures. In addition, fabrication cost and time were reduced significantly, thereby saving use of material without compromising print quality. The proposed SU concept was also applied by Kumar et al. [56] in fabricating closed-cell lattice structures using PLA filaments. The effectiveness of the process was evident in their experimental results as the lattice structures exhibited, amongst others, high energy absorption and high strength, further confirming the potential of the proposed method.

Rossiter, Johnson, and Bingham [14] researched the impact of strut shape, strut cross-sectional area, cell orientation, cell width, and joint filleting on the energy absorption capacity of truncated octahedron lattices. Although the aforementioned variables had a significant effect on the lattice structures, the strut cross-sectional area was found to have the largest effect on the energy absorption capacity of the lattices, followed by cell width and orientation. Thus, Rossiter et al. [14] recommended strut cross-sectional area as the most suitable design parameter to "adjust for a cell-by-cell tailored response", while cell width adjustment was recommended for conformal lattice structures with varying cell size. Additionally, they observed that a larger strut cross-sectional area and a smaller cell width improves lattices' energy absorption capacity.

The compressive performance of ME wood-plastic composite (WPCs) lattices was explored by Tao et al. [57]. Experimental results were found to be inconsistent with the simulation results, this contradiction was attributed to the printing process parameters, including print line width and the software utilised. In conclusion, they suggested the use of high-quality 3D printers to reduce the impact of print quality on the compressive performance of lattices fabricated via the ME process.

In order to investigate ME's printing quality, Azmi et al. [58] studied the variation between the geometry of computer-based lattice model and ME lattices. They designed lattices with struts diameters 1.2 mm, 1.6 mm, and 2.0 mm. Following fabrication, the lattice specimens were measured, and the struts were found to have shrunk in size by 12.92%, 10.38%, and 7.9%, respectively. Azmi et al. [58] suggested adjusting ME process parameters to account for the reduction in the size of ME parts. Furthermore, following Azmi et al.'s suggestion, Rosli et al. [59] fabricated ME lattice structures with varying layer thickness—70 µm, 200 µm, and 300 µm—whilst keeping strut diameter and other parameters constant in order to obtain the optimum combination of manufacturing parameters and fabricate lattices with accurate dimensions. After the ME fabrication process, lattice structures with 200 µm layer thickness were found to have produced the most accurate lattice structure in terms of shape and relative arrangements based on the geometry of the computer model, and were also found to have better mechanical performance compared to the other lattice designs.

3. Failure Modes and Mechanisms of Lattice Structures under Compression

Failure modes and mechanisms of different lattice structures have been studied and reported in the literature. Maskery et al. [15] explored different aspects of designing and producing PBF fabricated Al-Si10-Mg lattice structures—gyroid lattice structures with cell sizes 3 mm, 4.5 mm, 6 mm, and 9 mm were fabricated. Following compression tests of as-built and heat-treated lattice specimens, they reported:

- Failure under compression (i.e., cell collapse) perpendicular to the loading and manufacturing directions for 4.5 mm and 6 mm cells;
- Brittle fracture/failure of cell walls in the direction parallel to the load applied for 6 mm and 9 mm cells;
- Diagonal shear for 3 mm cells. As expected, heat-treated specimens exhibited enhanced ductility compared to the as-built lattices. Moreover, they observed that post-manufacture heat treatment prevented the formation of diagonal shear in heat-treated specimens.

The impact of local geometric features on the compressive mechanical behaviour of lattice structures was studied by Zhao et al. [16] who compared DMLS fabricated Ti6Al4V TPMS optimised BCC lattice structures with unoptimised ones. For comparative purposes, the lattices were set at 10%, 20%, and 30% volume fractions, respectively. After uniaxial compression tests and scanning electron microscope (SEM) analysis of fracture surfaces of the specimens, they highlighted the following failure modes:

- 10% volume fraction lattices displayed deep ductile dimples pattern. On the other hand, 30% volume fraction lattices exhibited brittle and ductile fractures with a 45-degree shear crack failure mode;
- Unoptimised BCC lattices' fractures were found to be closer to the nodes than the TPMS ones, thus confirming the impact of geometric features on the mechanical behaviour of lattices.

Similarly, the failure mechanism and compressive strength of DMLS fabricated Ti6Al4V TOP lattices was investigated numerically and experimentally by Xu et al. [41]. In particular, thinner micro-struts were found to buckle and collapse completely at 45 degrees, and some thicker micro-struts experienced a recoverable bend while other specimens experienced elastic-brittle failure mechanism. Utilising the same TOP technique, Xiao et al. [40] studied the failure modes of SS316L TOP lattice structures. Their samples experienced a smooth and stable deformation process along the 45 degrees direction without signs of local deformation during compression tests. Bai et al.'s. [33,37] GBCC, AFCC, and BCC lattice samples exhibited similar failure/damage along the 45 degrees direction, however, with double shear slip and local deformation. AFCC samples experienced only plastic deformation, while BCC samples fractured and disengaged from the strut [33]. GBCC structures experienced failure away from the nodes, while BCC structures experienced failure along the nodes [37].

Moreover, Zhang et al. [60], whose lattice specimens experienced a 45-degree shear deformation angle and a shear deformation angle larger than 55 degrees, noted that deformation angle of lattice structures is based on the density of the structure, as denser structures do not easily deform due to their high stiffness. Additionally, their experimental results revealed that failure modes of structures are not only associated with the overall graded lattice structure but also local vulnerable areas such as lattice nodes and struts. Li et al. [61], Liu et al. [62], and Li et al. [63] observed local buckling of the vertical struts while examining the mechanical behaviour of PBF fabricated regular octet, rhombicuboctahedron, and BCC lattice structures. Interestingly, Li et al. [61] and Liu et al. [62] noted that the material utilised for fabrication, as well as the size of lattice struts, can control the failure mode of a lattice structure, thus further confirming the observation that local vulnerable areas, such as struts and nodes, influence the failure mechanism of lattices.

Liu et al. [55] fabricated BCC lattice structures using the snap-fitting method and the integrated ME method with relative density ranging from 2.1% to 8.3%. Following compression tests, it was found that specimens with high relative density failed by inelastic buckling, while those with low relative density failed by elastic buckling. Additionally, for integrated ME specimens, following struts deformation the lattices fractured into two parts at the struts' hinges, while snap-fitted lattices' struts only bent without any visible cracks. Similar findings were revealed by Mason and Leu [50] who compared ME BCC structures with acetone smoothed structures. While the former failed completely, the latter only fractured and bent without the struts breaking completely.

The influence of vertical struts on the compressive behaviour of lattice was studied by Gümrük et al. [34] and Fadeel et al. [64]. Gümrük et al. [34] studied lattice configurations BCC, BCCZ, and F2BCC. For BCC lattice configuration, all structures experienced localisation at the centre of the structure, which was attributed to strut imperfections and friction between the compressing plates and lattice structure. Similar to the BCC lattices, BCCZ and F2BCC also experienced deformation localisation, however were further categorised into deformation localisation at the centre of the structure and a diagonal shear deformation localisation at 45° angle. Using a similar lattice configuration used by Gümrük et al. [34], Fadeel et al. [64] studied the impact of vertical struts on the mechanical behaviour of lattices. They investigated the BCC, BCCV, BCCA, and BCCG lattice structures. BCC with vertical struts in alternating layers is BCCA, BCC with vertical struts connecting all nodes is BCCV, while BCCG has vertical struts at the bottom layer but none at the top layer. After experimental analysis, Fadeel et al. [64] observed that failure was initiated in the middle layer without vertical struts for BCCA lattice structure, while failure was observed to start at the top layer without vertical struts for BCCG lattice. On the other hand, BCC structures failed at both the bottom and top layers of the lattice cells, then progressed through the lattice structure while BCCV lattice with struts connected to all the nodes experienced failure first at the top before progressing down.

Recently, Ding et al. [38] studied the mechanical behaviour of ARCH SS316L lattice specimens fabricated via the PBF process with strut diameter ranging from 0.6 mm to 1.2 mm. Following compression tests, amongst other findings, their research revealed that the samples exhibited no sign of local brittleness failure, and they all experienced the same failure mode—diagonal direction inclined compacted collapse, regardless of the strut diameter. Additionally, samples with high strut diameter (and relative density) were found to have higher energy absorption capability and mechanical strength. The failure modes/mechanisms identified above are summarised in Table 2. Additionally, commonly reported failure modes/mechanisms in the reviewed literature are illustrated schematically in Figure 3.

Table 2. Summary of reviewed studies on compressive failure modes/mechanisms.

Failure Mode/Mechanism	**Material**	**Lattice Type**	**Reference**
Diagonal shear, cell collapse, and brittle fracture	Al-Si10-Mg	Gyroid lattices	Maskery et al. [15]
45-degree shear crack and deep ductile dimples	Ti6Al4V	TPMS BCC	Zhao et al. [16]
45° inclined fracture and recoverable bend	Ti6Al4V	TOP lattices	Xu et al. [41]
45° inclined fracture	SS316L	TOP FCC, VC, and ECC	Xiao et al. [40]
Double shear slip and local deformation along the 45° direction	Ti6Al4V	AFCC and BCC	Bai et al. [33]
45° failure/damage, failure along the nodes	Ti6Al4V	BCC and GBCC	Bai et al. [37]
Elastic and inelastic buckling	PLA	BCC	Liu et al. [55]
45° inclined fracture, ductile fracture and diagonal bending	ABS	BCC	Mason and Leu [50]
Deformation localisation at the centre of lattices and 45° shear deformation angle	SS316L	BCC, BCCZ, and F2BCC lattices	Gümrük et al. [34]
45° shear deformation angle and shear deformation angle larger than 55°	Ti6Al4V	FGS lattice and diamond lattice	Zhang et al. [60]
Diagonal direction inclined compacted collapse	SS316L	ARCH lattice	Ding et al. [38]
Failure initiated at the top, middle, and bottom depending on the lattice configuration	ABS	BCC, BCCV, BCCA, and BCCG	Fadeel et al. [64]
Shear fracture forming a 54.7° angle and plastic deformation triggered by diagonal strut bending	AlSi10Mg	Regular octet and rhombicuboctahedron lattices	Liu et al. [62]
Local buckling of struts, localised necking before final fracture, and plastic hinges in the nodal joints	SS316L	BCC	Li et al. [61]
Diagonal strut bending, vertical strut buckling, and layer-by-layer progressive damage	AlSi10Mg	BCCZ	Li et al. [63]

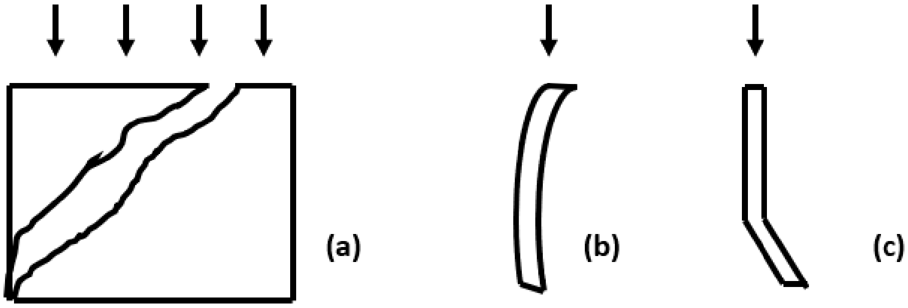

Figure 3. Schematic representation of failure modes/mechanisms commonly reported in the literature: (**a**) diagonal shear failure along the 45° direction, (**b**) elastic buckling, and (**c**) inelastic buckling.

4. Effect of Lattice Structure Geometry on Compressive Behaviour

It is also important to study the impact of lattice geometric structure on their failure modes. This section complements previous sections by focusing mainly on studies regarding the impact of lattices' geometric structure and design (e.g., cell size and topology shape) on their mechanical properties.

Understandably, design parameters such as cell topology, size, and wall thickness have been reported to govern the mechanical performance of lattices. Recently, Arjunan et al. [65] conducted an in-depth study into the influence of cell wall thickness (t) and auxetic angle (θ) on the mechanical performance of PBF fabricated auxetic AlSi10Mg lattices by modulating t (0.3–1 mm) and θ (45–85°). Experimental results confirmed that the elastic modulus and compressive strength of the lattices are indeed cell size and angle-dependent, i.e., increase in t and θ equals higher compressive strength and elastic modulus. In addition, they found the interaction effects (i.e., interdependence) of the aforementioned parameters less significant for elasticity modulus optimisation, and very significant for compressive strength optimisation. Crupi et al. [66] conducted similar studies with a focus on the influence of cell size and strut diameter on DMLS Ti6Al4V lattices' mechanical performance. The study reported that increase in unit cell size reduces mechanical performance, while an increase in strut diameter and aspect ratio improves mechanical performance. Azzouz et al. [67], Iyibilgin and Yigit [51], Ravari et al. [21], and Rossiter et al. [14] also confirmed the influence of lattice geometry on mechanical performance in a similar research on ME lattices.

Additionally, with the same aim of understanding the impact of lattice geometric structure on performance, Campanelli et al. [12] studied the effect of strut size, cell size, and vertical reinforcements on the mechanical performance of DMLS fabricated Ti6A14V lattice structures. Experimentally informed parametric analysis revealed that, in fact, these parameters can influence the mechanical performance of lattice structures. Maskery et al. [15] also confirmed this after comparing as-built and heat-treated lattice specimens following experimental analysis. Meanwhile, Yánez et al. [13] studied the mechanical characteristics of PBF fabricated Ti6Al4V. They fabricated structures with different strut angles, ranging from 19° to 68.5° with the aim of obtaining lattices with improved strength to weight ratio. Following uniaxial compression tests, lattices with low strut angles (<35°) were found to have higher compressive strength and elastic modulus than those with high strut angles (>35°) indicating that strut angle does affect lattice mechanical behaviour.

In terms of porosity, Vannutelli [22] attributed the high mechanical performance of PBF fabricated Inconel 718 lattices to their low porosity after studying their mechanical behaviour via simulations and experiments. Similar findings were also reported by Xu et al. [41] who affirmed that both dynamic elasticity modulus and ultimate compressive strength decrease with an increase in unit cell size and porosity. This case was also noted by Gümrük et al. [34] and Xiao et al. [40] during SS316L lattice structure compression tests. Gümrük et al. [34] observed that unit cell topology and cell size affect the mechanical properties of lattice structures, while Xiao et al. [40] noted that a higher porosity results in low energy absorption capacity and mechanical performance.

On the other hand, the impacts of volume fraction/ratio of lattice structures were reported by Zhao et al. [16] and Monkova et al. [25]. Their reports revealed that lattice specimens with a higher volume ratio exhibited superior mechanical properties than those with a lower volume ratio. A similar observation was made by Maharjan et al. [54]; namely that volume fraction has a significant effect on the compressive behaviour of lattice structures. In addition to volume fraction, Zhao et al. [16] believe local geometry features of lattice structures also affect their load-bearing capacity.

Mueller and Shea [24] focused their research on the impact of build orientation, buckling, and scaling (i.e., size) on the mechanical properties of material jetted lattices fabricated with VeroWhitePlus (RGD835)—a rigid opaque white polyjet photopolymer. Their experimental findings revealed that all three factors not only affect mechanical performance, but also the printing quality of lattices. In addition, they found lattices with a large strut diameter to perform better than those with a small diameter in terms of ultimate strength.

Furthermore, in order to overcome the dimensional variation between designed and produced DMLS fabricated samples (for thin struts), Abele et al. [68] compared lattice structures fabricated via the standard process (SP) and tailored process. SP parameters are recommended material values from the manufacturer, i.e., material-specific default values. Following experiments and X-ray analysis, the fabricated struts (diameter) were found to be smaller than designed strut diameters for both SP and tailored process parameters. However, it was found that struts printed via adapted process produced good dimensional accuracy and better print quality than SP prints; thus, they recommended the former for the fabrication of complex and intricate geometry.

On the other hand, Alberdi et al. [69] argue that focusing only on homogeneous lattice topology limits the capabilities offered by AM. Hence, they recommend utilising heterogeneous lattice design with multi-morphology lattices such as the combination of BCC and FCC unit cells in a lattice structure. Going further to prove the influence of lattice geometry on mechanical performance, Alberdi et al. [69] experimentally compared the performance of a homogeneous FCC lattice design with multi-morphology/heterogeneous lattice design (a combination of BCC and FCC cells). They utilised two base materials, Vero white photopolymer and SS316L, to fabricate homogeneous and multi-morphology lattices. The experimental results confirmed the influence of cell topology on energy absorption in lattice structures as the latter outperformed the former.

In addition to Figure 2 and Sections 2–4 above, a schematic representation of lattice structures proposed and commonly studied and reported in the literature are presented in Figure 4.

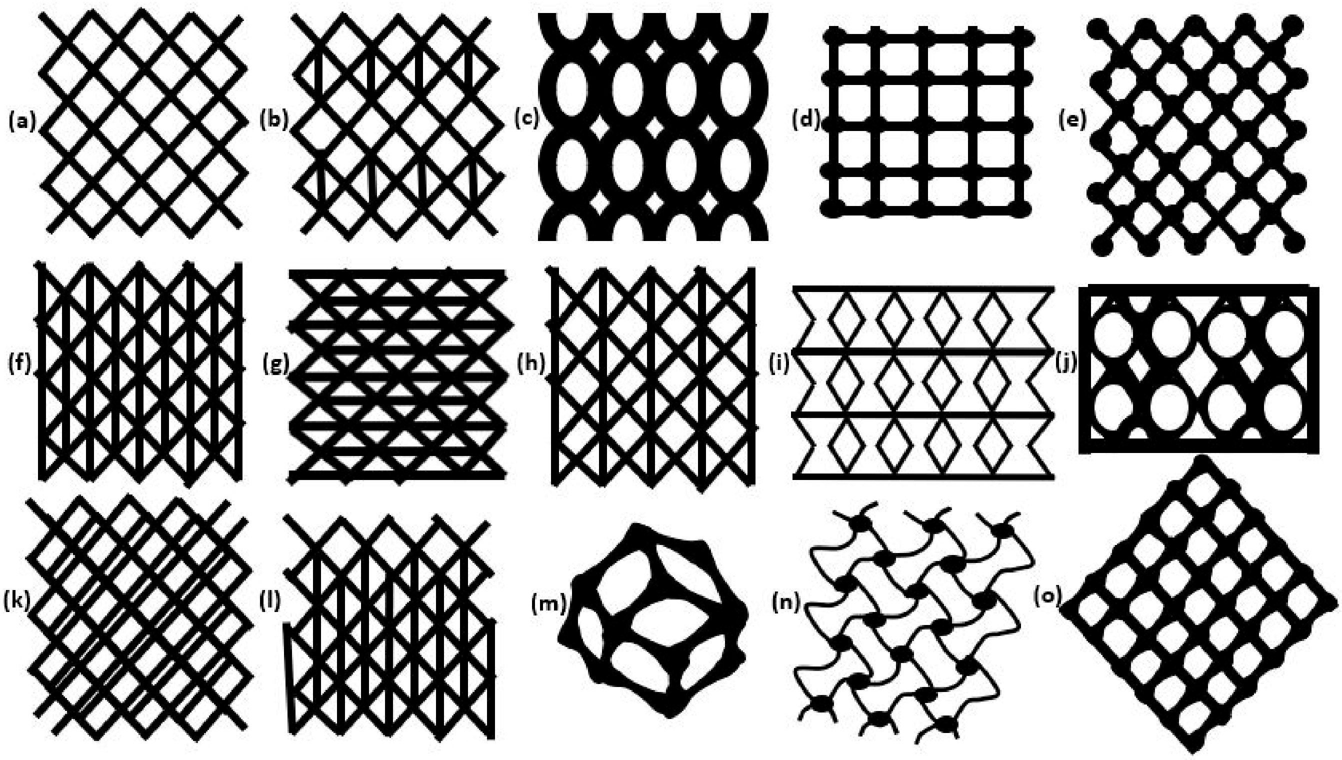

Figure 4. Schematic representation of Lattices proposed and commonly studied and reported in the literature: (**a**) BCC [7,16,23,24,33–35,37,44,50,55,56,58–61,64,66–69]. (**b**) BCCA with vertical struts in alternating layers [64]. (**c**) ARCH lattice with arch strut arched at the centre line [38]. (**d**) TOP cubic lattice [42]. (**e**) TPMS Based BCC [16]. (**f**) BCCZ or BCCV with vertical struts [23,34,35,63,64]. (**g**) BCCZ-H with horizontal struts [35]. (**h**) FCCZ with vertical struts [23]. (**i**) Auxetic lattices assembly without crosslink [65]. (**j**) Sea urchin (SU) lattice structure [7,56]. (**k**) F2BCC a combination of two BCC cells [34]. (**l**) BCCG with an increasing number of vertical struts from none at the top to all at the bottom [64]. (**m**) Rhombic dodecahedron (RD) lattice with modified struts [39]. (**n**) Gyroid lattice [10,13,15,20,45,54]. (**o**) GBCC with increased radii corner of the BCC nodes [37].

5. Conclusions

From the reviewed literature, it was found that a significant amount of research has been undertaken to understand the mechanical behaviour and performance of metallic and non-metallic (i.e., polymer) lattice structures. Research efforts have been mainly geared around lattices produced via PBF methods for the case of metallic lattices and the ME AM method for fabrication of polymer lattices. A number of other researchers have explored the possibility of fabricating lattice structures via other AM methods, such as the MJ process [2], BJ process [46], and the VAT Photopolymerization process [20], which indicates a need to explore further other AM technologies and materials. The feasibility of manufacturing curved lattice structure has also been studied [70].

Regarding simulation models, for example, finite element simulations have been found to be in good agreement with experimental results [61,63,64]. As a result, the study of the mechanical properties of lattice structures is not only restricted to experiments; researchers typically utilise simulations to validate experimental results and/or to predict the performance of a structure. However, it is interesting that, even with these developments, the predicted mechanical properties (e.g., Young's modulus) of a lattice structure via experimental observations and simulations may underestimate actual in-service mechanical behaviour. This confirms Leary et al.'s. [23] call to AM researchers and designers to be mindful during experimental analysis. It is characteristic, for example, that Shen et al. [35] noted that lubricating the plates prior to conducting compression tests will reduce the effects of friction on the results obtained from mechanical compression testing.

The most commonly utilised lattice model identified in the literature is the BCC lattice structure. However, it has been found to exhibit poor mechanical performance, therefore researchers have proposed optimisation techniques, such TOP and TPMS, as well as other lattice models, such as the ARCH, TOP, TPMS, AFCC, GBCC, and BCCZ lattices due to their improved strength to weight ratio, high compressive strength, and energy absorption capacity when compared to the BCC model. In addition, it is important to note that these lattice models are loosely based on the BCC model, further confirming their distinctiveness.

Moreover, it was also observed in the literature that optimisation techniques for non-metallic lattices focused on improving process parameters, including build speed and layer height, whereas metallic lattice optimisation techniques have been focused mainly on improving design features, such as introducing vertical struts into a lattice model and proposing the aforementioned lattice models. Varying parameters and processes are equally important in obtaining the optimal combination of manufacturing parameters. Factors including laser power, scan speed, build orientation, layer height, raster angle, and nozzle extrusion temperature have been identified as substantially affecting the mechanical properties of AM fabricated lattice structures; varying these parameters will improve mechanical properties/performance.

One may note that geometry irregularities and variation between computer aided design (CAD) drawings and fabricated structures are other key issues affecting fabrication quality and accuracy. While adjusting process parameters and post-processing machining have been suggested to improve print quality and correct surface defects/imperfections, repeatability of the AM process remains a challenge. As a result, the need for further research has been stressed to improve the repeatability of the AM processes and to reduce irregularities occurring from fabrication [67].

The impact of strut diameter, volume fraction, and cell size on the mechanical properties of lattices cannot be ignored. The literature revealed that these factors are paramount in predicting the mechanical performance of a lattice structure. Of particular importance is the influence of cell size on the overall mechanical performance of a structure, which has been experimentally confirmed by several studies [12,16,41,65]. Various AM researchers reported that an increase in unit cell size reduces the mechanical properties of a lattice structure. However, Mason and Leu [50] argue that this is particularly common with metal fabricated lattices, that the case is different for non-metallic ME lattice structures—implying that, in fact, a decrease in cell size automatically decreases the compressive properties of ME lattices. Smaller cross-sectional area/cell size equals shorter scan distances for metal AM, leading to an increase in the temperature of a scanned area, as a result, creating the right conditions for higher mechanical properties such as compressive strength.

In addition to the findings discussed above, challenges, general recommendations, and suggestions as reported in the literature are collected and presented in Table 3. A closer look at these findings and recommendations leads to the following key insights:

- The deformation process/failure mode of lattices can be improved by post machining heat treatment;
- Increasing the radii corners of a lattice strut will improve its energy absorption capability;
- There is a high correlation between relative density and the mechanical properties/energy absorption capability of a lattice structure;
- Post fabrication chemical treatment of lattices will improve not only its surface roughness, but also its energy absorption capacity and its compressive strength.

Table 3. Summary of challenges, general recommendations, and suggestions arising from the reviewed literature.

Reference	FE Modelling/ Simulation	Research Focus	Suggestions/Challenges/ Future Work	Lattice Type	Material	AM Category
Xu et al. [41]	Yes	Effect of porosity and unit cell size on lattices	To study bone cell attachment and ingrowth experiment of TOP lattices	TOP Lattice	Ti6Al4V	PBF
Zhao et al. [16]	Yes	TPMS BCC for lattice design	Further investigation of the mechanical properties of TPMS BCC lattices	TPMS BCC	Ti6Al4V	PBF
Monkova et al. [25]	No	Impact of lattice volume ratio/fraction on its Young's modulus	There is a high correlation between the volume ratio of a lattice and its Young's modulus	Simple Lattice Structure	ABS	ME
Azmi et al. [58]	No	Dimensional accuracy of ME lattice structure bar	Recommended varying ME process parameters to improve print quality	BCC	ABS	ME
Rosli et al. [59]	No	Impact of process parameters on lattices	There is a high correlation between strut thickness and the failure mode and the mechanical properties of lattices	BCC	ABS	ME
Liu et al. [55]	No	Introduced the snap-fitting method for lattice fabrication	To introduce the snap-fitting method into other AM technologies	BCC	PLA	ME
Tao et al. [57]	Yes	Compressive performance of square, circle, and voronoi cellular structure	Print line width affects print quality. Suggested use of high-quality 3D printers	circle, square, and voronoi cellular structures	PLA	ME
Mazlan et al. [48]	No	Impact of manufacturing parameters on the mechanical performance of PLA lattices	Investigating composite fibre reinforced polymer for high structural applications	Truss collinear lattice structure	PLA	ME
Panda et al. [49]	No	Impact of design parameters on the mechanical performance of ABS lattices	Study other types of lattice structures fabricated via other ME materials with varying manufacturing parameters	honeycomb or hexagonal lattice	ABS	ME
Ravari et al. [21]	Yes	Effect of strut diameter on mechanical behaviour	Observed differences in as designed diameter and as-built diameter. As a result, suggested modelling the cross-section variations along the strut's length.	BCCZ	PLA	ME
Iyibilgin and Yigit. [51]	No	Effect of cellular lattices, cell size, and porosity on build time and compressive properties	Suggested the combination of the following parameters: honeycomb lattices, cell size with 0.76 cm edge length and 57% porosity to achieve the best mechanical properties and shortest print time.	Honeycomb, square, diamond, circle, and-triangle cellular lattice structures	ABS	ME

Table 3. *Cont.*

Reference	FE Modelling/ Simulation	Research Focus	Suggestions/Challenges/ Future Work	Lattice Type	Material	AM Category
Rossiter et al. [14]	No	Impact of geometric design variables on the compressive behaviour of lattices	Recommended adjusting strut cross-sectional area for a cell-by-cell tailored response and cell width for conformal lattice structures with varying cell size.	Truncated octahe-dron lattices	Ultimaker Nylon	ME
Gautam et al. [52]	Yes	Compressive behaviour of Kagome lattice structures	Post-fabrication chemical treatment of lattices will improve not only its surface roughness, but also its energy absorption capacity and its compressive strength	Kagome lattice structures	ABS	ME
Maharjan et al. [54]	No	Effect of variation of volume fraction and unit cell size	Study the compressive behaviour of polycarbonate and ABS material	Gyroid lattice	PLA	ME
Kumar et al. [7,56]	No	SU lattice structure	Application of SU lattices in ski boots and sports shoes and use of a fixed nozzle diameter to investigate the impact of flow rate on print quality.	Closed-cell, shell-shaped, and BCC lattices	TPU, PLA	ME
Mason and Leu [50]	No	Effect of cold acetone smoothing on the mechanical properties of BCC lattice structure	Decrease in compressive properties with decease in cell size is due to the decreasing uniformity and quality of the struts	BCC	ABS	ME
Azzouz et., al. [67]	No	Feasibility of using ME PLA lattices for structural application	Further research to improve the repeatability of the ME process	BCC, BCCZ, rectangu-larpattern of four vertical struts	PLA	ME
Xiao et al. [42]	Yes	TOP technique for the fabrication of biomedical scaffolds	Explore the relationship between TOP scaffolds and desired mechanical properties using the PBF process	TOP Cellular structures	Ti6Al4V	PBF
Challis et al. [10]	Yes	Mechanical performance of gyroid lattices and TOP lattices	Exploring other types of unit cells by employing the TOP approach	Gyroid and TOP lattice	Ti6Al4V	PBF
Challis et al. [43]	Yes	Biocompatibility of TOP and PBF fabricated porous lattices	The viability of employing the PBF process for scaffold fabrication	TOP lattice	Bronze and Steel powder	PBF
Melchels et al. [20]	Yes	Mechanical performance of mathematically defined lattice scaffolds	Recommended the use of mathematically defined lattice structures	Cube, diamond, and gyroid	PDLLA based resin	VATP
Yan et al. [45]	No	Mechanical properties of TPMS diamond and gyroid lattices	Use of PBF fabricated Ti6Al4V TPMS lattices for load-bearing bone implants	Gyroid and Diamond TPMS lattice	Ti6Al4V	PBF

Table 3. *Cont.*

Reference	FE Modelling/ Simulation	Research Focus	Suggestions/Challenges/ Future Work	Lattice Type	Material	AM Category
Dong et al. [47]	No	Influence of process parameters on lattice structures	To study the print quality of ME lattices via dynamic process parameters	BCC (with vertical and horizontal struts)	ABS	ME
Cheng et al. [2]	Yes	Experimental analysis and validation of the revised Hill's yield criterion and asymptotic homogenization technique for the design and manufacture of graded lattices	Proposed revised Hill's yield criterion and asymptotic homogenization technique to describe and obtain two mechanical properties: plasticity and elasticity	Cubic lattice	VerowhitePlus	MJ
Vannutelli. [22]	Yes	Mechanical behaviour of lattice structures	To study the relationship between mechanical properties and the level of porosity of NiMnGa &and Inconel 718 lattices	Rectangular paral-lelepiped	NiMnGa & Inconel 718 powder	PBF & BJ
Zhou et al. [46]	No	Usage of IIT to verify the mechanical properties of lattices	Use the IIT system to investigate the effects of indentation angles towards the measuring surface	Homogeneous rigid structure	SS316L	BJ
Mueller and Shea [24]	Yes	Effect of build orientation, buckling, and scaling on lattice structures	To use their findings as guidelines to establish the MJ process for lattices fabrication	BCC, FCC, and Kelvin cell	VerowhitePlus	MJ
Gümrük et al. [34]	No	Mechanical behaviour of micro-lattices under different loading conditions	High manufacturing costs of steel micro-lattice structures	BCC, BCCZ, and F2BCC lattice	SS316L	PBF
Zhang et al. [60]	Yes	Effect of porosity variation on the mechanical performance of FGS lattices.	To use porosity variation as a strategy to customise the design of functionally graded scaffold (FGS)	FGS lattice and diamond lattice	Ti6Al4V	PBF
Fadeel et al. [64]	Yes	Effect of vertical struts on the compression characteristics of BCC lattices	Further FEA analysis to study the BCCV lattice structure configuration	BCC, BCCV, BCCA, and BCCG	ABS	ME
Liu et al. [62]	Yes	Elastic and failure response of imperfect lattices	To study the sensitivity of stress–strain curves to variations in relative density and defects	Regular octet and rhom-bicubocta-hedron lattices	AlSi10Mg	PBF
Li et al. [61]	Yes	Deformation behaviour of micro-lattice structures	Recommended varying PBF process parameters to achieve optimum mechanical properties	BCC	SS316L	PBF

Table 3. *Cont.*

Reference	FE Modelling/ Simulation	Research Focus	Suggestions/Challenges/ Future Work	Lattice Type	Material	AM Category
Li et al. [63]	Yes	Crushing behaviour of multi-layer metal lattice panel	Recommended considering boundary effect when designing lightweight lattice structure	BCCZ	AlSi10Mg	PBF
Leary et al. [23]	Yes	Mechanical properties of PBF lattices	Observed that experimental Young's modulus may underestimate actual in-service stiffness	BCC, BCCZ, FCC, and FCCZ	AlSi12Mg	PBF
Bai et al. [33]	Yes	AFCC lattice structure	To investigate the influence of SLM fabrication process on the mechanical performance of the Ti6Al4V structures.	BCC and AFCC	Ti6Al4V	PBF
Shen et al. [35]	No	Properties of lattice structures	Suggested lubricating the platens prior to conducting compression tests	BCCZ, BCC, and BCCZ-H	SS316L	PBF
Abele et al. [68]	No	DMLS process parameters customised for lattice structures	To investigate different lattice designs and materials	BCC	SS Powder (type was not specified)	PBF
Campanelli et al. [12]	No	Fabrication of micro-lattice structures to produce lightweight components	There is a high correlation between strut thickness and print quality	Pillar textile	Ti6Al4V	PBF
Maskery et al. [15]	No	Relationship between cell size and lattice performance	Proved applying post-manufacture heat treatment will improve the deformation process of aluminium lattices	Gyroid lattice	Al-Si10-Mg	PBF
Yánez et al. [13]	No	Mechanical behaviour of gyroid lattices with regard to their strut orientation	There is a high correlation between the strut angle and compressive strength	Gyroid lattice anddia-mond cubic	Ti6Al4V	PBF
Bai et al. [37]	Yes	Graded-strut design method—GBCC lattice model	Increasing the radii corner of a lattice structure willimprove its energy absorption	GBCC & BCC	Ti6Al4V	PBF
Ding et al. [38]	Yes	Mechanical properties and energy absorption capability of ARCH lattice	There is a high correlation between relative density and the mechanical properties and energy absorption capability of a lattice structure	ARCH lattice	SS316L	PBF
Xiao et al. [40]	Yes	Mechanical properties of TOP lattices	To further study TOP lattices and use the design to improve the energy absorption capability of lattice structures	TOP FCC, VC and ECC lattices	SS316L	PBF
Cao et al. [39]	Yes	Modified rhombic dodecahedron (RD) lattice structure	There is a high correlation between the shape of a lattice structure and its mechanical properties	RD lattice structure	SS316L	PBF

Table 3. *Cont.*

Reference	FE Modelling/ Simulation	Research Focus	Suggestions/Challenges/ Future Work	Lattice Type	Material	AM Category
Crupi et al. [66]	Yes	Mechanical response of micro lattices	Lattices fabricated via the DMLS process can be applied in the biomedical and transport engineering fields due to their cost effectiveness, good mechanical properties, and design flexibilities	BCC	Ti6Al4V	PBF
Endo [5]	Yes	Impact of manufacturing defects on the mechanical performance of polymer lattices	There was inconsistency/variation between CAD designs and fabricated structures	Cross-truss and octet-truss lattices	Polycarbonate	ME
Alghamdi et al. [36]	Yes	Automated analysis of microscope images method for the characterisation and quantification of manufacturing defects	To study the effects of residual stresses on AM fabricated metal components. Additionally, recommended further research to quantify the relationship between as-manufactured geometry and idealised CAD	FCC	Ti6Al4V	PBF
Arjunan et al. [65]	No	Thin and thick-walled auxetic structures	Recommended layer-based arrangements and careful modulation of t and θ for enhanced mechanical performance of auxetic structures	Auxetic lattices	AlSi10Mg	PBF
Alberdi et al. [69]	No	Influence of heterogeneous lattice topology lattice on mechanical performance	Recommended the use of multi-morphology lattices to achieve higher energy absorption performance	Multi-morphology lattices (FCC and BCC)	Vero white photopolymer and 316L stainless steel	PBF & MJ
Yang and Li. [44]	Yes	Cuttlebone-like lattice (CLL) structure	Recommended the adaption TOP lattices such as CLL for impact energy absorption applications	Cuttlebone-like lattice (CLL), Octet, BCC	AA6063, Ti6Al4V, and HSSG350	FEA

Finally, it has been found from the review of the published literature that less attention has been paid to metal lattice fabrication via the AM material extrusion (ME) methods. ME of metal parts offers another affordable means of fabricating metals compared to the powder bed fusion technique. Moreover, even with the prevalence of the material extrusion (ME) technique, AM researchers and designers are still concerned about the challenges associated with it. Notably, all positions identify challenges, such as first layer adhesion, warping, shrinkage, and support structure removal. However, it has been postulated that the ME process requires further research in order to optimise material utilisation without comprising on ME print quality. Regarding support structures, Kumar et al. [56] recently proposed the SU lattice for the ME process; while this is a good alternative, it is relatively new in the AM world, and would require further study to understand its mechanical properties and possible introduction into other AM technologies.

Author Contributions: Conceptualization, S.O.O. and K.I.K.; methodology, S.O.O.; formal analysis, S.O.O.; investigation, S.O.O.; resources, S.O.O. and K.I.K.; data curation, S.O.O.; writing—original draft preparation, S.O.O. and K.I.K.; writing—review and editing, S.O.O. and K.I.K.; visualization, S.O.O.; and supervision, K.I.K. Both authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study does not report any data.

Conflicts of Interest: The authors declare no conflict of interest.

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