International Journal of Computer Integrated Manufacturing

ISSN: 0951-192X (Print) 1362-3052 (Online) Journal homepage: https://www.tandfonline.com/loi/tcim20

Design, analysis and manufacturing of lattice structures: an overview

Mark Helou & Sami Kara

To cite this article: Mark Helou & Sami Kara (2018) Design, analysis and manufacturing of lattice structures: an overview, International Journal of Computer Integrated Manufacturing, 31:3, 243-261, DOI: 10.1080/0951192X.2017.1407456

To link to this article: https://doi.org/10.1080/0951192X.2017.1407456

Published online: 03 Dec 2017.

INTERNATIONAL JOURNAL OF COMPUTER INTEGRATED MANUFACTURING, 2018
VOL. 31, NO. 3, 243–261
https://doi.org/10.1080/0951192X.2017.1407456

Taylor & Francis
Taylor & Francis Group

ARTICLE

Check for updates

Design, analysis and manufacturing of lattice structures: an overview

Mark Helou and Sami Kara

Sustainable Manufacturing and Life Cycle Engineering Research Group, School of Mechanical and Manufacturing Engineering, The University of New South Wales, Sydney, Australia

ABSTRACT

A lattice structure is a space-filling unit cell that can be tessellated along any axis with no gaps between cells. These structures are an emerging solution to weight, energy and advanced manufacturing time reduction. To date, there is no compilation of literature or state-of-the-art reviews in the lattice structure field due to their prevalence across a wide range of research areas. A systematic review would therefore aid in identifying the wide scope of lattice structure design and applications. The objective of this extensive review is to provide a summary of lattice structure literature as well as determine the latest research trends, in an attempt to identify future areas of investigation. Through the conducted research, significant limitations were identified in the lattice structure definition; a redefinition is proposed with the inclusion of a reference system as well as widening the scope to include scaled unit cell tessellation as a primary topology. This compilation of limitations and future work might provide a clearer understanding of technological and theoretical limitations regarding lattice structures, as well as highlighting areas of further research required in the design, design analysis, manufacturing, application and characterisation areas of lattice structures.

ARTICLE HISTORY
Received 24 May 2017
Accepted 1 November 2017

KEYWORDS
Lattice structures; advanced manufacturing processes; finite element analysis; additive manufacturing; free form surfaces

1. Introduction

Lattice structures are defined in literature as objects that are periodic in nature, continuously repeating unit cells that interconnect in three dimensions. They are typically created from truss structures, as well as minimalistic surfaces (Gorguluarslan et al. 2016; Zok, Latture, and Begley 2016; Helou, Vongbunyong, and Kara 2016; Gandy et al. 1999, 2001; Gandy and Klinowski 2000b; Gandy and Klinowski 2000a; Deshpande, Fleck, and Ashby 2001).

These structures have become more prominent recently due to the advancements in additive manufacturing, used as an attempt to achieve four major goals:

(1) Reduce the amount of material utilised in the manufacturing process
(2) Reduce the amount of time taken to produce an object
(3) Reduce the amount of energy utilised in the manufacturing process
(4) Optimise the strength of the produced object while minimising the weight

As a result of achieving these goals, the structures also are extremely useful when considered in product life cycles. They are particularly beneficial in minimising material wastage, energy consumption during manufacturing and are able to be recycled easily, particularly when comprises a single material. The issues that arise in the areas of manufacturing energy, material and time optimisation have specifically been targeted through the use of lattice structures in a wide range of ways, requiring a summary of the existing published research and innovation, as well as a summary of the latest trends in structure research in order to identify potential future research areas.

Lattice structures fill a niche in manufacturing. They not only satisfy requirements of weight, energy and time reduction but also allow for other extremely useful side effects to be leveraged. Some of these include energy absorption, acoustic and vibrational damping, high strength-to-weight ratios and thermal management capabilities. Lattice structures are widely known for their energy-absorption capabilities (Tancogne-Dejean, Spierings, and Mohr 2016; Helou, Vongbunyong, and Kara 2016; Li, Stephani, and Kang 2011). These properties have been utilised successfully in vehicular collision tests (Hou et al. 2017; Lee, Ma, and Kikuchi 2008).

Another way the energy-absorption feature of lattice structures is utilised is through the use of hollow trusses. Hollow trusses are used in the design of lattice structures, proven to result in a higher load carrying capacity in a specimen when compared to a solid truss, due to the higher second moment of inertia (Wadley 2002). Hollow trusses also show potential to even surpass the energy-absorption capabilities of other solid lattice structures (Evans et al. 2010). Hollow lattice structures are also very useful for energy-absorbing systems due to the specific energy absorption being higher than that of honeycombs when comparing relative density and material (Evans et al. 2010).

Acoustic and vibrational damping are also very useful features that have been capitalised on. Structures can be filled with materials such as rubber (Yin et al. 2014) and polymers (Murray, Gandhi, and Hayden 2012; Murray and Gandhi 2013). Filling the structures with such materials can reduce the amount of

CONTACT Mark Helou m.helou@student.unsw.edu.au

deformation undergone by a structure under load (Murray, Gandhi, and Hayden 2012) while increasing the Young's modulus of the overall shape (Murray and Gandhi 2013).

Lattice structures are also fairly well known to maintain relatively high levels of strength, even though they are lighter than a comparable solid object. There are a variety of ways that have been discovered that can increase the relative strength of lattice structures. These methods include being manufactured with diameters of only a few microns wide, which results in higher strength when compared to a pure copper material (Wendy Gu and Greer 2015), and being coated with alumina (Bauer et al. 2014). These structures are also effectively used in thermal management, proven to be suitable for multifunctionality, actively cooling while also serving as a load-bearing and energy-absorbing object (Maloney et al. 2012; Wadley and Queheillalt 2007; Tian et al. 2007). There has also been research conducted to find a multi-objective optimal trade-off between the thermal management, density, strength and stiffness (Roper 2011; Valdevit et al. 2006).

Lattice structures have, in the past, been easy to fabricate in the meso (ranging from 0.1 to 5 mm) and macro (>0.5 mm) scales due to the ease of large-scale manufacturing, particularly when compared to micro (100 nm to 100 μm) and nano (<100 nm) scale products. These have been used in civil engineering projects, such as bridges, due to their ability to distribute load and withstand large stresses; behaviour that is leveraged in modern literature (Huang and Xie 2008).

These structures are also commonly featured in the microscale, utilised in the medical industries in the creation of implants (Murr et al. 2010, 2011).

Recently, development of nanoscale fabrication technology has allowed the manufacturing of nanoscale lattice structures (Tancogne-Dejean, Spierings, and Mohr 2016), which exhibit features that are particularly unique. When manufactured at the nanoscale, hollow lattice structures can provide a constant stiffness per unit mass density and a Young's modulus-to-density ratio that is comparable to solid specimens (Zheng et al. 2014).

Examples such as these show that the rise in additive manufacturing technologies directly corresponds to the increase of lattice structure usage due to their new ease of manufacturing in micro and nanoscales. However, due to the reliance on additive manufacturing methods, the fabrication of lattice structures is limited to the restrictions of additive manufacturing processes. These processes are limited in manufacturing speed, build space and resolution. To date, there are no economically viable high-volume manufacturing methods for the production of lattice structures in literature.

Although lattice structures have in the past been able to be created using traditional manufacturing methods, fabricating such complex objects has been fairly limited due to the inability to leverage traditional manufacturing processes to create structures without requiring labour-intensive assembly processes. Weaving, braising and casting are all traditional processes that can be utilised to manufacture lattice structures in the mesoscale; however, they struggle to create microstructures. Lattice structure unit cell sizes are generally limited to a minimum size of approximately 2–5 mm in methods such as selective laser sintering (SLS); however, smaller cell sizes can be achieved using hybrid manufacturing techniques such as photo-polymerisation and electro-deposition plating (Evans et al. 2010). When compared to additive manufacturing, these traditional manufacturing methods are superior in creating large-scale lattice structures such as those seen in bridges (trusses), due to the ease of structure approximations in larger applications.

A significant amount of progress in additive manufacturing fields has enabled researchers to reliably manufacture lattice structures and vary parameterised cell designs to research their behaviours. Although 3D printing is not a relatively new process (Kruth 1991), commercial pressure and advancement in materials (Kruth, Leu, and Nakagawa 1998) have pushed the technology to progress to allow for the creation of structures with greater accuracy and in higher volume, with an ever-increasing amount of additive manufacturing techniques. Previously, there were build volume restrictions that limited the size of lattice structures, preventing larger objects from being manufactured, accompanied by limitations in manufacturing methods (such as extrusion diameters and laser focusing diameters). Progressive research in advanced manufacturing has allowed for advancements in the technology. Examples of such developments include the production and utilisation of smaller diameters of material wire spools, particularly used in processes such as fused deposition modelling (FDM), as well as developments made in the tighter focusing of lasers used in the curing process of SLS-like processes.

Although there is much research being conducted on additive manufacturing processes, there are many issues related to the application of the manufacturing techniques of lattice structures. Additive manufacturing processes have an immense impact on the form and functionality of the specimen being produced. Due to the inherent nature of manufacturing methods such as selective laser melting (SLM) and SLS, there can be many issues with a specimen when additively fabricated, including a significant loss in the material stiffness and strength (Gümrük and Mines 2013). The additively manufactured specimens are also very sensitive to small imperfections during building (Gümrük, Mines, and Karadeniz 2013), which can cause premature failure, particularly when accompanied with fracture propagation using the SLS method (Helou, Vongbunyong, and Kara 2016). There are also issues in the inherent strength of lattice structures; in literature, whenever a lattice structure is manufactured using the SLS method, it is assumed that the lattice structure was a homogeneous solid (Gorguluarslan et al. 2016). This has been reported to be an inaccurate assumption (Helou, Vongbunyong, and Kara 2016).

It is common to produce lattice structures using traditional manufacturing methods. The creation of lattice structures via traditional manufacturing methods are limited to only some specific cells; complex designs such as the Kagome cell can only be made using a limited amount of traditional manufacturing techniques such as investment casting (Wadley, Fleck, and Evans 2003) and weaving (Kang 2015), often requiring multiple post-processing techniques to finish production.

Although there is a large amount of lattice structure designs currently available, a significant amount of them are drawn from pre-existing structures; that is, there is a lack of innovative lattice structure designs that are specific to different situations. It is important to have a large amount of potential lattice structures for any given purpose to be utilised in innovative and unique designs, exploiting the innate natures and benefits of the lattice structure (Evans et al. 2010; Ozdemir et al. 2016; Tancogne-Dejean, Spierings, and Mohr 2016; Zheng et al. 2014).

2. Methodology

More than 80 publications were initially reviewed. After careful consideration, 45 of them were selected and analysed to establish the different unit cell designs, manufacturing processes and materials utilised. Literature was located through the use of the SCOPUS database as well as extensive Google Scholar searches to ensure literature from a wide range of research fields was utilised, extending from the past 50 years to the present. The literature was classified into different categories depending on their main area of research (Figure 1).

3. Definition of lattice structures

Typically, lattice structures are composed of two different topologies, stochastic or periodic. Stochastic lattice structures are those such that their distribution of cells and shapes is defined through a random probability distribution. These randomised structures can be analysed and approximated statistically but cannot be recreated or predicted precisely. Such types of structures include those present in bone structures, cellulose aggregates in wood or collagen aggregates in cartilage (Brooks et al. 2005).

As seen in the honeycomb lattice structure, periodic lattice structures can have their topology repeated along two separate axes. They can also have their topology repeated along three separate axes, as seen in triply periodic minimalistic surfaces (TPMS) structures (Gümrük, Mines, and Karadeniz 2013). Periodic lattice structures are created as functions of their inherent geometric properties such as cell dimensions, angle, quantity and final object boundaries. Examples of periodic truss structures include the octet truss lattice structure (Deshpande, Fleck, and Ashby 2001) and the gyroid (Schoen 1970).

There exists literature that attempts to define an overarching definition of what constitutes a lattice structure; however, they have a large amount of shortcomings. Typically, the definitions ignore stochastic lattice structures due to their random nature and instead concentrate on periodic structures. In an attempt to separate lattice structure definitions and terminology from crystallographic-based ones, redefinitions concentrate on polyhedra-based terminology (Zok, Latture, and Begley 2016). However, basing the definition on truss structures leaves a gap in the literature, limiting the definition by restricting the scope to non-stochastic and non-minimalistic surface-based lattice structures, thereby concentrating on properties that are only present in truss structures such as rotational transformations, translational shifts and nodal locations to generate a unique name for each structure via the naming convention (Zok, Latture, and Begley 2016).

Due to the fact that lattice structures appear in varied disciplines such as structural and civil engineering, biological and material sciences and crystallography, there are conflicting definitions of what a lattice structure is. Repeatedly throughout literature, lattice structures are described as 'space-filling' structures that are structurally, 'space efficient' (Dong, Deshpande, and Wadley 2015). Space-filling structures, or close packing structures, are three-dimensional solids that are able to copy themselves in any axial direction. This space filling, or tessellation, traditionally comprises primarily polyhedra and space-filling, RN127 curves. In the context of lattice structures, it is beneficial to remove the limitation of the term in primarily targeting polyhedral solids and instead redefining the term to describe any repeatable solid or 'structure' that can be tessellated with no gaps.

These lattice structures are theoretically infinitesimal in size; however, physical manufacturing has been able to create

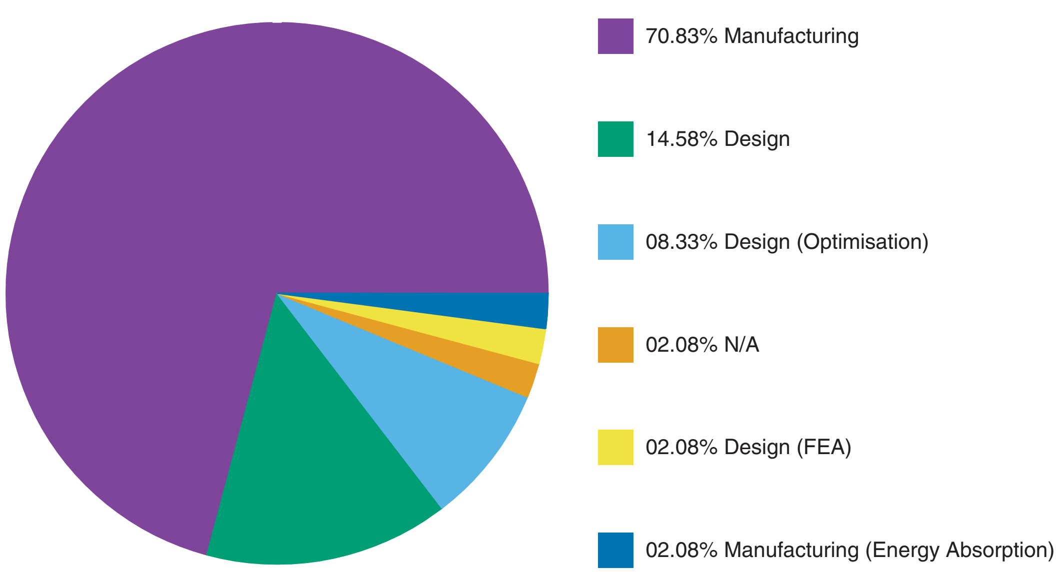

Figure 1. Classifications of literature areas that lattice structures are found in – as summarised in Table A1.

structures ranging from the nanoscale to large scale through a variety of traditional manufacturing methods, as well as a growing amount of advanced manufacturing methodology (Tancogne-Dejean, Spierings, and Mohr 2016). The concept and need for lattice structures comes from the same requirements that sparked the advanced manufacturing industry, namely only putting material where it is needed to create an object (Gorguluarslan et al. 2016).

There exists no classification of lattice structures that, despite being stochastic or periodic in nature, their main topology is primarily dictated by scaled tessellations of their unit cell (The core 'kernel' of the structure). The extent of the structure scaling is directly related to the distance being tessellated across. For example, as seen in Figure 2, the tessellating bone unit cell is larger in the centre of the bone (the cancellous bone region), and as it is arrayed radially towards the wall, the unit cell is scaled down until a solid region of bone (cortical bone) is formed. The bone lattice structure, although stochastic, predictably begins to be scaled down towards the wall depending on the functional requirements of the specific bone.

Any lattice structure must be generated with reference to a plane or axis. There currently exists no definition in which the structure generated has a clearly defined reference system; it is generally assumed that the structure is generated in reference to a normal Cartesian coordinate system. However, this is not beneficial in all cases. In the case of a bone structure, the primary axis can be said to be the vertical Z axis due to the vertical loading placed upon it; with secondary transverse X and Y axes performing impact resistance (refer to Figure 2). Therefore, it is suggested that the definition of a lattice structure be expanded in order to accommodate the lack of reference system as well as incorporate a scaled unit cell tessellation topology as a classification. In the context of redefinition, in each specific case of any lattice structure being generated, it is important to note which axis and plane are the primary ones, in order to then further define any variable angles that are utilised within the generation of the lattice structure itself.

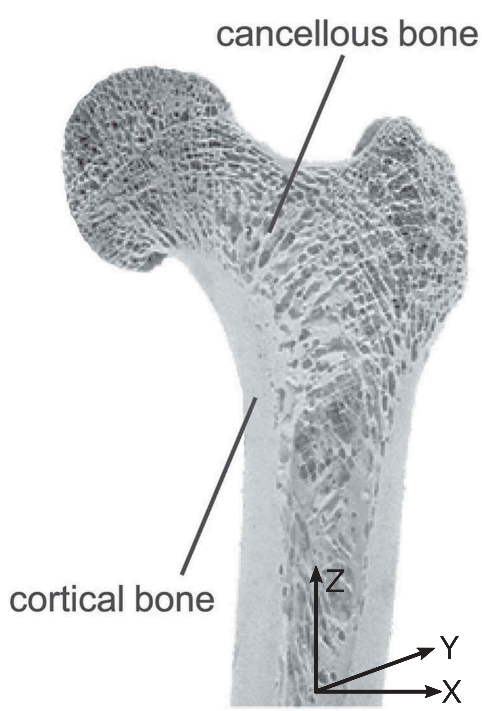

Figure 2. Bone structure SEM (Willems et al. 2014).

For the purposes of this paper, the following definition of a lattice structure is proposed. A lattice structure is a space-filling unit cell that is able to be tessellated along any axis with no gaps between cells. The structures are able to be parameterised based on geometry, scale and volume, with either a stochastic, periodic or gradient-dependant topology. They are defined by a reference system that is based on the functional requirements of the end application of the structure.

4. Applications and benefits

The benefits of lattice structures are exploited throughout a variety of industries, in particular, the medical industry. Due to their maximisation of surface areas, lattice structures can be particularly useful in the characterisation and production of scaffolds optimised for tissue and bone replacement in order to encourage osseointegration (Dantas et al. 2016; Yoo 2011). There has also been research put into the accurate recreation of cancellous and cortical bone structures through the variation of density scaling parameters, in particular optimising characterisation and modelling for additive manufacturing (Dumas, Terriault, and Brailovski 2017). They are very useful in minimising material requirements during implantation, drastically decreasing invasiveness and recovery time.

Applications of lattice structures in the automotive industry have also been applied in an attempt to decrease noise conduction, increase weight reduction and also increase the ease of recycling automotive parts (Borsellino and Di Bella 2009). The aerospace and Aeronautic industries also leverage the benefits of lattice structures, aiming to increase the performance-to-weight ratio of parts to increase the efficiency of aeronautical and aerospace vehicles (Frulloni et al. 2007). The structures are utilised in the creation of strong and lightweight parts in the industry such as payload adaptors (Del Olmo et al. 2012; Vasiliev, Barynin, and Razin 2012) and also fuselages skins and beams (Vasiliev, Barynin, and Razin 2012).

The energy-absorption properties of the lattice structures are also leveraged, in particular for protective applications. As the lattice structures are able to propagate energy through their structure, they are very useful in distributing an impact shock across the object and therefore serve as a sacrificial protection (Ozdemir et al. 2016; Evans et al. 2010). Auxetic lattice structures which posses negative Poisson's ratios are particularly useful in absorbing energy (Yang et al. 2012). Furthering these energy-absorption properties, there are also some structures that feature multiple yield points as they are compressed (Helou, Vongbunyong, and Kara 2016). This behaviour can be exploited to provide more protective capabilities of structures and objects, which could be particularly useful in the automotive and aerospace industries.

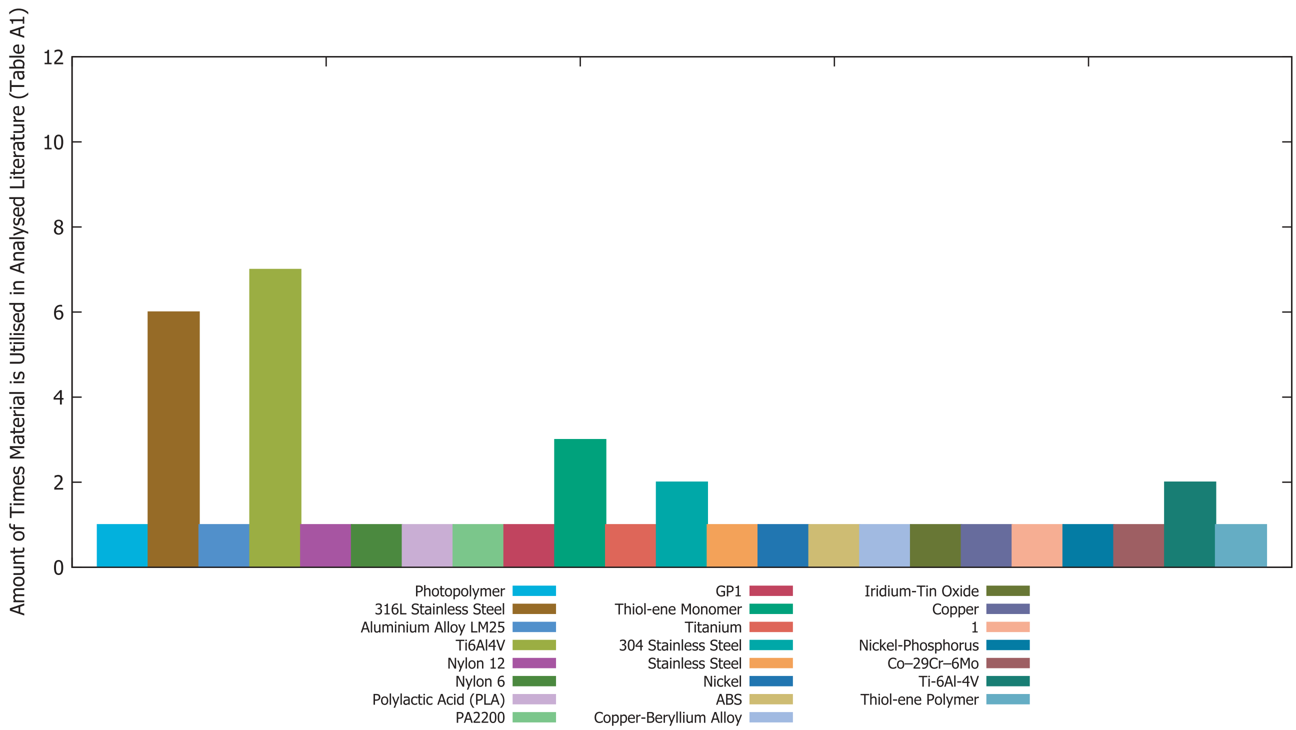

Figure 3. Differing materials utilised in lattice structure manufacturing in literature – as summarised in Table A1.

5. Manufacturing processes

Lattice structures can be created through either traditional methods, such as water-jet cutting, weaving and braising, or through advanced manufacturing methods such as SLS, SLM and electron beam additive manufacturing (EBAM).

Traditional manufacturing processes are useful for creating lattice structures due to the prevalence of the technologies, as well as having many experts in their utilisation. Unlike additively manufactured lattice structures, traditionally manufactured unit cells must be individually created and later assembled to form a final structure. Water-jet cutting is a highly precise manufacturing method that utilises a jet of pressurised water to cut through metal and plastic sheets. Lattice structures are created through this process, capitalising on the precision of water-jet cutting to allow press fitting segments to be assembled together into a final lattice structure (Dong, Deshpande, and Wadley 2015). However, this process is limited, as the segments must be bonded for strength in the structure. This issue is typically overcome through the process of braising to permanently fix the segments together.

The braising process is also utilised in other processes such as weaving, due to the lack of strength and increased flexibility of the structure inherent of the process. The metal textile technology of weaving is practically identical to the traditional process of weaving of fabrics albeit with the use of any metal alloy that can be drawn into a flexible wire. Weaving of metal and plastic wires can be utilised to create lattice structures; however, without braising and fixing the nodes of each intersecting wire, the fabric itself is too flexible, causing irregular spacing between unit cells (Wadley, Fleck, and Evans 2003).

Additive manufacturing, although only comprises a singular process, undertakes many approaches to achieve the same final product. The basis of most additive manufacturing processes involves the laying down of material in a two-dimensional layer and applying a successive layer on top. This procedure is repeated until the final object is completed. The additive manufacturing process can be defined by seven different manufacturing processes: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerisation (ASTM International 2016). The material extrusion process utilises the controlled application of a material, typically through heat. An example of this process is FDM, which uses a wire that is uncoiled and heated into strands that are layered on top of each other to produce a final object (Masood and Song 2004). The vat photopolymerisation process utilises an ultraviolet light to cure a photopolymer or other material to produce the intended structure (Schaedler et al. 2011). An example of this process is photopolymer wave-guide prototyping, which uses a photo-monomer material and a photopolymer wave guide to produce the 3D geometry. These processes use a limited amount of materials in the manufacturing of lattice structures (Figure 3).

Additive manufacturing processes are more adaptable and precise in comparison to traditional manufacturing methods due to the fact they are able to manufacture lattice structures by only placing material where it is required and being able to join multiple layers of lattice structures together without further strength and flexibility post-processing such as braising which is required in traditional manufacturing processes. The two main additive manufacturing processes utilised in the creation of lattice structures are powder bed fusion technologies such as SLS and SLM, as can be seen in Figure 4. Both SLS and SLM processes have been able to be applied to materials such as bronze, steel, titanium and aluminium (Kruth, Leu, and Nakagawa 1998); however, only SLS is able to additively

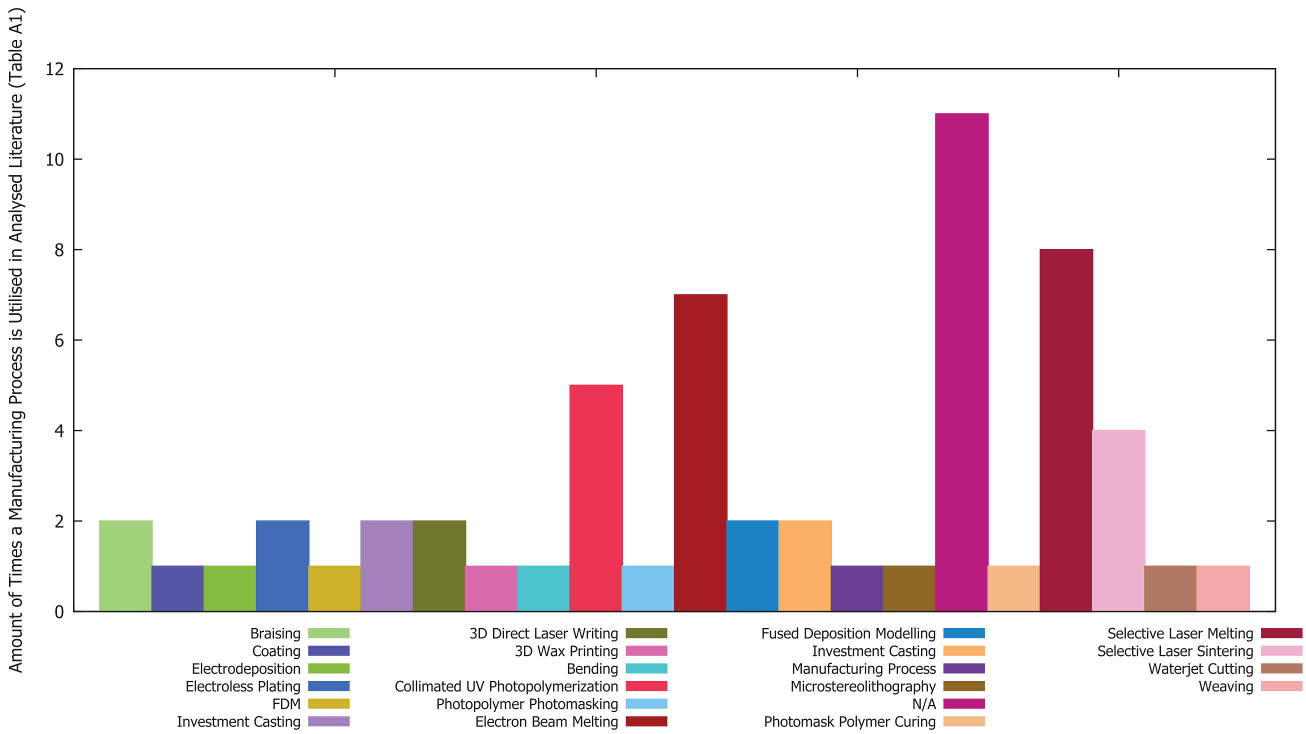

Figure 4. Manufacturing methods utilised in literature – as summarised in Table A1.

manufacture parts out of plastics and ceramics. The SLS and SLM manufacturing methods have been utilised to produce a variety of lattice structures (Helou, Vongbunyong, and Kara 2016; Gorguluarslan et al. 2016; Tancogne-Dejean, Spierings, and Mohr 2016; Gümrük and Mines 2013; Gümrük, Mines, and Karadeniz 2013; Yan et al. 2014) exploiting the accuracy of the additive manufacturing technology accompanied by the quick manufacturing turnaround. Both processes are essentially the same with a few distinct differences. The SLS process utilises atomised powders, or very small-sized particles of material, sintering through the heat produced from the laser. The porosity of the part is able to be controlled by precisely and repeatedly heating the powder to the point where the powder fuses together. This process binds the particles together successively in layers to produce the final object (Chua, Leong, and Lim 2010). However, the SLS process causes voids and inaccuracies to be created within the part that may cause premature failure (Helou, Vongbunyong, and Kara 2016). In contrast, SLM allows the powder to be heated to the melting point, creating a homogeneous part; however, this process can only be utilised on parts created from a non-alloy metal.

Other additive manufacturing methods such as EBAM, another powder bed fusion technology, are also very commonly utilised (Figure 4) to produce lattice structures, in particular due to the faster production speeds but at the cost of a lower surface quality (Li et al. 2012; Ozdemir et al. 2016). EBAM is extremely similar to the SLS and SLM processes, in that it utilises the exact same work flow; however, instead of utilising a laser, the processes utilises an electron beam as a heat source under a vacuum. The electron beam fully melts each layer making it more similar to SLM than SLS; however, it has the same material limitations of SLM, being able to only utilise metals.

The sheet lamination, material jetting, binder jetting and directed energy deposition additive manufacturing technologies are not very commonly seen in the production of lattice structures. Only a single article has been published in the production of lattice structures using directed energy deposition (Plotkowski et al. 2017), whereas two have been published using binder jetting (Druschitz et al. 2014; Tang et al. 2016).

There is an extremely large number of issues with lattice structures that are inherent with both traditional and advanced manufacturing processes. There currently does not exist a method to produce lattice structures in high volume, with unit lengths 10 cm or larger. Many attempts have been made to design processes for large-scale lattice structures using traditional manufacturing methods such as braising, weaving and water-jet cutting (Anderson 2016; Wadley, Fleck, and Evans 2003; Queheillalt, Deshpande, and Wadley 2007; Zok et al. 2003; Dong, Deshpande, and Wadley 2015); however, they are extremely inefficient at creating larger scale structures due to the manual post-processing that is required. Additive manufacturing build size limitations are prohibitive in producing larger scaled homogeneous lattice structures.

There is an issue in the additive manufacturing of lattice structures in different materials due to the inherent properties of the processes. In the SLS, SLM and EBAM processes, any overhanging geometry must have support structures created for it, in order for the manufacturing processes to complete successfully, so the integrity of the lattice structure is not compromised. The SLS process is able to manufacture any part in plastic material due to there being no requirement of support in the manufacturing processes, as well as the plastic powder itself acting as structural support.

Although there are many examples of high-volume manufacturing techniques utilised in the manufacturing of lattice structures, including investment casting, foaming and wire forming (Figure 4), there is no reliable evidence of any defined processes that are used to reliably produce consistent lattice structures at a high-volume rate for mass manufacturing. Further, there is little evidence of lattice structures being manufactured at high volume for large-scale projects without requiring assembly.

6. Lattice structure design

In order for a lattice structure to be fully defined, the unit cell must be fully characterised in terms of fully describing the structure design, the method of generation and the inherent properties.

A significant amount of existing lattice structure cells are extracted from structures found in traditional geometry, such as the octet truss (Richard 1961) or the Kagome Lattice (Trihexagonal Tile) (Hyun et al. 2003). An in-depth study of existing literature shows that there currently exists only a relatively small amount of lattice structures (<40), of which a significant amount are slight variations of other existing cells. Due to this, a definition of what classifies a structure to be counted as a 'new' structure as opposed to an 'existing' structure needs to be developed to prevent variations of existing structures being labelled as a 'new' design. Further, there needs to be an extensive investigation into currently existing lattice structure designs in order to classify each structure as a unique 'new' design or a variation of an 'existing' structure. This means proper classifications need to be set up to define what satisfies a move from an 'existing' structure to a 'new' structure.

Each cell type should in theory possess unique capabilities that make them superior to other cells in a certain way, such as increased energy absorption or relatively high strength to weight ratios. However, in literature, almost all experiential publications of lattice structures do not conduct a design of experiments in order to properly analyse the effects that differing design variables contribute to the strength of the structure. Due to this, there is a significant lack of design data and statistical analysis to allow the generalisation of cell properties in regards to the inherent strengths and weaknesses of the structure. Without this data, it is difficult to predict and validate the capabilities of a given lattice structure when simulating the performance using finite element analysis (FEA), as well as determining where efficiency compromises can be drawn. Predicting when a decrease of the unit cell size begins to provide diminishing returns in terms of compressive strength or energy absorption is also currently problematic due to lack of comparable results in literature.

There are a limited amount of commercial software tools available to aid in the design of lattice structures. These include packages such as Autodesk Within Medica (Autodesk, Inc., USA), Materialise Magics (Materialise NV), nTopology Element (nTopology, Inc., USA) and Simpleware CAD (Simpleware, Exeter, UK), as well as software plugins such as IntraLattice. The issues prevalent in these software packages include limited flexibility in merging lattice structures with objects, a small selection of lattice cell types available, a lack of FEA integration, as well as limited optimisation capabilities.

There are a number of methods that are utilised to generate lattice structures in literature. These are broken down into two different categories, manually generated and mathematically generated.

A manually generated lattice structure is created through the utilisation of beams and truss structures, with joints modified to create seamless transitions between unit cell elements. Octet trusses (Deshpande, Fleck, and Ashby 2001) and rhombicuboctahedrons (Wettergreen et al. 2005) are examples of manually created lattice structures.

Current literature does not describe any method of approximating manually generated structures in order to minimise these post-processing issues that exist with manually generated structures. Mathematically generated lattice structures are created with algorithms and constraints, utilising mathematically described patterns and surfaces to create a lattice structure. These structures, in contrast to manually created ones, do not need any post-processing to connect the structures as they are in most cases periodic. Examples of mathematical procedures of generation include nodal approximation (Gandy et al. 2001), variational level set approaches (Jung, Chu, and Torquato 2007) and Weierstrass formulas (Wang 2007).

As can be seen by comparing Sections 6.1 and 6.2, a majority of the lattice structure unit cells are manually created, as the bulk of mathematically created structures are variations of a single unit cell algorithm. Although there are a large amount of mathematical patterns that may be able to be leveraged in order to create more mathematically generated lattice structures, there is currently no relevant literature that outlines a 'rule of thumb' to successfully convert a mathematical pattern into a lattice structure.

6.1. Manually generated structures

There are a large amount of manually generated structures, as seen in Figure 5. They are simplistic in nature and can be broken down to very basic geometric shapes. Due to their simplicity as well as being able to parameterise most of the structure, manually generated structures are very prevalently utilised in literature. As shown in Figure 6, the majority of lattice structures utilised in literature are manually generated.

Comparing structure designs in Figure 6 shows that a significant amount of designs are variations of another more basic design. The reinforced body centric cubic structure (Figure 5(m)) can be approximated through the combination of two other structures, the body centric cubic structure (Figure 5(l)) and the Cross 1 symmetric structure (Figure 5(f)). Further, the hierarchical single layer pyramidal truss structure (Figure 5(p)) is a variation of the pyramidal structure (Figure 5(j)).

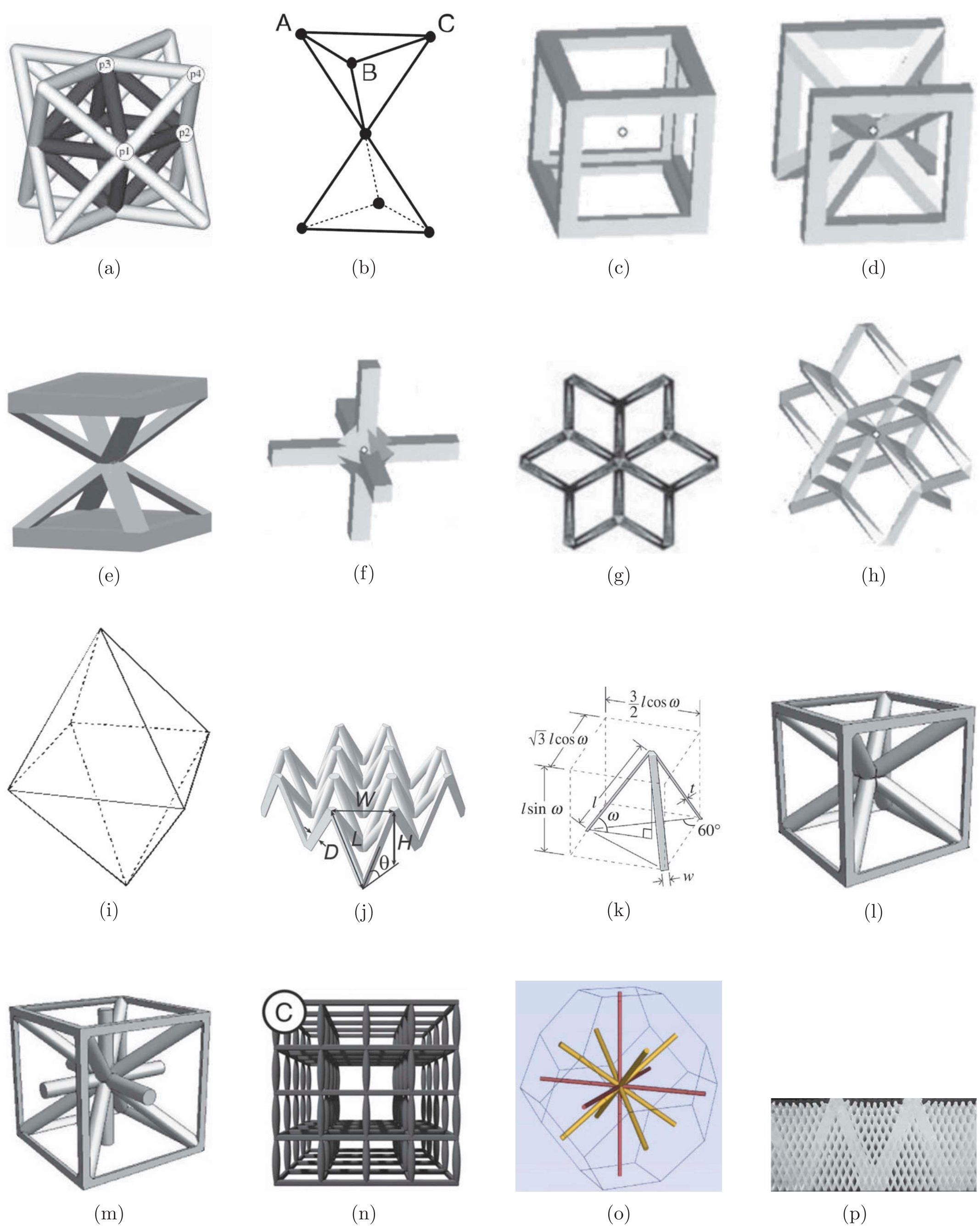

Figure 5. Examples of manually generated lattice structures. (a) Octet truss (Deshpande, Fleck, and Ashby 2001). (b) 3D Kagome structure (Hyun et al. 2003). (c) G6 structure (Murr et al. 2010). (d) G7 structure (Murr et al. 2010). (e) G7R structure (Li et al. 2014). (f) Cross 1 symmetric structure (Murr et al. 2010). (g) Dode thin 2D slice (Murr et al. 2010). (h) Dode thin 3D structure (Murr et al. 2010). (i) Octahedral-type structure (Jacobsen, Barvosa-Carter, and Nutt 2007b). (j) Pyramidal structure (Hammetter, Rinaldi, and Zok 2013). (k) Tetrahedral structure (Wadley 2006). (l) Body centric cubic structure (Pettermann and Hüsing 2012). (m) Reinforced body centric cubic structure (Pettermann and Hüsing 2012). (n) Orthotropic cubic structure (Bauer et al. 2014). (o) Regular truncated octahedron structure (Gurtner and Durand 2014). (p) Heirarchial single layer pyramidal truss structure (Doty, Kolodziejska, and Jacobsen 2012).

Simple lattice structures can be recreated through the utilisation of a simple network structure frame and transforming it into a watertight geometric structure. This allows for powerful variations of parameters to create differing structures from a single source structure.

In comparison to mathematically generated lattice structures, manually generated structures require multiple steps in their creation. After generating the geometry based on the structure frame, a significant amount of post-processing is required in order to refine and simplify the mesh. Unless the structure is further processed, the structure can possess non-filleted edges that can cause stress concentrations and premature structure failure, as seen in Figure 7(b) detail C. There is also the issue of inconsistent transitioning between curved and straight geometrical faces, as seen in Figure 7(b) details A and B, which can cause further issues when the geometry is utilised in further processes.

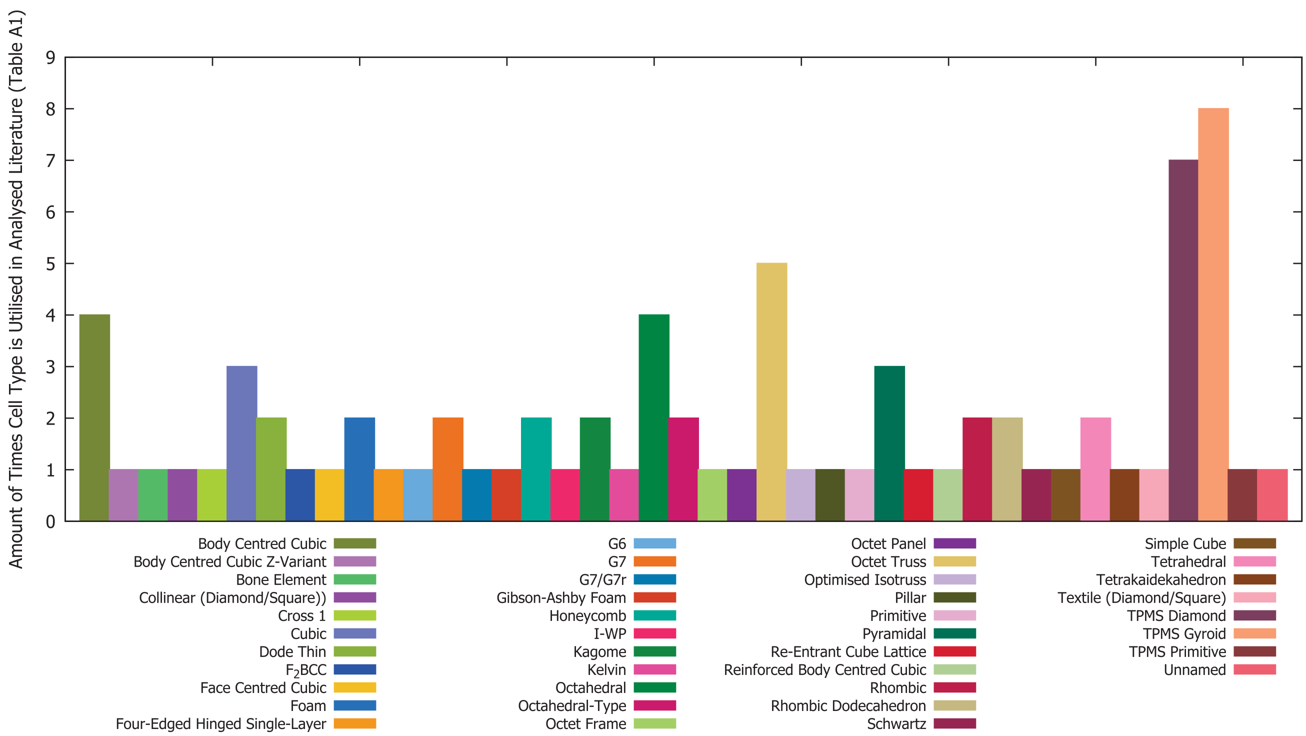

Figure 6. Differing types of lattice structure cells found in literature – as summarised in Table A1.

6.2. Mathematically generated structures

6.2.1. Triply periodic minimalistic surfaces

TPMS are minimal surfaces, which are a subset of hyperbolic surfaces. A hyperbolic surface is one created utilising hyperbolic geometry. The main difference between a surface in normal Euclidean geometry and hyperbolic geometry is that in hyperbolic geometry, there are at least two distinct lines that pass through a given point and are parallel to a given line. Alternatively, Euclidean geometry has exactly one line through a given point in the same plane as a given line which is never intersected.

A minimal surface is defined as a surface in hyperbolic space which possesses a mean curvature or zero. TPMS are defined as minimal surfaces that are infinitely periodic in all three axes in 3D space, with a crystallographic space group as its symmetry group (Wang 2007; Gandy et al. 2001). They also have their topology partitioned into two regions that penetrate each other to form a single surface (Lord and Mackay 2003). TPMS are described as surfaces that are free from self-intersections, which proves to be useful to additive manufacturing. A surface that is free of self-intersection is said to have the whole surface contained within bounding constraints denoted as the convex hull of the surface's boundary curve (Schoen 1970). Although TPMS are always defined to be periodic, they are not necessarily always non-self-intersecting (Schwarz 1890). Examples of such structures can be seen in Figure 8.

TPMS can be generated in multiple ways, such as Weistreass formula evaluations, nodal approximations of the Weistreass formula and numerical generation (e.g.

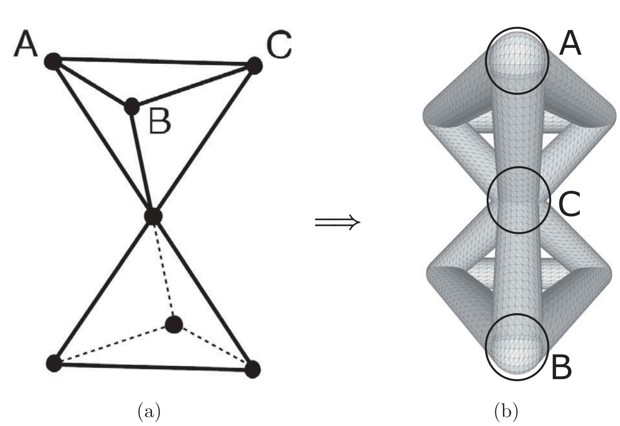

Figure 7. Conversion from structure frame to (problematic) geometry. (a) 3D Kagome structure (Hyun et al. 2003). (b) Geometric Kagome structure with problems.

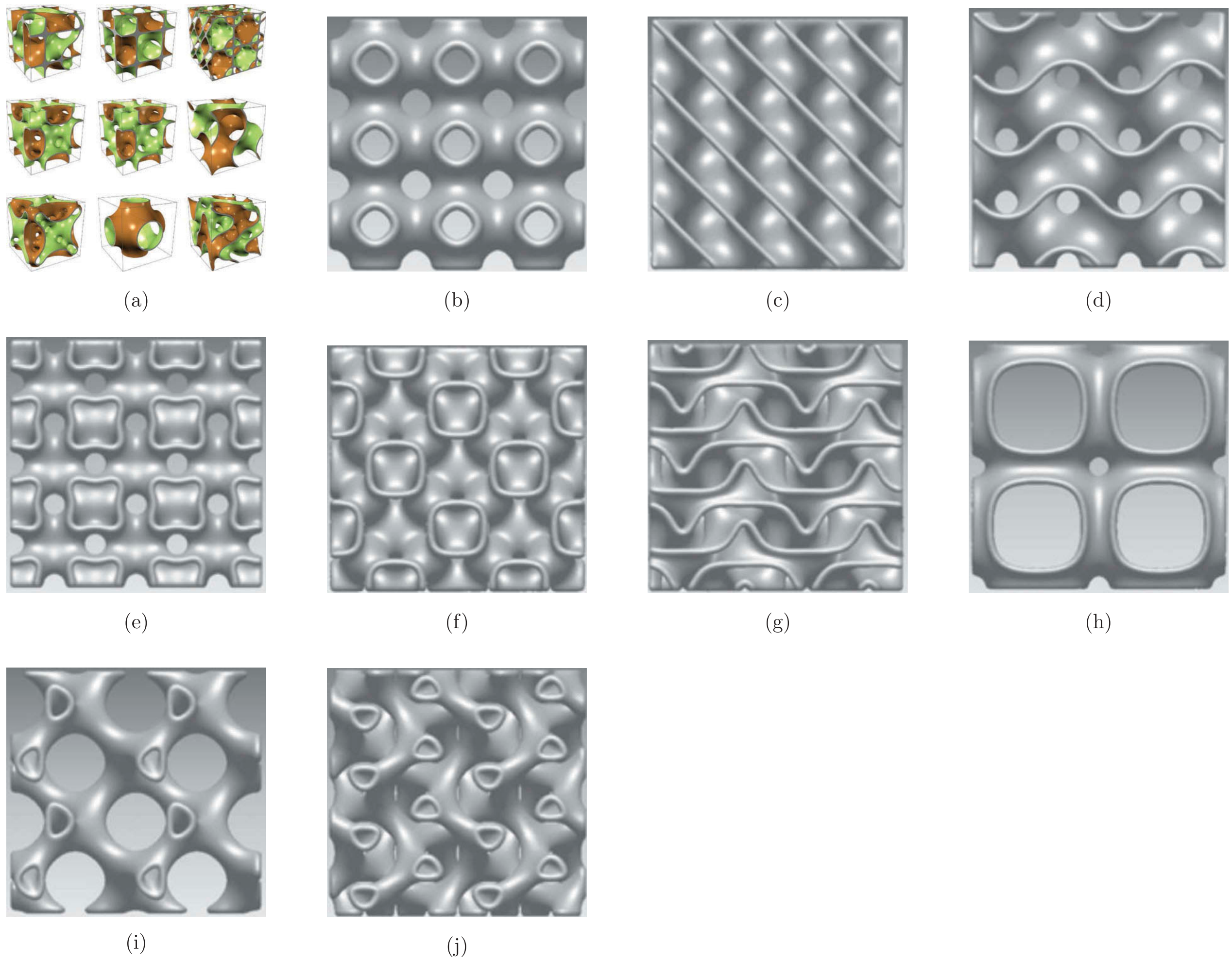

Figure 8. Examples of mathematically generated lattice structures. (a) TPMS lattice structures. (b) P- type TPMS lattice structure. (c) D- type TPMS lattice structure. (d) G- type TPMS lattice structure. (e) I- WP type TPMS lattice structure. (f) F- RD type TPMS lattice structure. (g) L- type TPMS lattice structure. (h) Tubular P-type TPMS lattice structure. (i) Tubular G-type TPMS lattice structure. (j) I_2-Y-type TPMS lattice structure..

through the application surface evolver). Essentially, the variations of the two former specified methods only differ in accuracy when calculating end Cartesian coordinates due to the approaches taken by each method (i.e. Weierstrass utilises evaluation of values in the imaginary plane and only accepting real segments of the result, whereas nodal approximations use trigonometric approximations to calculate coordinates).

7. Methods of optimisation

Although lattice structures are beneficial in weight and energy consumption reduction, they are inherently non-optimal in regards to material usage and structure configuration. Many attempts (Huang and Xie 2008; Deshpande, Ashby, and Fleck 2001; Brooks et al. 2005; Torquato, Hyun, and Donev 2003; Winslow, Pellegrino, and Sharma 2010; Pasko et al. 2010; Yan et al. 2012; Strano et al. 2013) have been made to optimise the positioning and variables of the unit cell components within a lattice structure in order to accommodate the functional requirements of the given object. The final generated object is governed by an objective function constrained by variable value limitations, as well as constraint equations. There exist multiple methods of lattice structure optimisation, each giving different priorities to external inputs in order to generate the most suited lattice structure design for the given object.

7.1. Stress, strain and buckling optimisation

Of the functional requirements that may be placed on a lattice structure, one of the most important requirements can objectively be said to be withstanding a given stress, strain or buckling load. The structure must be optimised in order to maximise its strength. These optimisation methods are identical with differing functional requirements (Messner 2016; Gorguluarslan et al. 2016), finding a solution (minimise value of stress, strain or buckling load) to the algorithmic requirements (other external variables and requirements). The algorithm seeks to find the global minima or maxima to the solution while iterating through all the available combinations generated by changing the values of variables such as the beam thickness, cell angles and porosity (Figure 9).

7.2. Elastic, thermal and fluidic optimisation

A significant amount of work has been undertaken in literature in order to topologically optimise lattice structure cells, participially

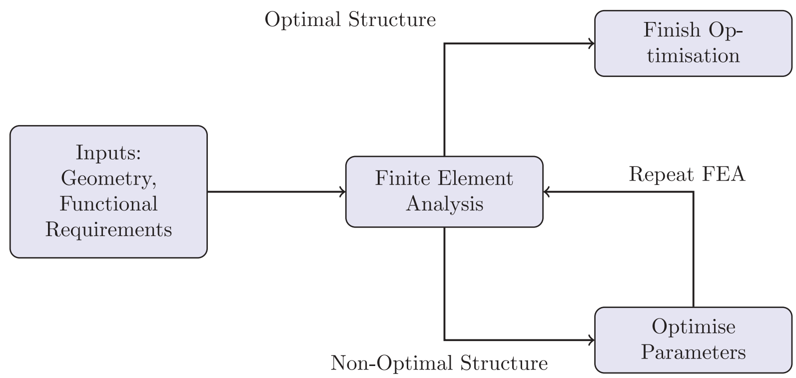

Figure 9. Cell optimisation procedure.

optimising the elastic, thermal and fluidic properties of the cell. The optimisation of these structures to find the best solutions for each given purpose in test cases has been extensively researched, maximising the elastic moduli, thermal expansion and conduction, and fluid permeability of cells through intelligent placement of cells in the overall structure, as well as the optimisation of variables and governing constraint equations in the overall structure (Osanov and Guest 2016).

7.3. Cell-size optimisation

Cell-size optimisation stems from the natural phenomena of the tessellation of a single unit cell, with varying unit cell sizes directly dependant on the distance from the original 'node' that the structure is generated from, as seen in cancellous bone (Willems et al. 2014). Recent work has been undertaken to show that biomedical applications of lattice structures usually have the functional requirement of the object becoming denser approaching the surface. This functional requirement can require the lattice structure to be optimised with varying surface thicknesses and transitional distances. This requirement can be satisfied by adjusting the lattice parameters to attempt to achieve a near-zero value closer to the surface, essentially parameterising the generation algorithm to possesses varying densities dependant on distance (Pasko et al. 2010).

8. Design analysis (FEA)

An important part of lattice structure design is ensuring that the structure is correctly optimised for the functional requirements imposed. As shown in Figure 9, FEA is integral to the work flow of lattice structure design. The FEA process allows for each permutation of the optimisation process to be tested in order to check that the functional requirements have been met (Wadley 2006; Gorguluarslan et al. 2016; Winslow, Pellegrino, and Sharma 2010; Feng et al. 2016; Messner 2016).

FEA has been used as a tool throughout literature to determine whether a lattice structure is efficient at withstanding large forces while maintaining structural integrity and whether simulated structures perform as they should in empirical testing.

Table 1 shows any FEA performed on lattice structures that are currently available in literature. It shows the information provided in each publication regarding the boundary conditions and set-up of each FEA. The table also displays what information is found from the analysis and how the calculated data are verified to be accurate.

From the information provided in Table 1, there is no standardised method of running FEA on lattice structures. Each publication features a different method of simulating the theoretical behaviour of the structure being investigated, adjusting the boundary conditions to suit the cell type being analysed. Although the results from the analysis are valid in the specific test conditions set up in each publication, overall the study results cannot be compared to different publications. The creation of a detailed FEA procedure identifying and clarifying boundary conditions specific to lattice structures would be an immensely useful asset in researching lattice structure behaviour, allowing multiple sources of data to verify experimental data. Table 1 also shows that there is no testing of different scales within a single publication.

9. Results

To achieve the four goals of reduction in material consumption, energy consumption and manufacturing time as well as strength optimisation, there is a lot of work to still be completed in rectifying problematic issues in current literature, as well as beginning to fill important gaps in knowledge to further move research in the right direction.

A summary of issues in literature can be segmented into the areas of design analysis, manufacturing, design, application and characterisation.

9.1. Design analysis

This research found that there was a consistent lack of proper statistical analysis to analyse which variables had the largest effects on the feature of the unit cell that each author was examining, due to an improper design of experiments. A significant amount of this literature also was limited in their comparisons in terms of combinations of materials, unit cells and manufacturing methods within any single journal article. Inter-article comparisons of lattice structures are limited due to the different set-up parameters and processes utilised

Table 1. FEA of lattice structures in literature.

Publication	Solver	Mesh	Material	Boundary conditions Fixed support	Force applied	Young's	Verified
Hyun et al. (2003)	ABAQUS	10,000 Elements	Undefined	Compression: bottom plate Shear: *XY*, *YZ*, *XZ* planes	Compression: top plate Shear: top plate	Modulus	Experimentally (Wang et al. 2003)
Hedayati et al. (2016)	ANSYS	Undefined amounts of Timoshenko beam elements	Steel	Compression: structure rigid in *Z* (X3) direction Top and bottom Vertices rigid in *X* (X1) direction	Compression: iteratively in each direction (*X*+; *X*−; *Y*+; *Y*−)	Yield stress	Experimentally (Gibson and Ashby 1982)
Tancogne-Dejean, Spierings and Mohr (2016)	ABAQUS	80 μm	Stainless steel 316L	Compression: bottom plate	Compression: Top plate (displacement)	Young's modulus	Experimentally (Tancogne-Dejean, Spierings, and Mohr 2016)
Hammetter, Rinaldi and Zok (2013)	ABAQUS	Dependant on strut diameter ($D = 4$)	Unnamed	Compression: top and bottom plates	Compression: Top face	Young's modulus	Theoretical (Hammetter, Rinaldi, and Zok 2013)
Mohr (2005)	ABAQUS	Undefined	Undefined	Shear: *XY* plane Tension: *XY* plane Bending: *XY* plane	Shear: ZX Plane Tension: Z Axis Bending: ZY Plane	Force-displacement	Theoretical (Mohr 2005)
Gümrük and Mines (2013)	LS-DYNA	Single strut S/R 4 node tetrahedron (Hallquist 2006)	Stainless steel 316L	Compression: Bottom face	Compression: Top face	Young's modulus	Experimental (Gümrük and Mines 2013)
Wettergreen et al. (2005)	ABAQUS	75,000 Elements	Biomaterial approximation	Compression: bottom	Compression: top face (displacement)	Yield stress	Theoretical (Wettergreen et al. 2005) Experimental (Evans et al. 2010)
Evans et al. (2010)	ABAQUS	5000 Elements	Aluminium 7076 T6	Compression: bottom face	Compression: top face	Young's modulus	Experimental (Deshpande, Fleck, and Ashby 2001)
Deshpande, Fleck and Ashby (2001)	ABAQUS	20–40 Timoshenko beam elements	Unnamed	Compression: all vertices Tension: all vertices Shear: all vertices	Compression: *X*, *Y*, *Z* axes Tension: *X*, *Y*, *Z* axes Shear: *X*, *Y*, *Z* axes	Young's modulus Shear modulus	Experimental (Gorguluarslan et al. 2016)
Gorguluarslan et al. (2016)	ABAQUS	Undefined	Variable	Compression: bottom face	Compression: top face (displacement)	Young's modulus	Theoretical (Feng et al. 2016)
Feng et al. (2016)	ANSYS	Variable	Undefined	Undefined	Undefined	Displacement	Experimentally (Feng et al. 2016)

between articles which prevent structures from being accurately compared, which could have been solved through an intra-article comparison between differing lattice structures with identical set-up parameters and processes.

A significant amount of lattice structure literature does not have empirical testing validated using FEA. This limited analysis leads to a lack of scientific analysis of what exactly happens to each structure's compression, shear and tensile strengths as variables such as strut diameters, strut angles, build angles and density are adjusted. There is also a lack of multi-scale simulation run on lattice structures in an attempt to examine the effects that size has in the design analysis stage. Due to this, there is a lack of comparison between optimised and unoptimised lattice structures, as well as verification of mechanical performance not being performed on these structures using FEA. In particular, there is a lack of FEA testing on lattice structures produced using some manufacturing methods, such as 3D-DLW and photo-masking. In other manufacturing methods, there are issues with the utilisation of traditional FEA techniques; SLS manufactured lattice structures do not consider manufacturing defects or material behaviour when FEA is performed (Helou, Vongbunyong, and Kara 2016).

9.2. Manufacturing

This review found that there currently exist no methods to create a lattice structure using traditional manufacturing methods without requiring assembly or post-production treatment. In the electrodeposition manufacturing method, involving the coating of hollow lattice structures, there exist a lack of alternative materials being electrodeposited on cells. Further, a lack of comparison between the testing of hollow lattice structures exists, particularly in the comparison of hollow tubes being braised and advanced manufacturing methods such as SLS and SLM.

9.3. Design

A significant portion of the literature review found (approximately 98%) were predominantly a periodic structure, with only 2% of the unit cells created being of a stochastic nature. Most unit cells that currently have been discovered are able to be generated with different amounts of stochastic distribution for such purposes of osseointegration and surface roughening.

Most structures are manually generated as opposed to mathematically generated, as seen in Figure 5. Within the mathematically generated structure literature, there is a lack of comparison between different generation methods such as exact computation, trigonometric approximations and nodal generation.

There is no analysis of trade-offs when using the nodal generation method; that is, there is no statistical analysis to draw conclusions between the accuracy, resolution, generation time and print quality variables. Although new ways of manual lattice structure generation are being created, there is a lack of comparison between methods such as manual engineering design and imaging recreation (via CT/MRI scans of existing objects).

9.4. Applications

Although most publications have produced a prototype of their research, only a few (approximately three) publications have attempted to convert a solid object into one that features lattice structures. There however are a limited amount of instances of lattice structures being included in designs in order to leverage their beneficial aspects.

There have been cases where lattice structures have been added to objects in order to improve design aspects dependant on functional requirements. For example, lattice structures are particularly useful for osseointegration (Cheng et al. 2014) and thus have been repeatedly investigated in their ability to promote increased levels of osseointegration (Chahine et al. 2008; Obaton et al. 2017). Along these lines, clinically applied implants have also utilised lattice structures to increase implant anchoring in bone while simultaneously leveraging their osseointegration abilities (Helvajian et al. 2014).

The energy-absorption features of lattice structures have also been utilised in the form of impact resistance. There have been studies conducted on lattice structure reinforced warheads that show through the use of topological optimisation, lattice structures have been able to increase the resistance of impact loadings, increasing the capability of ammunition and warheads surviving penetration (Richards and Liu 2015; Jr Graves, Liu, and Palazotto 2017).

Further, computation time for the generation of lattice structures could be problematic, taking a significant amount of time to construct lattice structures due to generation methods not being optimised (Yoo 2011; Yoo and Kwon 2009; Wang, Chen, and Rosen 2005).

9.5. Characterisation

This research found that only small amounts of literature (approximately 8%) utilised optimisation techniques conducted on lattice structures to maximise the strength of the object while maintaining the properties a lattice structure inherently possesses (such as increased energy absorption and decreased weight). It also found that although there is a multitude of research conducted on the optimisation of thermal, fluidic and elastic properties, there is a lack of optimisation concentrating on the strength, weight and energy usage during manufacturing. There is also a lack in multiscale topology optimisation, due to a large amount of assumptions that need to be made during the process (Osanov and Guest 2016). There is also a lack in research conducted in optimising the overall structure as well as optimising the unit cell.

10. Discussion and future work

The research conducted has collated a significant amount of lattice structure-based literature in order to identify areas with severe limitations and research gaps. A large amount of literature had limitations in their design analysis, where a proper design of experiments was often not considered, leading to problematic statistical analysis. This contributes to the lack of overall understanding of the effects structure parameters can have on overall structure strength, also causing an inability to effectively compare different structure types. This was also compounded by FEA consistently not being run on structures, limiting understanding of structure behaviour at different scales.

The manufacturing of lattice structures using traditional manufacturing methods seems to be currently prohibitive, as there are no effective methods to create structures without assembly or post-production treatment. Treatment techniques such as electro-deposition are also limited to a specific subset of materials that does not effectively demonstrate the differences in behaviour the structures undergo.

Because a large amount of literature has been published concentrating on the design of lattice structures, the limitations that have been identified in this study become more apparent. The bulk of lattice structures are still periodic and manually generated, neglecting other structure designs. These limitations are directly linked to the structure characterisation, as there is a significant lack of optimisation conducted on lattice structures in order to maximise object strength while minimising other parameters.

The lack of a design tool to aid researchers and end-users to incorporate lattice structures into designs has prevented the application of lattice structures to relevant designs. This may be due to the software limitations that currently exist in currently available software. Although it has been previously shown that lattice structures have benefits such as weight reduction and energy absorption, only a small amount of literature has been produced aiming to find the benefits of applying the structures with specific functional requirements.

This research has provided a redefinition of lattice structures, in order to incorporate new literature that has recently been produced. With this, it will become easier for future researchers to achieve the goals set out to be accomplished by lattice structures, namely to meet the goals of a reduction in energy, material and manufacturing time while maximising the strength of a given object that has lattice structures applied. The primary areas of future work that is required in order to further understand lattice structures include researching a multi-scale FEA simulation solution to understand the behaviour of lattice structures at all scales, the development of a standard design of experiments in order to produce statistically relevant data to be utilised for further research of lattice structures as well as developing a tool that aids end-users utilise lattice structures in their designs.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Anderson, P. 2016. “Finite Element Analysis and Validation of the Superplastic Forming of Multi-Sheet Structures.” *Materials Science Forum* 838-839: 621–626. ISSN 978-3-03835-672-1. doi:10.4028/www.scientific.net/MSF.838-839.

ASTM International. 2016. “ISO/ASTM52910-17.” *Standard Guidelines for Design for Additive Manufacturing*. West Conshohocken, PA. doi:10.1520/ISOASTM52910-17.

Bauer, J., S. Hengsbach, I. Tesari, R. Schwaiger, and O. Kraft. 2014. “High-Strength Cellular Ceramic Composites with 3D Microarchitecture.” *Proceedings of the National Academy of Sciences of the United States of America*. 111, 2453–2458. ISSN 1091-6490 (Electronic)0027-8424 (Linking). http://www.pnas.org/content/111/7/2453.full.pdf

Bernal Ostos, J., R. G. Rinaldi, C. M. Hammetter, G. D. Stucky, F. W. Zok, and A. J. Jacobsen. 2012. “Deformation Stabilization of Lattice Structures via Foam Addition.” *Acta Materialia* 60: 6476–6485. ISSN 13596454. doi:10.1016/j.actamat.2012.07.053.

Borsellino, C., and G. Di Bella. 2009. “Paper-Reinforced Biomimetic Cellular Structures for Automotive Applications.” *Materials and Design* 30: 4054–4059. doi:10.1016/j.matdes.2009.05.013.

Brooks, W., C. Sutcliffe, W. Cantwell, P. Fox, J. Todd, and R. Mines (2005). Rapid Design and Manufacture of Ultralight Cellular Materials. *Solid Freeform Fabrication Symposium*, 231–241.

Chahine, G., M. Koike, T. Okabe, P. Smith, and R. Kovacevic. 2008. “The Design and Production of Ti-6Al-4V ELI Customized Dental Implants.” *JOM* 60 (11): 50–55. doi:10.1007/s11837-008-0148-2. ISSN 1543-1851.

Cheng, A., A. Humayun, D. J. Cohen, B. D. Boyan, and Z. Schwartz. 2014. “Additively Manufactured 3D Porous Ti-6Al-4V Constructs Mimic Trabecular Bone Structure and Regulate Osteoblast Proliferation, Differentiation and Local Factor Production in a Porosity and Surface Roughness Dependent Manner.” *Biofabrication* 6 (4): 045007. https://www.ncbi.nlm.nih.gov/pubmed/25287305.

Cheng, X. Y., S. J. Li, L. E. Murr, Z. B. Zhang, Y. L. Hao, R. Yang, F. Medina, and R. B. Wicker. 2012. “Compression Deformation Behavior of Ti-6Al-4V Alloy with Cellular Structures Fabricated by Electron Beam Melting.” *Journal of the Mechanical Behavior of Biomedical Materials* 16: 153–162. ISSN 1359-6454. doi:10.1016/j.jmbbm.2012.10.005.

Chua, C. K., K. F. Leong, and C. S. Lim. 2010. “Rapid Prototyping: Principles and Applications.” *World Scientific. Page 176*ISSN 9812778985.

Dantas, A. C. S., D. H. Scalabrin, R. De Farias, A. A. Barbosa, A. V. Ferraz, and C. Wirth. 2016. “Design of Highly Porous Hydroxyapatite Scaffolds by Conversion of 3D Printed Gypsum Structures A Comparison Study.” *Procedia CIRP* 49: 55–60. doi:10.1016/j.procir.2015.07.030.

Del Olmo, E., E. Grande, C. R. R. Samartin, M. Bezdenejnkh, J. Torres, N. Blanco, M. Frovel, et al. 2012. “Lattice Structures for Aerospace Applications.” Proceedings of 12th European Conference on Spacecraft Structures, Materials, and Environmental Testing 691 SP:1-6. ISSN 9788578110796.

Deshpande, V. S., M. F. Ashby, and N. A. Fleck. 2001. “Foam Topology: Bending versus Stretching Dominated Architectures.” *Acta Materialia* 49: 1035–1040. ISSN 1359-6454. doi:10.1016/S1359-6454(00)00379-7.

Deshpande, V. S., N. A. Fleck, and M. F. Ashby. 2001. “Effective Properties of the Octet-Truss Lattice Material.” *Journal of the Mechanics and Physics of Solids* 49: 1747–1769. ISSN 0022-5096. doi:10.1016/S0022-5096(01)00010-2.

Dong, L., V. Deshpande, and H. Wadley. 2015. “Mechanical Response of Ti-6Al-4V Octet-Truss Lattice Structures.” *International Journal of Solids and Structures* 60-61: 107–124. ISSN 0020-7683. doi:10.1016/j.ijsolstr.2015.02.020.

Doty, R. E., J. A. Kolodziejska, and A. J. Jacobsen. 2012. “Hierarchical Polymer Microlattice Structures.” *Advanced Engineering Materials* 14: 503–507. ISSN 1438-1656. doi:10.1002/adem.v14.7.

Druschitz, A., C. Williams, D. Snelling, and M. Seals. 2014. *Additive Manufacturing Supports the Production of Complex Castings*, 51–57. John Wiley & Sons, Hoboken, New Jersey. ISBN 9781118888100. doi:10.1002/9781118888100.ch7.

Dumas, M., P. Terriault, and V. Brailovski. 2017. ““Modelling and Characterization of a Porosity Graded Lattice Structure for Additively Manufactured Biomaterials.” *Materials & Design* 121: 383–392. doi:10.1016/j.matdes.2017.02.021.

Evans, A. G., M. Y. He, V. S. Deshpande, J. W. Hutchinson, A. J. Jacobsen, and W. B. Carter. 2010. “Concepts for Enhanced Energy Absorption

Using Hollow Micro-Lattices." *International Journal of Impact Engineering* 37: 947–959. ISSN 0734-743X. doi:10.1016/j.ijimpeng.2010.03.007.

Feng, R.-Q., F.-C. Liu, W.-J. Xu, M. Ma, and Y. Liu. 2016. "Topology Optimization Method of Lattice Structures Based on a Genetic Algorithm." *International Journal of Steel Structures* 16: 743–753. doi:10.1007/s13296-015-0208-8.

Frulloni, E., J. M. Kenny, P. Conti, and L. Torre. 2007. "Experimental Study and Finite Element Analysis of the Elastic Instability of Composite Lattice Structures for Aeronautic Applications." *Composite Structures* 78: 519–528. ISSN 0263-8223. doi:10.1016/j.compstruct.2005.11.013.

Gandy, P. J. F., S. Bardhan, A. L. Mackay, and J. Klinowski. 2001. "Nodal Surface Approximations to the P, G, D and I-WP Triply Periodic Minimal Surfaces." *Chemical Physics Letters* 336: 187–195. ISSN 0009-2614. doi:10.1016/S0009-2614(00)01418-4.

Gandy, P. J. F., D. Cvijović, A. L. Mackay, and J. Klinowski. 1999. "Exact Computation of the Triply Periodic D ('Diamond') Minimal Surface." *Chemical Physics Letters* 314: 543–551. doi:10.1016/S0009-2614(99)01000-3.

Gandy, P. J. F., and J. Klinowski. 2000a. "Exact Computation of the Triply Periodic G ('Gyroid') Minimal Surface." *Chemical Physics Letters* 321: 363–371. doi:10.1016/S0009-2614(00)00373-0.

Gandy, P. J. F., and J. Klinowski. 2000b. "Exact Computation of the Triply Periodic Schwarz P Minimal Surface." *Chemical Physics Letters* 322: 579–586. doi:10.1016/S0009-2614(00)00453-X.

Genoese, A., A. Genoese, N. L. Rizzi, and G. Salerno. 2016. "On the Derivation of the Elastic Properties of Lattice Nanostructures: The Case of Graphene Sheets." *Composites Part B: Engineering* 115: 316–329, ISSN 1359-8368, doi:10.1016/j.compositesb.2016.09.064.

Gibson, L. J., and M. F. Ashby. 1982. "The Mechanics of Three-Dimensional Cellular Materials." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 382: 43–59. ISSN 00804630. doi:10.1098/rspa.1982.0088.

Gorguluarslan, R. M., U. N. Gandhi, R. Mandapati, and S.-K. Choi. 2016. "Design and Fabrication of Periodic Lattice-Based Cellular Structures." *Computer-Aided Design and Applications* 13: 50–62. doi:10.1080/16864360.2015.1059194.

Gümrük, R., and R. A. W. Mines. 2013. "Compressive Behaviour of Stainless Steel Micro-Lattice Structures." *International Journal of Mechanical Sciences* 68: 125–139. doi:10.1016/j.ijmecsci.2013.01.006.

Gümrük, R., R. A. W. Mines, and S. Karadeniz. 2013. "Static Mechanical Behaviours of Stainless Steel Micro-Lattice Structures under Different Loading Conditions." *Materials Science and Engineering: A* 586: 392–406. ISSN 0921-5093. doi:10.1016/j.msea.2013.07.070.

Gurtner, G., and M. Durand. 2014. "Stiffest Elastic Networks." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 470: 20130611. doi:10.1098/rspa.2013.0611.

Hallquist, J. 2006. "LS-DYNA Theory Manual." *Livermore Software Technology Corporation*, Livermore, CA.

Hammetter, C. I., R. G. Rinaldi, and F. W. Zok. 2013. "Pyramidal Lattice Structures for High Strength and Energy Absorption." *Journal of Applied Mechanics* 80: 041015. ISSN 0021-8936. doi:10.1115/1.4007865.

Hao, L., D. Raymont, C. Yan, A. Hussein, and P. Young. 2012. "Design and Additive Manufacturing of Cellular Lattice Structures". *Innovative developments in virtual and physical prototyping*. Taylor & Francis Group, London, Pages 249–254. ISSN 9780415684187.

Hedayati, R., M. Sadighi, M. M. Aghdam, and A. A. Zadpoor. 2016. "Mechanical Properties of Additively Manufactured Thick Honeycombs." *Materials* 9: 613. ISSN 0928-4931. doi:10.3390/ma9080613.

Helou, M., S. Vongbunyong, and S. Kara. 2016. "Finite Element Analysis and Validation of Cellular Structures." *Procedia CIRP* 50: 94–99. ISSN 978-3-03835-672-1. doi:10.1016/j.procir.2016.05.018.

Helvajian, H., A. Piquãl', M. Wegener, B. Gu, and P. Unwin. 2014. "Fabricating Specialised Orthopaedic Implants Using Additive Manufacturing." *Proc.SPIE* Page 8970. doi:10.1117/12.2044272.

Hou, W., X. Yang, W. Zhang, and Y. Xia. 2017. "Design of Energy-Dissipating Structure with Functionally Graded Auxetic Cellular Material." *International Journal of Crashworthiness* 1–11. ISSN 1358-8265 1754-2111. doi:10.1080/13588265.2017.1328764.

Huang, X., and Y. M. Xie. 2008. "Optimal Design of Periodic Structures Using Evolutionary Topology Optimization." *Structural and Multidisciplinary Optimization* 36: 597–606. ISSN 1615-147X. doi:10.1007/s00158-007-0196-1.

Hussein, A., L. Hao, C. Yan, R. Everson, and P. Young. 2013. "Advanced Lattice Support Structures for Metal Additive Manufacturing." *Journal of Materials Processing Technology* 213: 1019–1026. ISSN 0924-0136. doi:10.1016/j.jmatprotec.2013.01.020.

Hyun, S., A. M. Karlsson, S. Torquato, and A. G. Evans. 2003. "Simulated Properties of Kagomé and Tetragonal Truss Core Panels." *International Journal of Solids and Structures* 40: 6989–6998. ISSN 0020-7683. doi:10.1016/S0020-7683(03)00350-0.

Jacobsen, A. J., W. Barvosa-Carter, and S. Nutt. 2007a. "Compression Behavior of Micro-Scale Truss Structures Formed from Self-Propagating Polymer Waveguides." *Acta Materialia* 55: 6724–6733. doi:10.1016/j.actamat.2007.08.036.

Jacobsen, A. J., W. Barvosa-Carter, and S. Nutt. 2008. "Micro-Scale Truss Structures with Three-Fold and Six-Fold Symmetry Formed from Self-Propagating Polymer Waveguides." *Acta Materialia* 56: 2540–2548. ISSN 1359-6454. doi:10.1016/j.actamat.2008.01.051.

Jacobsen, A. J., W. Barvosa-Carter, and S. Nutt. 2007b. "Micro-Scale Truss Structures Formed from Self-Propagating Photopolymer Waveguides." *Advanced Materials* 19: 3892–3896. ISSN 1521-4095. doi:10.1002/(ISSN)1521-4095.

Jr Graves, W. T., D. Liu, and A. N. Palazotto. 2017. "Impact of an Additively Manufactured Projectile." *Journal of Dynamic Behavior of Materials* 3 (3): 362–376. doi:10.1007/s40870-017-0102-x. ISSN 2199-7446 2199-7454.

Jung, Y., K. T. Chu, and S. Torquato. 2007. "A Variational Level Set Approach for Surface Area Minimization of Triply-Periodic Surfaces." *Journal of Computational Physics* 223: 711–730. ISSN 00219991. doi:10.1016/j.jcp.2006.10.007.

Kang, K.-J. 2015. "Wire-Woven Cellular Metals: The Present and Future." *Progress in Materials Science* 69: 213–307. ISSN 0079-6425. doi:10.1016/j.pmatsci.2014.11.003.

Kruth, J. P. 1991. "Material Incress Manufacturing by Rapid Prototyping Techniques." *CIRP Annals - Manufacturing Technology* 40: 603–614. ISSN 0007-8506. doi:10.1016/S0007-8506(07)61136-6.

Kruth, J.-P., M. C. Leu, and T. Nakagawa. 1998. "Progress in Additive Manufacturing and Rapid Prototyping." *CIRP Annals - Manufacturing Technology* 47: 525–540. ISSN 3-905-27730-1. doi:10.1016/S0007-8506(07)63240-5.

Lee, D., Z. Ma, and N. Kikuchi. 2008. "An Innovative I-Bumper Concept for Improved Crashworthiness of Military and Commercial Vehicles." *SAE Technical Paper*.

Lee, J.-W., H.-J. Choi, T.-K. Jung, B.-P. Lee, M.-G. Kim, K.-T. Kim, T.-B. Kim, H.-J. Choi, and S.-K. Hyun. 2016. "Mechanical Properties of a Tetrahedrally Cored Titanium Lattice Structure Fabricated by Pressure-Assisted Investment Casting." *Journal of Nanoscience and Nanotechnology* 16: 11214–11218. doi:10.1166/jnn.2016.13480.

Li, M.-Z., G. Stephani, and K.-J. Kang. 2011. "New Cellular Metals with Enhanced Energy Absorption: Wire-Woven Bulk Kagome (Wbk)-Metal Hollow Sphere (MHS) Hybrids." *Advanced Engineering Materials* 13 (1–2): 33–37. http://onlinelibrary.wiley.com/doi/10.1002/adem.201000165/full.

Li, S. J., L. E. Murr, X. Y. Cheng, Z. B. Zhang, Y. L. Hao, R. Yang, F. Medina, and R. B. Wicker. 2012. "Compression Fatigue Behavior of Ti-6Al-4V Mesh Arrays Fabricated by Electron Beam Melting." *Acta Materialia* 60: 793–802. ISSN 1359-6454. doi:10.1016/j.actamat.2011.10.051.

Li, S. J., Q. S. Xu, Z. Wang, W. T. Hou, Y. L. Hao, R. Yang, and L. E. Murr. 2014. "Influence of Cell Shape on Mechanical Properties of Ti-6Al-4V Meshes Fabricated by Electron Beam Melting Method." *Acta Biomaterialia* 10: 4537–4547. ISSN 1742-7061. doi:10.1016/j.actbio.2014.06.010.

Lord, E. A., and A. L. Mackay. 2003. "Periodic Minimal Surfaces of Cubic Symmetry." *Current Science* 85: 346–362. ISSN 0011-3891.

Maloney, K. J., K. D. Fink, T. A. Schaedler, J. A. Kolodziejska, A. J. Jacobsen, and C. S. Roper. 2012. "Multifunctional Heat Exchangers

Derived from Three-Dimensional Micro-Lattice Structures." *International Journal of Heat and Mass Transfer* 55 (9–10): 2486–2493. doi:10.1016/j.ijheatmasstransfer.2012.01.011. ISSN 00179310.

Masood, S. H., and W. Q. Song. 2004. "Development of New Metal/Polymer Materials for Rapid Tooling Using Fused Deposition Modelling." *Materials and Design* 25: 587–594. ISSN 6139214505. doi:10.1016/j.matdes.2004.02.009.

Messner, M. C. 2016. "Optimal Lattice-Structured Materials." *Journal of the Mechanics and Physics of Solids* 96: 162–183. doi:10.1016/j.jmps.2016.07.010.

Mohr, D. 2005. "Mechanism-Based Multi-Surface Plasticity Model for Ideal Truss Lattice Materials." *International Journal of Solids and Structures* 42: 3235–3260. doi:10.1016/j.ijsolstr.2004.10.032.

Murr, L. E., K. N. Amato, S. J. Li, Y. X. Tian, X. Y. Cheng, S. M. Gaytan, E. Martinez, P. W. Shindo, F. Medina, and R. B. Wicker. 2011. "Microstructure and Mechanical Properties of Open-Cellular Biomaterials Prototypes for Total Knee Replacement Implants Fabricated by Electron Beam Melting." *Journal of the Mechanical Behavior of Biomedical Materials* 4: 1396–1411. ISSN 1751-6161. doi:10.1016/j.jmbbm.2011.05.010.

Murr, L. E., S. M. Gaytan, F. Medina, H. Lopez, E. Martinez, B. I. Machado, D. H. Hernandez, L. Martinez, M. I. Lopez, R. B. Wicker, and J. Bracke. 2010. "Next-Generation Biomedical Implants Using Additive Manufacturing of Complex, Cellular and Functional Mesh Arrays." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 368: 1999–2032. ISSN 1364-503X (Print)1364-503X (Linking). doi:10.1098/rsta.2010.0010.

Murray, G., F. Gandhi, and E. Hayden. 2012. "Polymer-Filled Honeycombs to Achieve a Structural Material with Appreciable Damping." *Journal of Intelligent Material Systems and Structures* 23 (6): 703–718. doi:10.1177/1045389X12439636. ISSN 1045-389X 1530-8138.

Murray, G. J., and F. Gandhi. 2013. "Auxetic Honeycombs with Lossy Polymeric Infills for High Damping Structural Materials." *Journal of Intelligent Material Systems and Structures* 24 (9): 1090–1104. doi:10.1177/1045389X13480569. ISSN 1045-389X 1530-8138.

Obaton, A.-F., J. Fain, M. Djemaï, D. Meinel, F. Léonard, E. Mahé, B. Lécuelle, -J.-J. Fouchet, and G. Bruno. 2017. "In Vivo XCT Bone Characterization of Lattice Structured Implants Fabricated by Additive Manufacturing." *Heliyon* 3 (8): e00374. doi:10.1016/j.heliyon.2017.e00374.

Osanov, M., and J. K. Guest. 2016. "Topology Optimization for Architected Materials Design." *Annual Review of Materials Research* 46 (1): 211–233. doi:10.1146/annurev-matsci-070115-031826.

Ozdemir, Z., E. Hernandez-Nava, A. Tyas, J. A. Warren, S. D. Fay, R. Goodall, I. Todd, and H. Askes. 2016. "Energy Absorption in Lattice Structures in Dynamics: Experiments." *International Journal of Impact Engineering* 89: 49–61. ISSN 0734-743X. doi:10.1016/j.ijimpeng.2015.10.007.

Pasko, A., T. Vilbrandt, O. Fryazinov, and V. Adzhiev. 2010. "Procedural Function-Based Spatial Microstructures." *SMI 2010 - International Conference on Shape Modeling and Applications, Proceedings*, 47–56. ISSN 9780769540726. http://ieeexplore.ieee.org/document/5521448/?reload=true

Pettermann, H. E., and J. Hüsing. 2012. "Modeling and Simulation of Relaxation in Viscoelastic Open Cell Materials and Structures." *International Journal of Solids and Structures* 49: 2848–2853. doi:10.1016/j.ijsolstr.2012.04.027.

Plotkowski, A., O. Rios, N. Sridharan, Z. Sims, K. Unocic, R. T. Ott, R. R. Dehoff, and S. S. Babu. 2017. "Evaluation of an Al-Ce Alloy for Laser Additive Manufacturing." *Acta Materialia* 126: 507–519. ISSN 1359-6454. doi:10.1016/j.actamat.2016.12.065.

Queheillalt, D., V. Deshpande, and H. Wadley. 2007. "Truss Waviness Effects in Cellular Lattice Structures." *Journal of Mechanics of Materials and Structures* 2: 1657–1675. doi:10.2140/jomms.

Rathbun, H. J., Z. Wei, M. Y. He, F. W. Zok, A. G. Evans, D. J. Sypeck, and H. N. G. Wadley. 2004. "Measurement and Simulation of the Performance of a Lightweight Metallic Sandwich Structure with a Tetrahedral Truss Core." *Journal of Applied Mechanics* 71: 368. ISSN 00218936. doi:10.1115/1.1757487.

Rehme, O., and C. Emmelmann. 2006. "Rapid Manufacturing of Lattice Structures with Selective Laser Melting." *Laser-Based Micropackaging* 6107: 61070K–61070K-12. https://www.spiedigitallibrary.org/proceedings/Download?fileName=61070K. ISSN 0819461490.

Richard, B. F. 1961. "Synergetic Building Construction." https://www.google.com/patents/US2986241

Richards, H., and D. Liu. 2015. "Topology Optimization of Additively-Manufactured, Lattice-Reinforced Penetrative Warheads", 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech Forum, (AIAA 2015-1430) doi: 10.2514/6.2015-1430.

Roper, C. S. 2011. "Multiobjective Optimization for Design of Multifunctional Sandwich Panel Heat Pipes with Micro-Architected Truss Cores." *International Journal of Heat and Fluid Flow* 32 (1): 239–248. doi:10.1016/j.ijheatfluidflow.2010.07.002. ISSN 0142727X.

Schaedler, T. A., A. J. Jacobsen, A. Torrents, A. E. Sorensen, J. Lian, J. R. Greer, L. Valdevit, and W. B. Carter. 2011. "Ultralight Metallic Microlattices." *Science* 334: 962–965. ISSN 0036-8075. doi:10.1126/science.1211649.

Schoen, A. H. 1970. "Infinite Periodic Minimal Surfaces without Self-Intersections." *Nasa Technical Note D-5541*, 92.

Schwarz, H. A. 1890. *Gesammelte Mathematische Abhandlungen*. Chelsea Publishing Company, New York. ISBN 9780828402606. https://books.google.com.au/books?id=cKWBJBcM_18C

Strano, G., L. Hao, R. M. Everson, and K. E. Evans. 2013. "A New Approach to the Design and Optimisation of Support Structures in Additive Manufacturing." *The International Journal of Advanced Manufacturing Technology* 66: 1247–1254. ISSN 0268-3768. doi:10.1007/s00170-012-4403-x.

Tancogne-Dejean, T., A. B. Spierings, and D. Mohr. 2016. "Additively-Manufactured Metallic Micro-Lattice Materials for High Specific Energy Absorption under Static and Dynamic Loading." *Acta Materialia* 116: 14–28. doi:10.1016/j.actamat.2016.05.054.

Tang, Y., Y. Zhou, T. Hoff, M. Garon, and Y. F. Zhao. 2016. "Elastic Modulus of 316 Stainless Steel Lattice Structure Fabricated via Binder Jetting Process." *Materials Science and Technology* 32 (7): 648–656. doi:10.1179/1743284715Y.0000000084. ISSN 0267-0836.

Tian, J., T. J. Lu, H. P. Hodson, D. T. Queheillalt, and H. N. G. Wadley. 2007. "Cross Flow Heat Exchange of Textile Cellular Metal Core Sandwich Panels." *International Journal of Heat and Mass Transfer* 50 (13–14): 2521–2536. doi:10.1016/j.ijheatmasstransfer.2006.11.042. ISSN 00179310.

Torquato, S., S. Hyun, and A. Donev. 2003. "Optimal Design of Manufacturable Three-Dimensional Composites with Multifunctional Characteristics." *Journal of Applied Physics* 94: 5748–5755. ISSN 0021-8979. doi:10.1063/1.1611631.

Valdevit, L., A. Pantano, H. A. Stone, and A. G. Evans. 2006. "Optimal Active Cooling Performance of Metallic Sandwich Panels with Prismatic Cores." *International Journal of Heat and Mass Transfer* 49 (21–22): 3819–3830. doi:10.1016/j.ijheatmasstransfer.2006.03.042. ISSN 00179310.

Vasiliev, V. V., V. A. Barynin, and A. F. Razin. 2012. "Anisogrid Composite Lattice Structures - Development and Aerospace Applications." *Composite Structures* 94: 1117–1127. ISSN 0263-8223. doi:10.1016/j.compstruct.2011.10.023.

Wadley, H. N. G., and D. T. Queheillalt. 2007. "Thermal Applications of Cellular Lattice Structures." *Materials Science Forum* 539-543: 242–247. ISSN 1662-9752. doi:10.4028/www.scientific.net/MSF.539-543.

Wadley, H. N. G. 2002. "Cellular Metals Manufacturing." *Advanced Engineering Materials* 4: 726–733. ISSN 1438-1656. doi:10.1002/1527-2648(20021014)4:10<726::AID-ADEM726>3.0.CO;2-Y.

Wadley, H. N. G. 2006. "Multifunctional Periodic Cellular Metals." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 364: 31–68. ISSN 1364-503X (Print) 1364-503X (Linking). doi:10.1098/rsta.2005.1697.

Wadley, H. N. G., N. A. Fleck, and A. G. Evans. 2003. "Fabrication and Structural Performance of Periodic Cellular Metal Sandwich Structures." *Composites Science and Technology* 63: 2331–2343. ISSN 0266-3538. doi:10.1016/S0266-3538(03)00266-5.

Wang, H., Y. Chen, and D. W. Rosen. 2005. "A Hybrid Geometric Modeling Method for Large Scale Conformal Cellular Structures." *25th Computers and Information in Engineering Conference, Parts A and B*. 3, 421–427. ISSN 0-7918-4740-3. http://proceedings.asmedigitalcollection.asme.org/data/conferences/idetc/cie2005/72587/421_1.pdf

Wang, J., A. G. Evans, K. Dharmasena, and H. N. G. Wadley. 2003. "On the Performance of Truss Panels with Kagomé Cores." *International Journal of Solids and Structures* 40: 6981–6988. ISSN 0020-7683. doi:10.1016/S0020-7683(03)00349-4.

Wang, Y. 2007. "Periodic Surface Modeling for Computer Aided Nano Design." *CAD Computer Aided Design* 39: 179–189. ISSN 0010-4485. doi:10.1016/j.cad.2006.09.005.

Wendy Gu, X., and J. R. Greer. 2015. "Ultra-Strong Architected Cu Meso-Lattices." *Extreme Mechanics Letters* 2: 7–14. doi:10.1016/j.eml.2015.01.006.

Wettergreen, M. A., B. S. Bucklen, B. Starly, E. Yuksel, W. Sun, and M. A. K. Liebschner. 2005. "Creation of a Unit Block Library of Architectures for Use in Assembled Scaffold Engineering." *CAD Computer Aided Design* 37: 1141–1149. ISSN 0010-4485. doi:10.1016/j.cad.2005.02.005.

Wicks, N., and J. W. Hutchinson. 2001. "Optimal Truss Plates." *International Journal of Solids and Structures* 38: 5165–5183. ISSN 0020-7683. doi:10.1016/S0020-7683(00)00315-2.

Willems, N. M. B. K., G. E. J. Langenbach, V. Everts, and A. Zentner. 2014. "The Microstructural and Biomechanical Development of the Condylar Bone: A Review." *The European Journal of Orthodontics* 36: 479–485. doi:10.1093/ejo/cjt093.

Winslow, P., S. Pellegrino, and S. B. Sharma. 2010. "Multi-Objective Optimization of Free-Form Grid Structures." *Structural and Multidisciplinary Optimization* 40: 257–269. ISSN 0015800903. doi:10.1007/s00158-009-0358-4.

Yan, C., L. Hao, A. Hussein, and D. Raymont. 2012. "Evaluations of Cellular Lattice Structures Manufactured Using Selective Laser Melting." *International Journal of Machine Tools and Manufacture* 62: 32–38. ISSN 0890-6955. doi:10.1016/j.ijmachtools.2012.06.002.

Yan, C., L. Hao, A. Hussein, P. Young, and D. Raymont. 2014. "Advanced Lightweight 316L Stainless Steel Cellular Lattice Structures Fabricated via Selective Laser Melting." *Materials & Design* 55: 533–541. ISSN 0261-3069; 1873-4197. doi:10.1016/j.matdes.2013.10.027.

Yang, L., D. Cormier, H. West, O. Harrysson, and K. Knowlson. 2012. "Non-Stochastic Ti–6Al–4V Foam Structures with Negative Poisson's Ratio." *Materials Science and Engineering: A* 558 (SupplementC): 579–585. http://www.sciencedirect.com/science/article/pii/S0921509312011744.

Yin, S., L. Wu, J. Yang, L. Ma, and S. Nutt. 2014. "Damping and Low-Velocity Impact Behavior of Filled Composite Pyramidal Lattice Structures." *Journal of Composite Materials* 48 (15): 1789–1800. doi:10.1177/0021998313490582. ISSN 0021-9983 1530-793X.

Yoo, D.-J. 2011. "Computer-Aided Porous Scaffold Design for Tissue Engineering Using Triply Periodic Minimal Surfaces." *International Journal of Precision Engineering and Manufacturing* 12: 61–71. doi:10.1007/s12541-011-0008-9.

Yoo, D.-J., and -H.-H. Kwon. 2009. "Shape Reconstruction, Shape Manipulation, and Direct Generation of Input Data from Point Clouds for Rapid Prototyping." *International Journal of Precision Engineering and Manufacturing* 10: 103–113. doi:10.1007/s12541-009-0016-1.

Zheng, X., H. Lee, T. H. Weisgraber, M. Shusteff, J. DeOtte, E. B. Duoss, J. D. Kuntz, M. M. Biener, Q. Ge, J. A. Jackson, S. O. Kucheyev, N. X. Fang, and C. M. Spadaccini. 2014. "Ultralight, Ultrastiff Mechanical Metamaterials." *Science* 344: 1373–1377. ISSN 0036-8075. doi:10.1126/science.1252291.

Zok, F. W., R. M. Latture, and M. R. Begley. 2016. "Periodic Truss Structures." *Journal of the Mechanics and Physics of Solids* 96: 184–203. doi:10.1016/j.jmps.2016.07.007.

Zok, F. W., H. J. Rathbun, Z. Wei, and A. G. Evans. 2003. "Design of Metallic Textile Core Sandwich Panels." *International Journal of Solids and Structures* 40: 5707–5722. ISSN 00207683. doi:10.1016/S0020-7683(03)00375-5.

Appendix. Existing literature

Table A1. A summary of cell types, sizes, manufacturing processes and materials in existing lattice structure literature.

Publication	Focus	Cell size	Cell scale	Cell type	Structure type	Area	Manufacturing process	Material
Bauer et al. (2014)	M	10 µm × 10 µm × 10 µm (*A, B, C*)/ 5 µm × 10 µm (*D*)/1.5/3 µm × 5/10 µm (*E*– with curved walls)	µ	Unnamed	P, Man	Re	3D DLW	Polymer (nanoscribe)
Bernal Ostos et al. (2012)	M	Sample 1: strut diameter: 1.6 mm, strut length: 14.4 mm; sample 2: strut diameter: 1.8 mm, strut length: 14.4 mm	Ma	Pyramidal	P, Man	Re	ColUVPho, Coa	Thiol–ene, polyurethane foam
Brooks et al. (2005)	M	0.8–5 mm	Meso	Pillar, octahedral	P, Man	Re	SLM	316L stainless steel
Cheng et al. (2012)	M	Rhombic dodecahedral density: 0.62, 0.73, 0.91, 1.18, 1.68; foam density: 0.37, 0.40, 0.44	Ma	Rhombic dodecahedron, foam	Sto, P, Man	Re	EBM	Ti–6Al–4V
Deshpande, Fleck and Ashby (2001)	D	Var	Var	Octet truss	P, Man	Re (LSC)	InvCa	Aluminium alloy LM25
Dong, Deshpande and Wadley (2015)	M	Var	Var	Octet truss	P, Man	Re	WaCu	Ti–6Al–4V
Doty, Kolodziejska and Jacobsen (2012)	M	Small scale: 100 µm; strut diameter, 1200 µm node spacing; large scale: 1250 µm strut diameter, 12,500 µm node spacing	Ma	Octahedral	P, Man	Re	PhoPolCu	Photopolymer
Evans et al. (2010)	M	Var, element radius *R*, length *L*, wall thickness *t*, angle theta = 60°	Ma	Pyramidal	P, Man	Re	ElDep, PhMask	Nickel-plated photopolymer
Feng et al. (2016)	DO	Var	Var	Four-edged-hinged single layer	P, Man	Re	N/A	N/A
Gandy et al. (1999)	D	Var	Var	TPMS diamond	P, Math	Re	N/A	N/A
Gandy and Klinowski (2000a)	D	Var	Var	TPMS gyroid	P, Math	Re	N/A	N/A
Gandy and Klinowski (2000b)	D	Var	Var	TPMS primitive	P, Math	Re	N/A	N/A
Gandy et al. (2001)	D	Var	Var	TPMS gyroid, diamond, I-WP, primitive	P, Math	Re	N/A	N/A
Gorguluarslan et al. (2016)	M	For nylon 6/12 material test: 20 mm × 20 mm × 20 mm (2 mm radius for each strut/no cut face/cut face at 2 mm radius/cut face at 1.5 mm radius) for optimisation test: 1.5 mm radius struts 20 mm × 20 mm × 20 mm	Ma	Octet frame	P, Man	Re	SLS, FDM	Nylon 6, Nylon 12
Gümrük and Mines (2013)	M	*L*mm × *L*mm × *L*mm, where *L* = 1.25, 1.379, 1.6, 2, 2.5	Ma	BCC	P, Man	Re	SLM	Undefined
Gümrük, Mines and Karadeniz (2013)	M	*L*mm × *L*mm × *L*mm, where *L* = 1.25, 1.379, 1.6, 2, 2.5	Ma	BCC, BCCZ, F_2BCC	P, Man	Re	SLM	316L stainless steel
Hammetter, Rinaldi and Zok (2013)	D	Var, dependant on height (*H*), strut angle (theta) and strut slenderness ratio (*L/D*)	Var	Pyramidal	P, Man	Re	N/A	N/A
Hao et al. (2012)	M	2, 5, 8 mm	Ma	TPMS gyroid, diamond	P, Math	Re	SLM	316L stainless steel
Hedayati et al. (2016)	M	Wall thickness (0.09, 0.18, 0.27, 0.36) *T/L* (thickness/length)	Ma	Honeycomb	P, Man	Re	FDM	PLA
Helou, Vongbunyong and Kara (2016)	M	6, 10 mm	Ma	TPMS gyroid, diamond	P, Math	Re	SLS	PA2200, GP1
Huang and Xie (2008)	DO	Var	Var	N/A	P, Man	Re	N/A	N/A
Hussein et al. (2013)	M	3, 4, 5 mm	Ma	TPMS gyroid, diamond	P, Math	Re	SLS	Ti–6Al–4V
Hyun et al. (2003)	D	Var	Var	Kagome	P, Man	Re	N/A	N/A

(*Continued*)

Table A1. (Continued).

Publication	Focus	Cell size	Cell scale	Cell type	Structure type	Area	Manufacturing process	Material
Jacobsen, Barvosa-Carter and Nutt (2007b)	M	Density (p/p_s) = 0.21/0.26/0.22/0.11, diameter (D) = 180/80/150/150 μm, angle (theta) = 60/60/60/140°	μ	Octahedral	P, Man	Re	ColUVPho	Thiol–ene monomer
Jacobsen, Barvosa-Carter, and Nutt (2007a)	M	900 μm	μ	Octahedral-type	P, Man	Re	ColUVPho	Thiol–ene monomer
Jacobsen, Barvosa-Carter and Nutt (2008)	M	2.8 mm	μ	Octahedral-type	P, Man	Re	ColUVPho	Thiol–ene polymer
Lee et al. (2016)	M	Length of strut (s) = 13 mm, width (w) = 16 mm, length (L) = 15.3 mm, height (H) = 14.6 mm, strut thickness = 3 mm	Ma	Tetrahedral	P, Man	Re	3DWP	Titanium
Li et al. (2012)	M	Density: 1.68, 1.12, 0.91, 0.73 g cm^{-3}; porosity: 62%, 74.4%, 79.8%, 83.5%	Ma	Rhombic dodecahedron	P, Man	Re	EBM	Ti–6Al–4V
Li et al. (2014)	M	0.5–3 mm	Ma	Cubic, G7, Rhombic	P, Man	Re	EBM	Ti–6Al–4V
Messner (2016)	DO	Var	Var	Optimised isotruss, octet truss	P, Man	Re	N/A	N/A
Murr et al. (2010)	M	Bone element cell: 4, 5, 7 mm cross 1: 2 mm – channel size 0.9 mm – strut size G6: 2 mm – channel size 1.4 mm – strut size G7/G7r: 2 mm – channel size 1.1 mm – strut size dode thin: 0.3 mm – channel size 0.3 mm – strut size	Ma	Bone element, Cross 1, G6, G7/G7r, dode thin	P, Man	Med	EBM	Ti–6Al–4V
Murr et al. (2011)	M	Co–29Cr–6Mo foam density: 0.77, 0.69, 0.66, 0.63; Co–29Cr–6Mo dode thin density: 1.85, 1.25, 0.98; Ti–6Al–4V foam density: 0.58, 0.68, 0.83; Ti–6Al–4V dode thin density: 0.86, 0.78, 1.59	Ma	Dode thin, foam	P, Sto, Man	Med	EBM	Ti–6Al–4V, Co-29Cr-6Mo
Ozdemir et al. (2016)	M	5 mm	Ma	Cubic, diamond, re-entrant cube lattice	P, Man	Re	EBM	Ti–6Al–4V
Pettermann and Hüsing (2012)	DFEA	Var	Var	Simple cube, Gibson–Ashby, Kelvin, BCC, reinforced BCC	P, Man	Re	N/A	N/A
Queheillalt, Deshpande and Wadley (2007)	M	Wire radius: 0.73, 0.69 mm spacing: 5 mm/5 mm	Ma	Collinear (diamond/square), textile (diamond/square)	P, Man	Re	Weav, Brai	304 stainless steel
Rathbun et al. (2004)	M	Height: 9.8, strut length: 12.2	Ma	Tetrahedral	P, Man	Re	Ben, Brai	304 stainless steel (Fe–18Cr–8Ni)
Rehme and Emmelmann (2006)	M	2.5 mm	Ma	Face centred cubic, BCC	P, Man	Re	SLM	Stainless steel
Schaedler et al. (2011)	M	1–4 mm	Ma	Octahedral	P, Man	Re	ColUVPho, ElecPla	Thiol–ene monomer, nickel
Strano et al. (2013)	M	Var	Var	TPMS gyroid, diamond, Schwartz	P, Man	Re	SLS	Undefined
Tancogne-Dejean, Spierings and Mohr (2016)	MEA	3.08 mm with densities (pbar) = 0.05, 0.1, 0.2, 0.3, 0.4, 0.5	Ma	Octet truss	P, Man	Re	SLM	316L stainless steel
Wang et al. (2003)	M	Diameter: 1.5 mm	Ma	Kagome	P, Man	Re	FDM, InvCa	ABS, copper–beryllium alloy
Wendy Gu and Greer (2015)	M	6, 8 μm	μ	Octet truss	P, Man	Re	DLW, ElDep	Copper, iridium–tin oxide
Wicks and Hutchinson (2001)	DO	Undefined	Ma	Octet panel, honeycomb	P, Man	Re	N/A	N/A
Yan et al. (2012)	M	2, 3.5, 4.5,5. 5, 6.5, 8 mm	Ma	TPMS gyroid	P, Math	Re	SLM	316L stainless steel
Yan et al. (2014)	M	5 mm	Ma	TPMS gyroid	P, Man	Re	SLM	316L stainless steel
Zheng et al. (2014)	M	Unclearly defined	μ	Tetrakaidekahedron	P, Man	Re	MicSte, ElecPla	1,6-Hexanediol diacrylate, nickel–phosphorus

M: Manufacturing; D: design; DO: design optimisation; DFEA: design FEA; MEA: manufacturing energy absorption; μ: micro; Var: variable; Ma: macro; P: periodic; Mar: manually generated; Math: mathematically generated; Sto: stochastic; Re: research; Med: medical; DLW: direct laser writing; SLM: selective laser melting; InvCa: investment casting; WaCu: water-jet cutting; PhoPolCu: photopolymer curing; ElDep: electrodeposition; PhMask: photomasking; SLS: selective laser sintering; FDM: fused deposition modelling; ColUvPho: collimated UV photopolymerisation; 3DWP: 3D wax printing; Weav: weaving; Brai: braising; ElecPla: electroless plating; MicSte: microstereolithography; EBM: electron beam melting; PLA: polylactic acid; DLW: direct laser writing; BCC: body centred cubic.