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Design and Additive Manufacturing of Cellular Lattice Structures

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ABSTRACT: The concept of designed cellular lattice materials is motivated by the desire to put material only where it is needed for a specific application. From a mechanical engineering viewpoint, a key advantage offered by cellular materials is high strength accompanied by a relatively low mass. These materials can provide good energy absorption characteristics and good thermal and acoustic insulation properties as well. Designed cellular structures typically exhibit strong structure strength per unit weight than typical foam structures. However, due to their complexity, these structures are often difficult to generate using existing CAD packages. Furthermore, metallic additive manufacturing techniques, such as selective laser melting process which shows the great capability to fabricate strong and lightweight metallic lattice structures, are still facing certain process limitations in terms of the geometrical capability and support structure requirement for the fabrication of cellular lattice structures. This paper presents an efficient approach to generate and design periodic lattice structures and investigates the manufacturability of some selected structures using selective laser melting (SLM) process. The design of cellular structures is based on image-based algorithms to efficiently generate implicitly defined periodic lattice structure and rapidly construct volume and surface meshes. The experimental investigation on the SLM fabrication has studied the effects of unit cell type and cell sizes on the manufacturability of some typical cellular structures.

1 INTRODUCTION

The design and manufacturing of cellular lattice structures is motivated by the desire to save the expensive functional materials, build time, energy consumption, and provide high performance such as high strengths accompanied by a relatively low mass, good energy absorption characteristics and good thermal and acoustic insulation properties to aerospace, medical and engineering products. However, due to their complexity, these structures are often difficult to generate using existing CAD packages. Currently, there is great interest in manufacturing cellular lattice structures with tailored properties. A number of manufacturing methods including investment casting, deformation forming, brazing etc. are proposed to make cellular structures. Limitations of such techniques include the fitness of the structures, and the actual cell geometry (Santorinaios, et al. 2006). Additive Manufacturing (AM) technologies have been developed over the years to produce three dimensional objects directly from a digital model by the successive addition of materials without the use of a specialized tooling. Selective laser melting (SLM) is one of the most widely used metal AM processes and has the potential to manufacture cellular lattice structures with fine features at a resolution of 50 microns.

Therefore, this paper presents an efficient approach to the design and generation of periodic lattice structures and investigates the manufacturability of some selected structures using the SLM process.

2 BACKGROUND

2.1 *Design of Cellular Structures*

Recent advances in AM have allowed for the creation of complex geometries to a relatively high level of precision. These manufacturing processes are particularly well-suited to fabricating computationally generated cellular lattice structures and have allowed for the recent development of methods for doing so.

As with the design of the vast majority of components that are to be manufactured, cellular lattice structures have previously been created using traditional commercial CAD packages. However these packages have proven to be unsuitable for potentially large complex micro-architectures due to the vast number of Boolean operations required, as shown in Wang, et al. 2005. To overcome the difficulties in using generic CAD packages Wang, et al. 2005 developed a hybrid geometric modelling method for conformal truss structures. Their method was demonstrated to be able to create large triangulated surfaces of repeating unit cells, such as the tetrahedron and Kelvin Foam structures. By using open-ended cylinders for trusses and ‘sealing’ joins with spheres, repeatable unit cells were generated. This, however, relied on the use of a solid modeller (ACIS) to perform the Boolean operations on the trusses and spheres. These methods were further developed in Chen 2006 to remove the need for a solid modeller by developing methods for handling the tessellation of truss-sphere intersections.

Voxel modelling is an alternative approach to the generation of cellular lattice structures and is often used in the creation of scaffold architectures. While high resolution images or volumes are normally required to sufficiently represent geometries using voxels, they have the advantage of being particularly straightforward to modify, particularly when using Boolean operations.

A relatively simple image-based approach to the generation of conforming scaffold architectures is presented in Starly 2006. In this work Starly slices the bounding geometry, as defined using a CAD model, into a number of equally spaced binary images. By using Boolean operations on each slice a number of simple unit cells are then introduced into the geometry. The unit cells themselves are typically solid cubes with spherical or cuboidal voids, thus ensuring they remain stackable. This slice-based approach avoids the need to handle triangulated surfaces for the creation of an STL file. However, this is likely limited to 3D printing where image-based slices may be used. As with any purely voxel-based method, it also results in a poorly defined geometry at the boundaries.

Another less frequently used approach to the generation of micro-architectures is through the use of implicit functions. This is the approach taken in the works by Gabbrielli (Gabbrielli 2008; Gabbrielli, et al. 2009) and more recently by Pasko (Pasko, et al. 2010; Pasko, et al. 2011). Gabbrielli uses a set of periodic implicit functions, such as the Schoen Gyroid (Schoen 1970), to create porous micro-architectures to be used as bone substitutes. By introducing functional variations to the equations Gabbrielli was also able to create functionally graded micro-architectures. However, there were no methods given for precisely controlling the grading, such as the minimum and maximum volume fractions. In comparison to other techniques these methods provide a compact representation of the complex structures and, through the use of an appropriate iso-surfacing algorithm, a straightforward way of producing triangulated surfaces.

2.2 *SLM fabrication of Cellular structures*

Recently, some attempts have been made to create cellular lattice structures using SLM process. Santorinaios, et al. 2006 studied the manufacturability of open cellular lattice structures with a simple geometry with vertical struts and cross bracing. Three cell sizes of 1.25, 2.5 and 5mm were considered, but the cell size of 5 mm proved to be problematic to fabricate. The struts tended to 'sag' during the SLM process. Brooks, et al. 2005 designed and manufactured regular metallic lattice structures with unit cell sizes in the range 0.8mm to 5mm and truss elements of 100-500 μm in diameter through the SLM of 316L stainless steel. McKown, et al. 2008 made a range of metallic lattice structures based on [±45°] and [0°, ±45°] unit-cell topologies by SLM process. The unit cell sizes of their lattice structures were 1.5mm and 2.5mm. However, the cellular structures manufactured in the current studies might not exhibit good manufacturability in SLM, and therefore current cellular structures with large unit cell sizes (greater than 5 mm) could not be built using the SLM process because of the occurrence of serious deformation.

In this paper, two unit cell types are chosen to design periodic cellular lattice structures with a volume fraction of 15% and the manufacturability of cell sizes in the range of 2 mm to 8 mm are investigated for SLM.

3 DEVELOPING DESIGN TOOLS FOR CELLULAR STRUCTURE GENERATION

3.1 *Surface Representations*

When dealing with solid 3D objects it is often convenient to only model the object's boundaries using a mathematical representation of the surfaces. The choice of surface representation is particularly important for the computational modelling of 3D objects as each has its own advantages and disadvantages. These include the availability and complexity of operations that can be used to manipulate the surface (e.g. smoothing, Boolean operations) as well as the efficiency of the representation. Each representation also has an impact on how models are visualised and ultimately realised (e.g. via rapid manufacturing). The most common representations can be classified as one of the following forms: explicit, parametric or implicit.

In explicit surface representations points which lie exactly on the surface are explicitly stored. The most common type of explicit surface is a mesh of polygons; typically these are triangles or quadrilaterals although others can be used. These polygons are often stored as an order list of vertex indices – the order being used to define the direction the polygon is facing (i.e. the surface normal).

Unlike explicit surfaces, parametric surfaces do not store points on a surface. Instead, points on a parametric surface are expressed as a function of the parametric variables *(u,v)*, which can be generalised to lie on the unit square $[0,1] \times [0,1]$ (Zheng 2008). Non-Uniform Rational B-Spline (NURBS) surfaces are a form of parametric surface commonly used in CAD packages due to their compact representation, smooth surfaces and easy of manipulation. Other forms of parametric surfaces exist, such as Rational Gaussian (RaG) surfaces (Goshtasby 1993) and Fourier Shape Descriptions.

Implicit surfaces are defined as an iso-surface of some function *f*. In 3D the surface is defined by a set of points $p \in \mathbb{R}^3$ satisfying the equality:

$$f(x, y, z) = 0 \quad (1)$$

where $f: \mathbb{R}^3 \mathbb{R}$.

As with parametric forms, implicit surfaces provide a compact representation for potentially complex surfaces. They also offer a number of advantages, notably their flexibility (as will be demonstrated later in this work) and well-defined Boolean operations. However, unlike parametric forms they offer little local shape control and manipulating them can be unintuitive.

The implicit formulation of a unit sphere is given below:

$$f(x,y,z) \equiv x^2 + y^2 + z^2 - 1 \quad (2)$$

In this instance the implicit form is not only more compact, but potentially more useful as the sign of the function can be used to designate points as either inside or outside the surface. For this purpose the following convention is adopted:

Table 1. Implicit surface in/out convention

Condition	Interpretation
f(x,y,z) = 0	On surface
f(x,y,z) < 0	Inside
f(x,y,z) > 0	Outside

The implicit functions of interest to this work are the set of infinitely periodic surfaces. The most notable of which are those discovered by Schoen 1970 and Schwarz 1890. In addition to being infinitely periodic these surfaces are also approximations of minimal surfaces, that is, the surfaces have a mean curvature of zero. Using a combination of trigonometric functions in the form given in Eq. (3) a number of periodic surfaces can be generated (Gabbrielli, et al. 2008).

$$\sum_{i=1}^{3} \prod_{j=1}^{n} \cos(x_i) + k = 0 \quad (3)$$

The simplest triply periodic (or dual periodic in 2D) function in this form is the Schwarz Primitive; $cos(x) + cos(y) + cos(z) + 1 = 0$.

3.2 *Mesh Generation*

Accurate and robust mesh generation is an important step towards the fabrication of lattice structures. The work presented in this section looks at methods for generating image volumes representing the implicit functions so that both volume and surface meshes can be constructed. An entirely image-based approach is taken to exploit the advantages of image-based meshing.

Methods previously used in (Gabbrielli, et al. 2008) relied upon the generation of a floating-point volume which was then iso-surfaced. While this method is straight-forward, simply requiring that the function be sampled at regular intervals, it becomes difficult to generate a volume mesh and integrate with other image data.

To overcome these difficulties we require that the generated volumes' data-type matches that used by +ScanFE from Simpleware Ltd. In the C programming language this is unsigned char, an 8 bit integer. By using this data-type the generated volumes can easily be combined with data from other sources, such as medical imaging devices and meshed with +ScanFE.

The most straight-forward translation to image-space that can be made from an implicit function is the generation of a binary volume. By evaluating the function, *f*, over a range of values voxels can be determined to be either inside or outside and their value set accordingly.

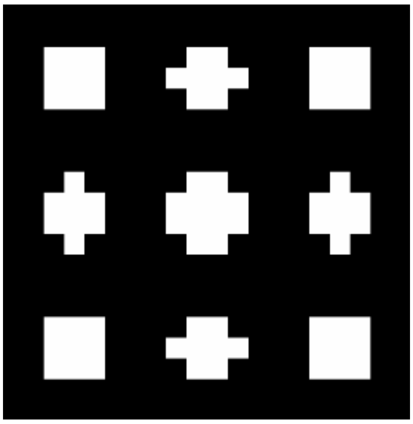


Figure 1. Binary slice representing the Schwarz Primitive using 20 × 20 px

Despite being efficient to generate, the binary representation yields a poor reconstruction, as can be seen in Figure 1. The reconstructed surface can be improved by introducing greyscale values into the volume. This can be achieved using a smoothing algorithm such as Gaussian smoothing, however these algorithms can have adverse effects such as shrinking the volume and removing small features. A more appropriate solution is to generate the volume with greyscale values such that they result in the reconstructed surface being placed as close as possible to the 'ideal' surface. The marching cubes algorithm will be used to generate a triangulated surface, as such, the volume can be generated so as to best utilise the greyscale values. As the position of the reconstructed surface is only dependent on the two voxels either side of it, a small region of greyscale values should be placed either side of the ideal surface. These greyscale values should reflect their distance to the surface, mimicking the partial volume effect. Voxels further from the surface may simply be marked as inside or outside. However, unlike many implicit functions used in computer graphics, the functions of interest are not distance functions.

That is, their value does not reflect a linear measure of distance from the surface. To overcome this a point is chosen, from the discretising volume, that is close to the ideal surface (i.e. such that $f(x,y,z) \approx 0$). The gradient at this point is then computed, allowing the greyscale values to be set such that their values reflect their distance from the surface. Values inside of the surface may be calculated as follows:

$$V_{\text{inside}} = \frac{|f(x,y,z)|}{G_p} \tag{4}$$

where G_p is the gradient near the surface. Figure 2 shows an example from a volume generated using this method. The reconstructed surface is shown in Figure 3.

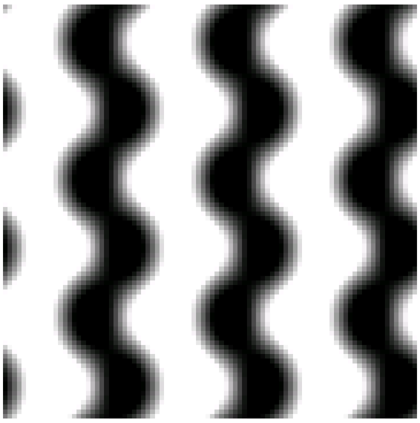


Figure 2. Greyscale slice representing the Schoen gyroid

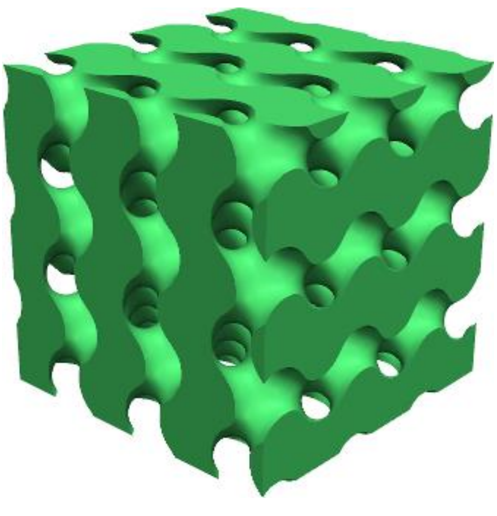


Figure 3. Reconstructed surface of the Schoen Gyroid

4 EXPERIMENTAL STUDY ON SLM OF METALLIC CELLULAR STRUCTURES

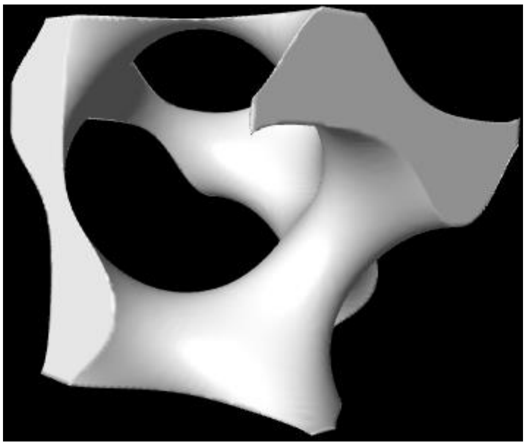
4.1 *Materials*

Cellular lattice structures were made from 316L stainless steel powders with average particle size of 45 µm±10 microns, which was gas atomized and produced by Sandvir Osprey Ltd., UK.

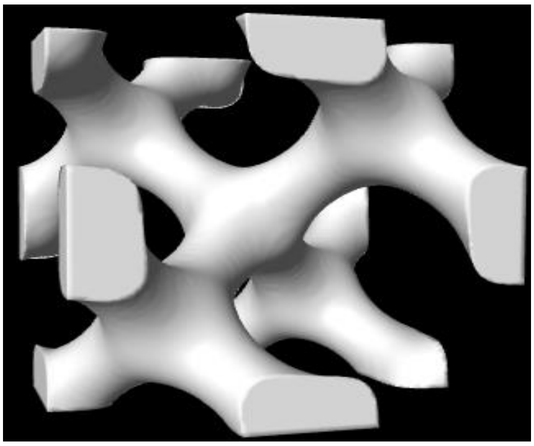
4.2 *The selective laser melting process*

The manufacturing process was carried out on a Realizer SLM Workstation made by MTT Technologies Group, UK. The SLM machine uses a 100 W CW Ytterbium fibre laser. All processing occurs in an Argon atmosphere with less than 1.0% O_2. The processing parameters used in this study were as follows: the laser power was 95 W; the scan speed was 500 mm/s; the scan spacing was 75 µm; the layer thickness was 75 µm.

This paper investigates the manufacturability of two unit cell types for SLM. The STL models of the two unit cells, the Schoen Gyroid and Schwartz Diamond, are shown in Figures 4 (a) and (b), respectively. The volume fraction was set as a constant of 15%. Cellular lattice structures with the unit cell sizes of 2 mm, 5 mm and 8mm were manufactured via SLM. The samples dimensions were 25×25×15 mm^3.



(a) Schoen Gyroid

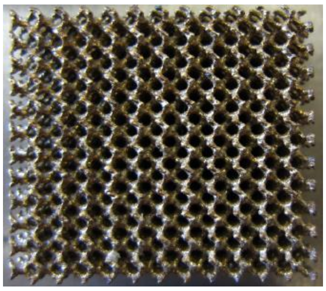


(b) Schwartz Diamond

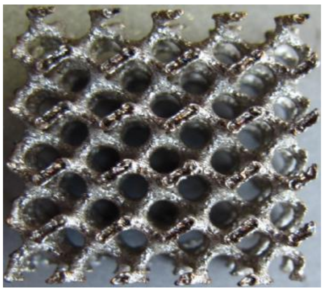
Figure 4. Two types of unit cells of Schoen Gyroid and Schwartz Diamond used in cellular lattice structures

4.3 *Effect of unit cell types and cell sizes on the Manufacturability of cellular structures by SLM process*

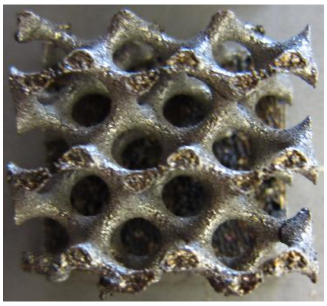
The Schoen Gyroid cellular structures with a volume fraction of 15% and unit cell sizes of 2 mm, 5 mm and 8 mm were successfully manufactured using SLM, as shown in Figures 5 (a)-(c), respectively. When the volume fraction is set as a constant of 15%, the amount of unit cells in the cellular lattice structures will increase with the decrease in unit cell sizes, and the struts in the cellular structures become thinner and thinner. When the unit cell size is very small, it may result in the loss of connectivity between adjacent cells. During the SLM process, the thin struts may be damaged by the wiper, resulting in it becoming difficult to remove loose powders following the completion of the build.



(a) Cell size=2mm



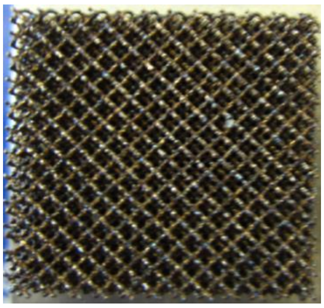
(b) Cell size=5mm



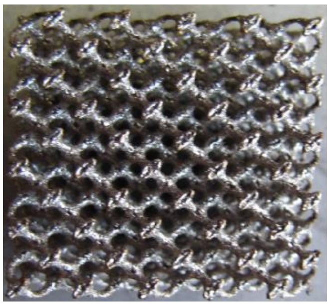
(c) Cell size=8mm

Figure 5. Schoen Gyroid cellular structures with a volume fraction of 15% and unit cell sizes in the range of 2mm to 8mm were successfully manufactured through SLM

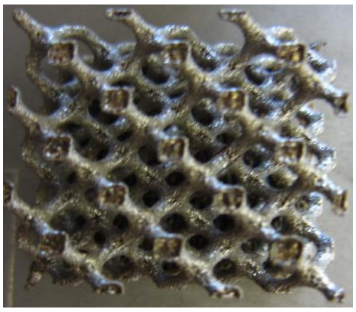
From Figure 5, it can be seen that the Gyroid cellular structure with a cell size of 2 mm has the greatest number of unit cells and the thinnest struts. However, the struts were not damaged by the wiper of SLM machine and the loose powder was completely removed. When the unit cell size is increased, the number of unit cells in the cellular structures decreases and the struts become stronger and longer. However, as the struts become longer, the amount of overhang in the structures increases and deformation may occur during the build process. This is why Santorinaios, et al. 2006 could not build their cellular structures with a cell size of 5 mm. From Figure 6(c), it can be seen that the cellular structure with a cell size of 8 mm has the smallest amount of unit cells and strongest struts, and no obvious deformation was observed during the build process. This can be attributed to the fact that the Schoen Gyroid unit cell has smooth struts rather than straight beam-like struts, and therefore enable SLM process to manufacture larger overhangs. Therefore the Gyroid cellular structures with bigger unit cell sizes can be manufactured by SLM.



(a) Cell size=2mm



(b) Cell size=5mm



(c) Cell size=8mm

Figure 6. Schwartz Diamond cellular structures with a volume fraction of 15% and unit cell sizes in the range of 2 mm to 8 mm were successfully manufactured through SLM

The Schwartz Diamond cellular structures with the same volume fraction of 15% and different unit cell sizes of 2 mm, 5 mm and 8 mm were also successfully manufactured through SLM process, as shown in Figures 6 (a)-(c), respectively. As with the Schoen Gyroid cellular structures, the Schwartz Diamond cellular structure with a cell size of 2 mm was manufactured with no struts damaged and the loose powders were completely removed, and the Diamond structure with a cell size of 8 mm was also built without any deformation.

5 CONCLUSIONS

The use of implicit modelling, particularly with triply periodic functions, has been shown to be highly flexible for the generation of open cellular structures. Several image-based algorithms were developed and evaluated and it was clearly shown that, to achieve accurate and smooth models, the generation of the volume with greyscale values would reconstruct more ideal surface. By taking an image-based approach it has been possible to ensure that the generation and manipulation of the cellular lattice structures remains robust, despite any geometric complexities.

The effect of unit cell types and cell sizes on the manufacturability of cellular structures by SLM was investigated. Two unit cell types, the Schoen Gyroid and Schwartz Diamond, were considered. The results reveal that the Schoen Gyroid and Schwartz Diamond cellular structures with the same volume fraction of 15% and different unit cell sizes of 2 mm, 5mm and 8mm are manufacturable through the use of SLM. The cellular lattice structures with a cell size of 2 mm were manufactured with no struts damaged and the loose powders were completely removed. The cellular structures with a cell size of 8 mm were built without any obvious deformation.

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