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To cite this article: Gopal K Maharjan *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **455** 012047

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Compressive Behaviour of 3D Printed Polymeric Gyroid Cellular Lattice Structure

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Abstract. 3D cellular lattice structures have multiple applications in engineering including uses in crash resistant and protective equipment. Gyroid type lattice structure has a complex geometric shape, which is very difficult to manufacture by conventional manufacturing processes. Additive manufacturing (AM) technique such as Fused Deposition Modelling (FDM) offers a convenient approach to fabricate such structure provided supports are carefully selected or avoided during their manufacture. This study involves designing the Schoen Gyroid type 3D lattice structure with different unit cell sizes and volume fractions and evaluating their manufacturability on the FDM 3D Printing machine. The study also presents the comprehensive behaviour of different Schoen Gyroid samples of four different unit cell sizes (ranging from 6 to 12 mm) and three different volume fractions of 14%, 20% and 25%. All the samples in this study were built without support. Results show that the smallest unit cell of size 6mm and the highest volume fraction of 25% was found to have the highest compressive strength among the samples tested in this study.

1. Introduction

During last twenty-five years, Additive Manufacturing (AM) has generated a significant impact on the techniques for producing complex cellular structures. Among various AM technologies, the Fused Deposition Modelling (FDM) is a polymer based process, which uses thermoplastic as the working material. The FDM is currently dominantly used for prototyping, modelling, and production applications. The possible limitations of FDM could be the longer build time and restricted set of materials but its significant advantages are that the FDM process is less complicated, safe and clean and compact. The FDM process allows removable supports, which is distinctly advantageous in producing complex geometrical shapes, which would otherwise have been extremely challenging to build through traditional manufacturing methods [1]. However, in manufacturing the complex cellular lattice structure by FDM, the support structures are not desirable because these would be very tedious to remove and result in wastage of material and energy.

Gyroid structures are a perfect example of complex geometrical shapes which are not possible to build using traditional manufacturing methods. Gyroid has a unique shape of the triply periodic minimal



surface (TPMS) discovered by NASA Scientist Alan Schoen in 1970 [2]. He describes that gyroid surface seems to be the only known example of an Intersection-free Infinite Periodic Minimal Surfaces (IPMS) which does not have plain lines or plane lines of curvature. The gyroid cellular lattice structure possesses designed topology with centre spherical core constructed by repeating Unit Cells (UCs). Previous research has shown that periodic cellular lattice structure with appropriate UC gives profiles superior to those which has been demonstrated by their stochastic analogues at the same porosity [3, 4]. Stochastic foam has random cells consisting of random distribution of open and closed voids. These structures are not simple to design and are also complicated to manufacture by conventional manufacturing processes than the stochastic structures [5].

Gyroid is defined by the equations involving elliptical integrals which are briefly described in [5-6]. A close approximation to the gyroid is given by Eq. 1 [7-8]. In this equation, 'a' is the periodicity of the gyroid and $t = 0$. A companion family of gyroid – like surfaces, with a constant mean curvature, is defined in [9-10]. $F(x,y,z)=t$,

where,

$$F(x,y,z)= \sin(2\pi xa)\cos(2\pi ya)+\sin(2\pi ya)\cos(2\pi za)+\sin(2\pi za)\cos(2\pi xa) \text{ Eq. 1}$$

Some researchers have attempted to study the behavior of such cellular structures made by metal based AM processes. Chunze et. al. [11] evaluated manufacturability of cellular lattice structure by using selective laser melting (SLM) additive manufacturing process. The effect of UC size and volume fraction on manufacturing was also analyzed. Lattice structure with 25x25x15 mm³ with 15% volume fraction and UC size ranging from 2-8mm (2, 3.5, 4.5, 5.5, 6.5, and 8) were built on steel plate successfully without any defects and without using support structure which was later confirmed with computed tomography scan results. The Scanning Electron Microscope (SEM) micrographs showed that the build lattice structure have a fairly smooth geometry similar to CAD models but many partially melted particles during the manufacturing process were bonded to the strut surface. The effect of UC size on the density of solid struts and compressive properties were analyzed. The results indicated that the struts within the smaller UC size gyroid structure have a higher density due to shorter scan vector length. The Young's modulus of the gyroid cellular lattice structure is inversely proportional to UC size, and therefore, the yield strength and Young's modulus of the gyroid lattice structure increase with the decrease in the unit cell size.

Strano et. al. [12] presented a novel approach in the design of support structures which are typically hollow or cellular in nature. Their approach applies a new optimisation algorithm to use mathematical 3D implicit functions for the design and generation of the cellular support structures including graded supports. The implicit function approach for designing the support structure has been proved to be versatile since it allows geometries to be designed by mathematical expression. With the help of mathematical expressions, various cellular structures such as gyroid and diamond structures can be easily defined and optimized to create graded structures providing robust support at locations with higher weight concentration and less support elsewhere, thus resulting in material conservation.

Horn et. al. [13] proposed open cellular structures fabricated with Ti6Al4V using electron beam melting (EBM) AM process for use as low stiffness implants and tissue scaffolds that could imitate the properties of human bone. They produced EBM- fabricated Ti6Al4V prismatic bars, populated with

rhombic dodecahedron UCs of various sizes and relative densities, and then investigated their properties by employing four-point flexural tests. The flexural test results obtained suggested that implants could be fabricated that are mechanically suitable for graft repairs of large segmental defects.

Evans et. al. [5], investigated gyroid cellular lattice structures made from 316L stainless steel powder by using Selective Laser Melting (SLM) process. The gyroid structures with the volume fraction of 15% and UC sizes of 2, 3.5, 4.5, 5.5, 6.5 and 8 mm were manufactured and no deformation was spotted during the SLM process. Later with the help of computer tomography, the reconstructed models of different UC size were analyzed to check whether there are any defects or broken cell in the cellular lattice structure. It was reported that no defects were observed.

Hussein et. al. [14] experimented to build lattice structure in direct metal sintering (DMLS) with Ti6Al4V titanium alloy powder. In this experiment, two different types of lattice structures - diamond and gyroid - with different UC size and volume fraction were investigated. Majority of the tested lattice structure were successfully built, however, a couple of them failed to build. The authors highlighted two reasons of the failure. The first reason was use of very thin lattice structure and with the volume fraction which was too fragile for the manufacturing process to continue consistently. The second reason was the large distance between the adjacent point's contacts to the supporting surfaces. This resulted in extra overhang cantilever area that is unsupported.

Literature reveals that very little work has been done to understand the mechanical behavior of polymeric Gyroid structures created by AM processes. In this study, FDM process has been used to fabricate Gyroid cellular models in PLA plastics with different unit cell (UC) sizes and volume fractions. The compressive behavior of such structures are analyzed experimentally. Such polymeric cellular structures can be applied in engineering devices where the weight of certain parts can be controlled by filling it up with the periodic cellular lattice structure with certain shell thickness. This would result in cellular structures with desired mechanical properties, higher porosity, and with reduced build time and energy consumption using AM techniques. Moreover, their high performance features with excellent thermal, acoustic insulation properties and energy absorption features will make them acceptable in multiple areas of application.

2. Experimental Procedure

2.1. Design of Gyroid Cellular Lattice Structure

The CAD model of Gyroid cellular lattice structures can be created using the commercial software (for example +CAD by Simpleware Ltd) or using open-source mathematical software (for example K3DSurf). In case of K3DSurf software, the unit cell (UC) model is required to transfer to some CAD software that can help in making a solid model from the point cloud data. In this study, the +CAD software was used to create the gyroid cellular structures. Figure 1 shows the unit cell of the solid CAD model of the gyroid structure.

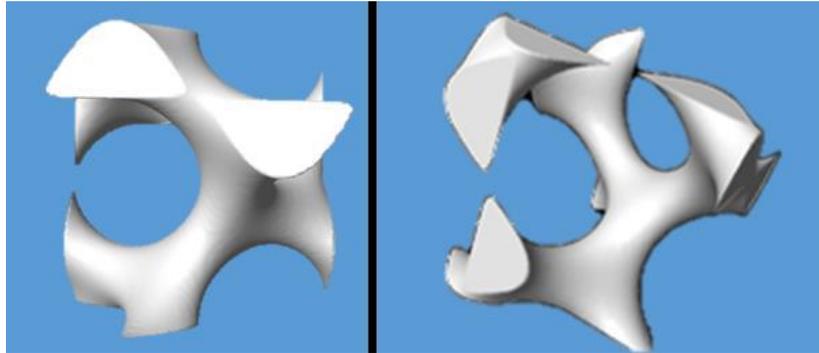


Figure 1: The unit cell (UC) of the gyroid structure

In this study total 12 different gyroid cellular lattice structures were analyzed with four different unit cell sizes (6mm, 8mm, 10mm, 12mm) having three different volume fractions (15%, 20%, and 25%), as shown in Table 1. The UCs have been connected in such a way that the size of the overall sample structure used was a cube of dimensions 50x50x50 mm. These dimensions were selected as per the American Society for Testing and Materials (ASTM) D1621-10 standards for the compressive testing of a polymer based cellular structures.

Table 1: Sample size and volume fractions for gyroid cellular lattice structure

Unit Cell Size (mm)		Volume Fraction	
6	15 %	20 %	25 %
8	15 %	20 %	25 %
10	15 %	20 %	25 %
12	15 %	20 %	25 %

2.2. Manufacturing using *FDM*

Gyroid cellular lattice structures were made from Polylactic acid (PLA) filament. PLA is a biodegradable thermoplastic derived from renewable sources, has low toxicity and environmentally friendly material used in many 3D printing machines. The Cube (2nd gen) FDM type 3D printer from 3D Systems was used to manufacture the designed structures using the STL file of the models. All the lattice structures with respective UC sizes and volume fractions were printed successfully. However, during the printing, some of the layers did not adhere to the adjacent layer properly and the extruded hot filament formed a web-like structure between the connecting struts of the structure as shown in figure 2. The thin web like structures has no load bearing capacity and most of these webs were removed by using a smoothing tool. In some of the cases, at the beginning of the printing, some initial layers did not stick to the base adhesive. This was observed due to the adhesive layer being given a long time to dry before the printing or due to uneven application of the adhesive layer. The issue was overcome by starting the printing immediately after applying the uniform layers of adhesive. All the samples printed were inspected for visual defects and those with minimal or no apparent defects were used in the compression test.

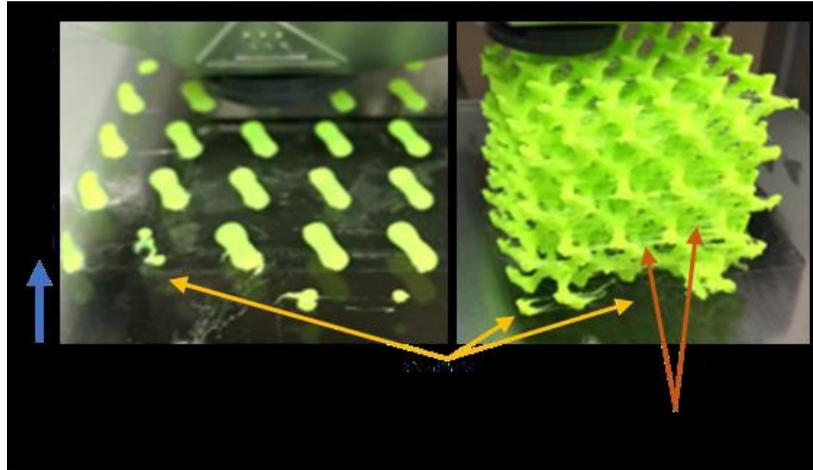


Figure 2: Problem of missing initial layers and extrusion flow - web like formation during printing of lattice structure.

Figure 3 shows the cross-section of the same layer in CAD for UC size of 6mm and 12mm for different volume fractions. This highlights the difference of the strut and the pores for increasing UC sizes. The lattice structure of UC of size 6mm has high dense struts and less void or pores. As the UC size increases, the density of the struts increases and the density of the pores is increased. The cellular structure with UC size of 12mm has the maximum size of pores compared to other structure. Figure 4 shows the comparison of CAD models and printed test specimens for all the samples.

Increasing density of small UC size will lead to shorter scan vector lengths during manufacturing. As the unit cell size decreases, the cross-section area of the strut also decreases and since the density of the struts are higher, all the unit cell are more close to each other. Therefore, the adjacent cells are scanned more quickly one after another with very little cool down time between them and the temperature of the scanned area remains higher. Due to this, the cellular structure with smaller unit cell size will have better wetting conditions and denser struts were formed

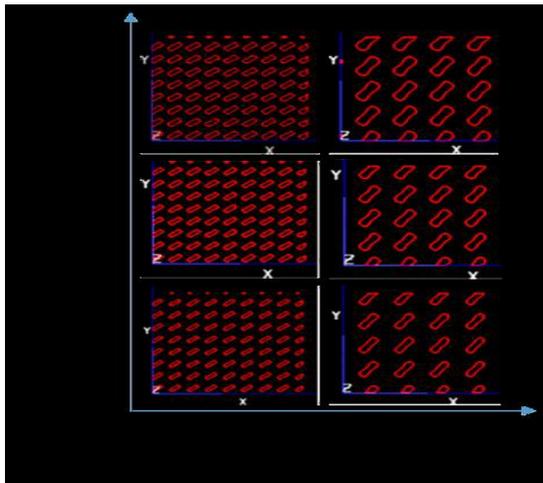


Figure 3: Cross-section CAD images

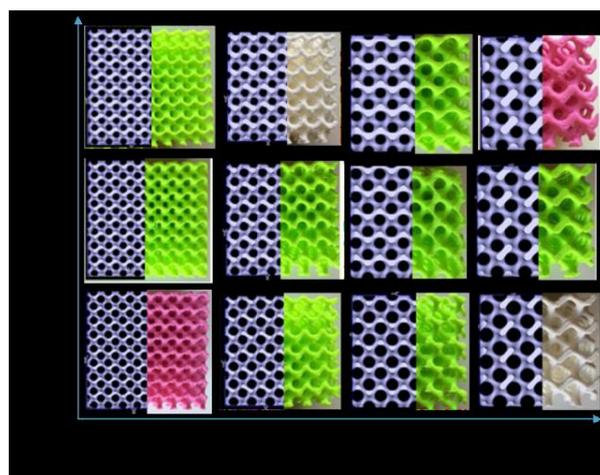


Figure 4: CAD model (right) and printed test of the gyroid cellular lattice structure. specimens (left) used in this study.

Figure 5 presents the total build time consumed from start to finish the printing of each specimen. This does not include the set-up time. The smallest UC and the highest volume fraction took the maximum time to print. The smaller dimension of the UC requires more UCs to make the model of cuboids of the same volumes, thus, requiring more time to print as each layer has more area to cover. The higher volume fraction means lower porosity that required more material to print and thus more time to print.

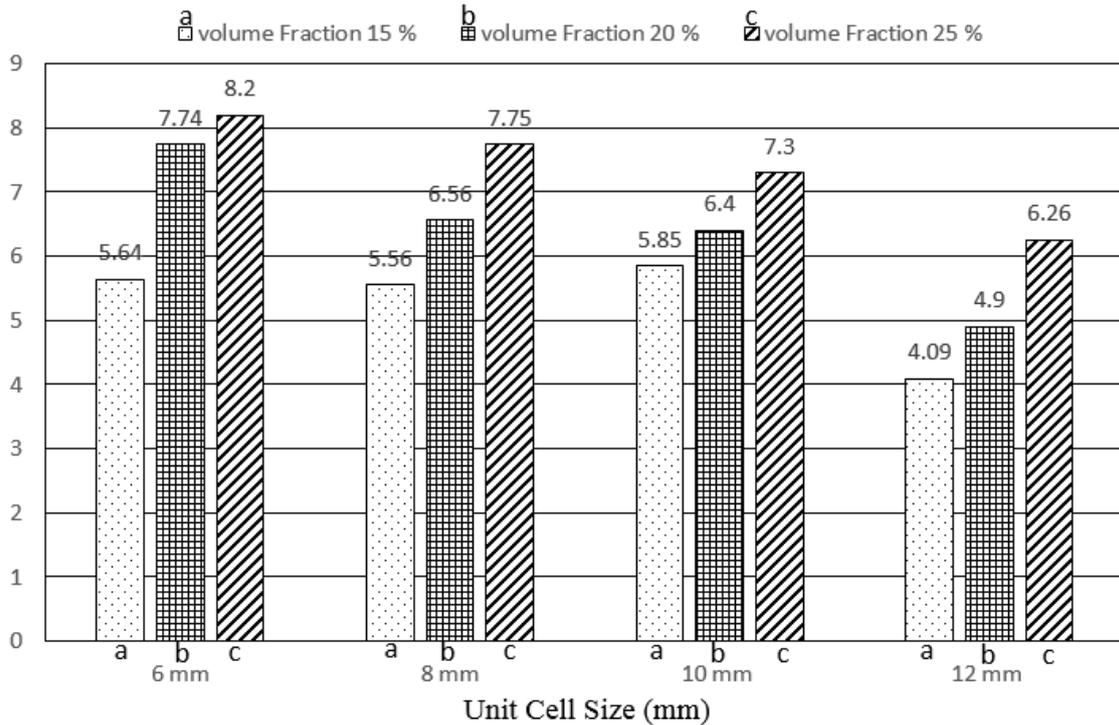


Figure 5: Build time (in hours) of the lattice structure using Cube 2ndGen printer.

2.3. Mechanical Testing

Compression testing of the gyroid specimens was carried out according to ASTM standard D1621-10 for compressive properties of rigid cellular plastics. The experiments were carried out using a universal testing machine (MTS Criterion Model 43). The compressive load on all the specimen was applied along the build direction as shown in figure 6. The deformation rate of the compressive load was set to 0.1 mm/minute and the load is applied up to the total deformation of 20 mm in the plastic deformation range. A video recorder was also used to monitor the deformation of the test specimen. The compressive stress and strain were obtained using the standard formulas.

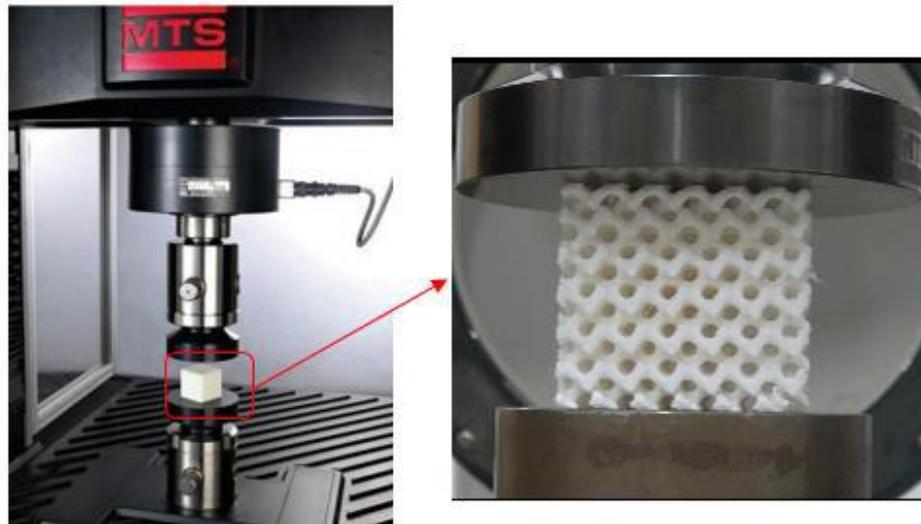


Figure 6: Set-up for the compressive testing of the lattice structure.

3. Results and Discussion

3.1. Compressive Behavior

Figure 7 shows the stress-strain curve of UC size 6 mm with different volume fractions. The stress-strain curve climbs linearly showing the elastic region. The curve with the volume fraction 15% reached its elastic limit at around 1.7MPa and the curve began to concave downward. Such behaviour can be referred as a brittle failure where some unit cells are collapsed or fractured completely. With the increasing load, other connecting cells starts to carry the load which resulted in bearing higher stress of the cellular structure. The curve with volume fraction 20% has obtained a much higher compressive strength of approximately 2.58MPa and this curve is also concaved downward showing a similar behavior of the cellular structure. The curve with volume fraction 25% has the highest compressive strength of the three test configurations, with approximately 2.99MPa and the curve is slowly concaved downward. Such stress-strain curves in the plastic domain can be referred as ductile failure where the unit cells are not catastrophically failed. The UCs demonstrated of having a gradual load-bearing capacity or load distribution to different connecting struts of connecting UCs.

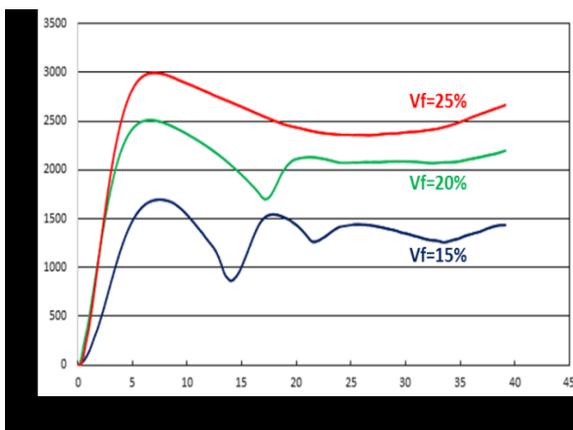


Figure 7: Stress-strain curves of unit cell 6 mm

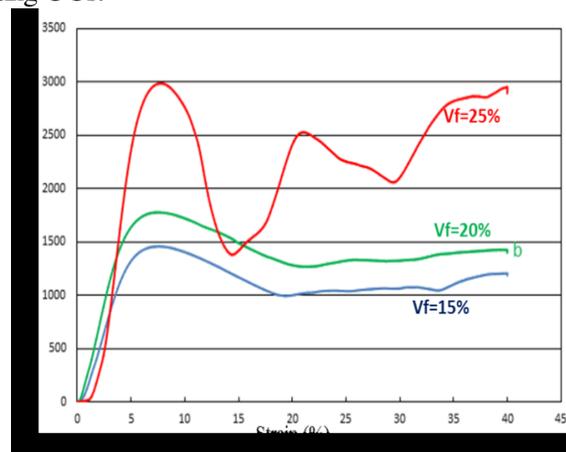


Figure 8: Stress-strain curves of unit cell 8 mm

Figure 8 shows the stress-strain curve for the UC of 8mm. In this case, the stress-strain curves suggested a dominant ductile failure for volume fractions of 15% and 20%, whereas the structure with the volume fraction of 25% showed the oscillating curve, which is typical of ductile failure. It can be observed that it follows the similar trend as with the UC of size 6mm. The compressive strengths of the volume fraction of 15%, 20% and 25% were approximately 1.46MPa, 1.78MPa and 2.97MPa respectively.

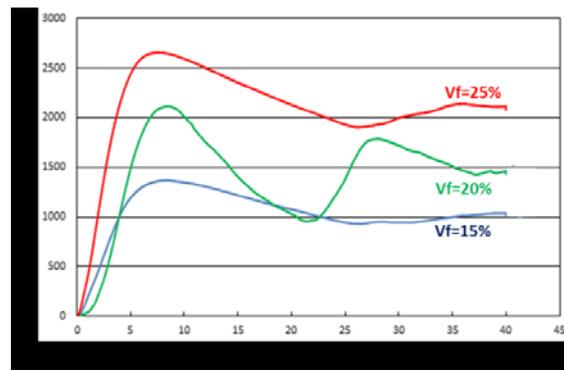
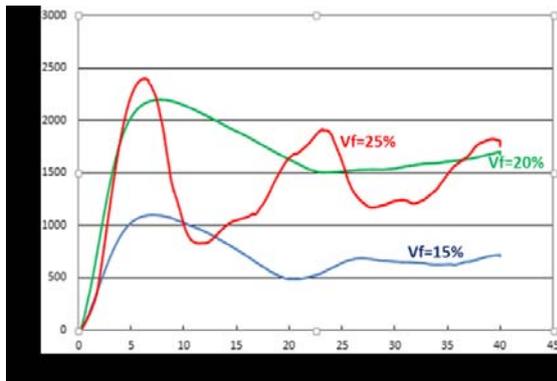


Figure 9: Stress-strain curves of unit cell 10 mm **Figure 10:** Stress-strain curves of unit cell 12 mm.

Figures 9 and 10 present the stress-strain curve for the UC of 10mm and 12 mm respectively. From these curves, it can be observed that the lattice structure with volume fraction 15% and 20% have a dominant brittle failure and 25% has a ductile failure. The overall trend remains the same as in the case of UC of 6mm and 8mm, showing the ascending order of the maximum compressive strength with respect to the decreasing volume fraction.

It can be summarized that the lattice structure with the least volume fraction has the least compressive strength and the structure with the highest volume fraction has the highest compressive strength. Therefore, in general, when volume fraction increases, the compressive strength of the lattice structures also increases. As the volume fraction increases, the density of the connecting struts in the lattice structure increases. This directly results in the increase of the struts' diameter. Thus, the struts with bigger cross-sectional area are able to withstand higher load than the struts with smaller cross-sectional areas. From this comparison, we can conclude that the volume fraction has a severe effect on the compressive properties of a lattice structure.

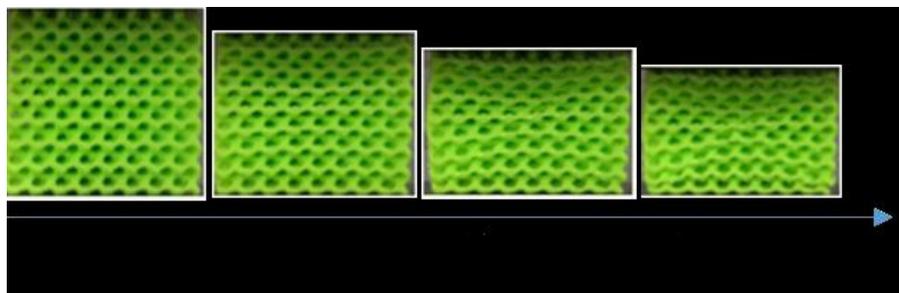


Figure 11: Compression behaviour of the gyroid cellular lattice structure at increasing displacement for UC size of 6mm and volume fraction of 20%.

In all the experiments carried out, the stress-strain curves showed gradual development of a plateau which suggest a uniform load bearing capacity, and can be regarded as similar to a ductile failure. Figure 11 illustrates the evolution of the compressive deformation behaviour of 6mm UC size structure. The sequence of images prove that all the layers contributed in bearing some portion of the total load and none of the connecting layers indicated signs of failure, in which case, abrupt oscillations in the stress-strain curve would have been observed. Instead, the compression curve undergoes a smooth and steady progression of deformation throughout the testing.

From the stress-strain curves, mechanical properties of the gyroid cellular structures with different UC sizes and volume fraction were estimated and these are summarized in Table 2. The yield strength and Young's Modulus of the gyroid cellular lattice both decrease with the decrease in the unit cell size.

The yield strength of UC size of 6mm and 15% volume fraction is approximately 30% higher than that of the UC of size 12mm with 15% volume fraction. Similarly, Young's Modulus of UC of 6mm with 15% volume fraction is approximately 57% greater than that of the UC of 12mm with 15% volume fraction. For the same UC size and for variation of volume fraction, the yield strength increases with the increase in volume fraction. The yield strength with 25% volume fraction is greater than that of 20% and 15% volume fractions. This kind of behavior is mainly attributed to the variation of strut density.

Table 2: Mechanical properties of various gyroid structure

Unit Cell Size	Volume Fraction (%)	Porosity (%)	Yield Strength (MPa)	Young's Modulus (MPa)	Mass M (gm)	Volume V (mm ³)	Density (kg/m ³)
6mm	15	85	1.70	32.70	26.65	18750	1421.33
	20	80	2.58	75.33	34.30	25000	1372
	25	75	2.99	61.46	38.13	31250	1220.16
8mm	15	85	1.46	25.75	24.30	18750	1296
	20	80	1.78	62.70	28.39	25000	1135.6
	25	75	2.97	38.96	37.91	31250	1213.12
10 mm	15	85	1.10	23.60	21.78	18750	1161.6
	20	80	2.17	56.95	31.47	25000	1258.8
	25	75	2.36	37.95	34.18	31250	1093.76
12mm	15	85	1.37	20.77	22.80	18750	1216
	20	80	2.106	20.16	30.47	25000	1218
	25	75	2.66	30.90	34.25	31250	1096

3.2. Compressive Strength

Figure 12 shows the compressive strength plotted as a function of volume fraction for structures with different unit cells. For the constant volume fraction, different UC size shows that the smallest UC size has the highest compressive strength.

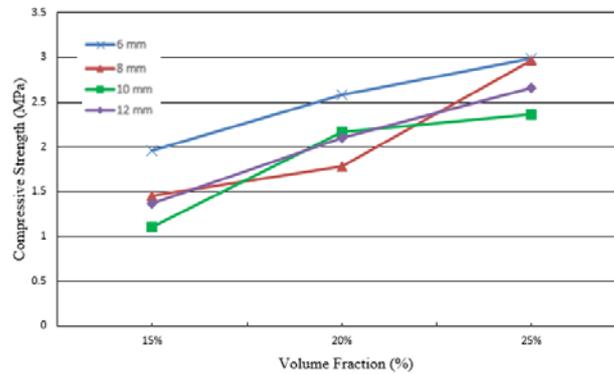


Figure 12: variation of the compressive strength of periodic cellular lattice structure with volume fraction.

Figure 13 shows the maximum compressive strength of the gyroid cellular structures. The compressive strength of a UC size of 6mm with 20% volume fraction has the highest strength and UC size of 10mm with volume fraction 15% has the lowest strength. In general, when the volume fraction increases, the compressive strength also has been increased. UC with volume fraction 15% has the lowest compressive strength in each unit cell size category.

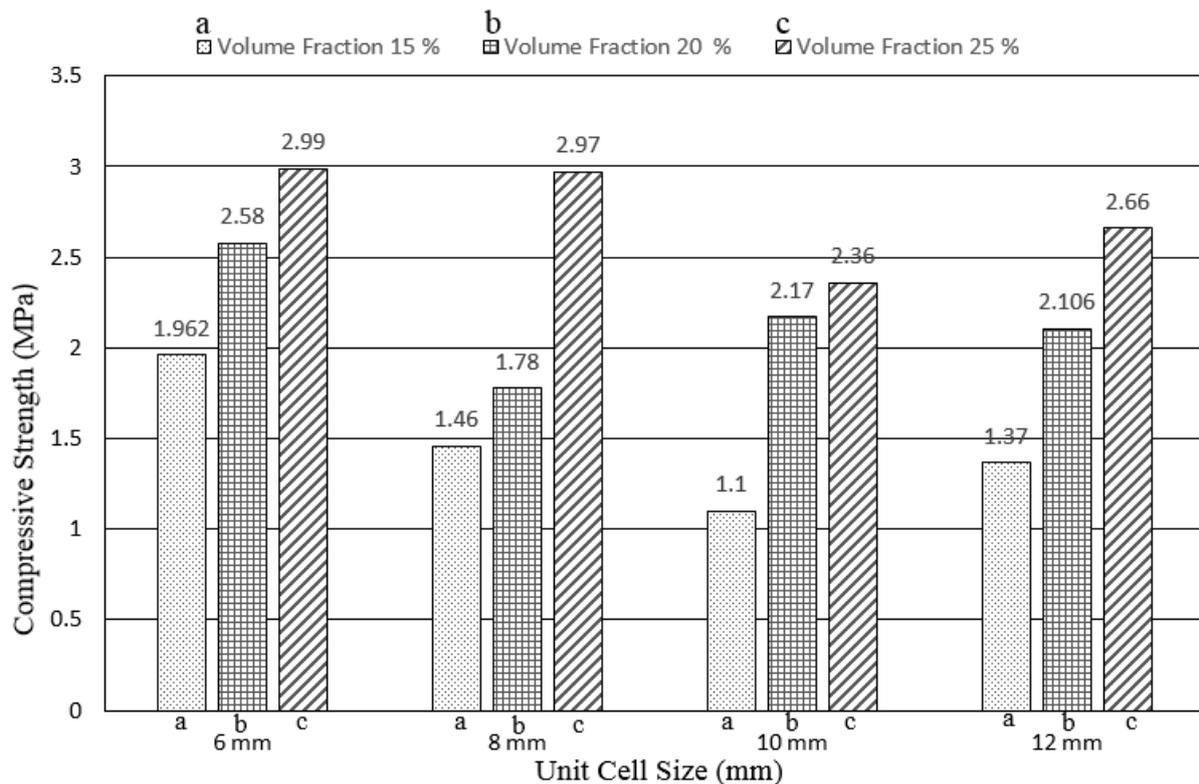


Figure 13: Compressive Strength of lattice structure.

4. Conclusions

The objective of this research was to evaluate the manufacturability of the polymeric gyroid lattice structure by using the FDM additive manufacturing process and to study the effect of variation of unit cell

size (UC) and volume fraction on the compressive properties. This study demonstrated that such structure with complex geometry is possible to manufacture in PLA plastics using the FDM additive manufacturing process. The manufacturing of the Gyroid cellular lattice structure with unit cell size ranging from 6 mm to 12 mm with three different volume fraction of 15%, 20% and 25% have been successfully done by using FDM. The 3D printed model had no major defects and have been made without using any support structure. Therefore, the FDM made cellular lattice structure of the gyroid type is a self-supporting structure. The structure made by FDM had a good geometric agreement with the original computer-aided design (CAD) models, but due to faster scanning speed and very thin filament extruding from the nozzle, some web like structure were seen between strut of the adjacent cells. The capacity of the structure to resist the maximum load has been evaluated. Within specific UC size, the structure having higher volume fraction has the highest capacity to withstand higher load. Unit cell size 6mm, 8mm, 10mm and 12mm followed this tendency. The stress-strain curves have been obtained from the compressive test of the gyroid samples. Out of twelve types of specimens tested, seven of them showed predominantly ductile failure which referred to the smooth transition of the compressive load within the layers of the lattice structure. It was found that the yield strength and Young's modulus both decrease with increase in the UC size. The compressive strength increases with the increase in volume fraction of the cellular lattice structure. The cellular lattice structure with unit cell size of 6mm has the highest compressive strength of all other UC sizes tested. The Young's Modulus of the lattice structure decreases with the increase in the UC size. Further research is required to study the compressive behaviour of cellular structure of other types and in other polymeric materials such as ABS and polycarbonate by AM processes for their possible applications in different engineering fields.

Acknowledgement:

The authors acknowledge technical supports of Mr Warren Gooch in 3D Printing and of Mr Michael Culton in compression testing of samples at Swinburne University of Technology.

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