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***Research paper***

# Investigation on Process-Properties Relationship with Mechanical Properties of Lattice-Structured Cellular Material for Lightweight Application

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## Abstract

Lattice structures possess exceptional mechanical strength resulting in highly efficient load supporting systems. The lattice structure has been receiving interest in a variety of application areas and industries such as automotive, shipping and aeronautic. The metallic or polymer micro lattice structure can be categorized as lightweight and energy-absorbing structure. These characteristics are best applied to transportation part where the lightweight structure will help reduce its overall weight, thus increase the operational time since energy and cost consumption is a big concern in the industry these days. The aim of this study is to investigate relationship between process-properties and mechanical performance of polymer lattice structure. The lattice structure was designed by using SolidWorks software and fabricated using CubePro 3D printing machine. Compression test was performed by Instron 5585 universal testing machine to analyse the strength of the lattice structure. It was found that lattice structure manufactured with the setting of solid print strength, honeycomb print pattern, 70 µm layer thickness and strut diameter of 2.4 mm possesses the optimum mechanical property.

***Keywords***: *3D printing; additive manufacturing; lattice structure material; lightweight material.*

## 1. Introduction

Cellular material is of interest in many engineering applications due to its excellent properties at low weight [1]. Gibson and Ashby [2] found that cellular solid is made up of an interconnected network of solid struts or plates that form the edges and faces of cell. Due to the characteristics of this material, researchers are having increasing interest to discover the best properties for industrial utilization. A previous study by Gibson and Ashby, shows that cellular materials can be classified into closed or open cell [2]. Rehme [3] grouped it into four categories; closed cell, open cell, periodic and stochastic. The simplest form of cellular structure is a two dimensional array of polygons which are packed to fill a plane area similar to the hexagonal cell of the bee. Hence it is called honeycomb. Three dimensional structures have a more complex like foams, where it can be either open or closed. Man-made foams are popular in lightweight structures as it is used as an impact energy absorption [2].

Numerous studies have been conducted focusing on the mechanical properties of the lattice structure. Maskery et al. [4] examined the mechanical behaviour of uniform and graded density of metallic aluminium lattices under quasi-static loading and their capability to absorb energy. Volume fraction or equals to relative density effect on the compression strength of lattice structure was determined by Yan et al. [5] by the method of direct metal laser sintering while in another study, the selective laser melting approach was utilized to study the influence to the unit cell size [5]. Comparison of stiffness and plastic collapse between lattice structure and other lightweight material by Ushijima, et. al. [6] found that lattice structure offer the lowest material properties and it has significant potential for use in the design of lightweight application. Gümrük and Mines [7] analyzed the compressive behavior of stainless steel micro-lattice structures by physical analysis and finite element analysis. Four deformation patterns were defined by Peirson [8] as shown in Figure 1 where the patterns were stated as elastic loading (I), elastic-plastic collapse (II), plastic collapse or constant stress area (III) and densification region (IV).

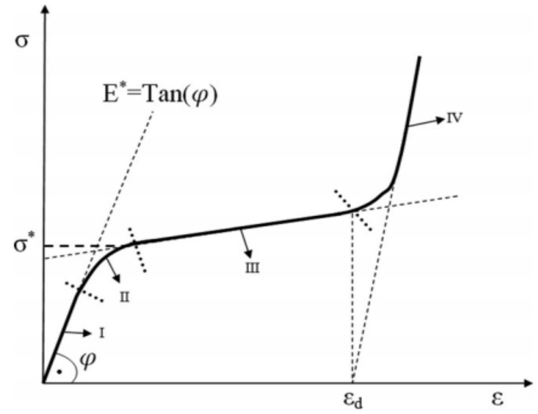


**Fig. 1:** Four regions for deformation history of micro lattice block [8].

The metallic micro lattice structure can be categorized as lightweight and energy-absorbing structure. The applications of metallic micro lattice structure in areas such as the cores of sandwich panels, thermal insulation, packaging and some automotive parts are due to their strength properties and superior specific stiffness. A study reported that polymer has lower specific density as compared to metal [8]. This makes polymer more desirable as a lightweight material. Weight reduction of material consumption has been a constant demand in the industry in order to fulfil minimal energy and cost utilization.

Another advantage of polymer is that it is a substance that can be diluted. Therefore, polymer which is in a liquid form can be injected into a mould or formed using rapid prototype. 3D printing is also known as rapid prototyping form of additive manufacturing technology where a three dimensional object is created by laying down successive layers of material [9]. An advantage of using the additive layer technique is it can produce a sample down to $10^{-6}$ meter scale, thus, material with high specific stiffness can be obtained [10].

Compression test is to determine material behavior on crushing load. In compression test, stress and strain are the important elements to plot the graph to determine the ultimate strength, yield strength, elastic limit and for some material's compressive strength. Numerous studies have utilized compression test to measure the strength [7, 11]. Ang et al. [12] studied the effect of fused deposition modelling (FDM) process parameters to the mechanical strength of tissue engineering scaffold by compression test. Analysis on the offset compressive yield strength is used instead of compressive strength due to some samples that do not possess a maximum peak on the stress-strain diagram [12]. There are numerous studies on the manufacturing lattice structure using the FDM technique. However, there is a little research focusing on the lattice structure manufactured by FDM technique specifically using CubePro 3D printer. Therefore, this paper investigated the printing process parameter of the CubePro 3D printer effect on the polymer lattice structure and its mechanical performance is to be studied.

## 2. Methodology

### 2.1. Sample Preparation

The design of lattice structure block in this study utilizes the body-centered-cubic (BCC) arrangement. Figure 2 shows the samples of acrylonitrile-butadiene-styrene (ABS) which is from polymer material fabricated using FDM technique. The mass of lattice structure was weight using SHIMADZU electronic balance, while density of lattice structure block was calculated using standard formula of mass (M/kg) over volume ($V/m^3$). CubePro 3D printing machine was used where there are numerous combination of parameters available as shown in Table 1.

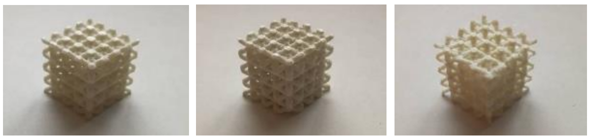

2.4 2.0 1.6

**Fig. 2:** Lattice block of strut diameter 2.4 mm, 2.0 mm and 1.6 mm

**Table 1:** List of print parameters for CubePro 3D printing machine

| Parameter | Thickness of Layer Resolution (μm) | Quality of Print Strength | Type of Print Pattern | Size of Strut (mm) |
|---|---|---|---|---|
| Range of properties | 70 | Solid | Cross | 1.6 |
| | 200 | Almost solid | Diamond | 2.0 |
| | 300 | Strong | Honeycomb | 2.4 |

The selection of combination of parameters as shown in Table 2 were based on Taguchi method and processed by using MINITAB software. A nomenclature for each batch of lattice structures according to different combination of parameter is: print strength/print pattern/layer thickness (μm)/strut diameter (mm).

**Table 2:** Print parameter with sample ID

| Layer Resolution (μm) | Print Strength | Print Pattern | Strut Diameter (mm) | Sample ID/Lattice ID |
|---|---|---|---|---|
| 70 | Strong | Cross | 1.6 | St/Cr/70/1.6 |
| 70 | Almost Solid | Diamond | 2.0 | As/Di/70/2.0 |
| 70 | Solid | Honeycomb | 2.4 | So/Hc/70/2.4 |
| 200 | Strong | Diamond | 2.4 | St/Di/200/2.4 |
| 200 | Almost Solid | Honeycomb | 1.6 | As/Hc/200/1.6 |
| 200 | Solid | Cross | 2.0 | So/Cr/200/2.0 |
| 300 | Strong | Honeycomb | 2.0 | St/Hc/300/2.0 |
| 300 | Almost Solid | Cross | 2.4 | As/Cr/300/2.4 |
| 300 | Solid | Diamond | 1.6 | So/Di/300/1.6 |

### 2.2. Testing Method

Block specimens of 20 ×20 × 20 mm size with different combination of parameters were tested with compression test in compliance to ASTM D695-15 standard test procedure using Instron 5585 universal testing machine at a rate of 1.3 mm/min. Data from the compression test were recorded by the Blue Hill Software. Compressive stress-strain graphs were plotted using these data and specific stiffness ($kPa/kgm^{-3}$) and specific yield strength ($kPa/kgm^{-3}$) were derived by dividing stiffness and yield strength values with density.

## 3. Results and Discussions

The mass and density of the lattice structures was recorded in Table 3. Referring to Table 3, three samples with strut diameters of 2.4 mm are amongst the highest in density, which are 430.00 $kg/m^3$, 396.25 $kg/m^3$ and 312.50 $kg/m^3$. Therefore, it can be said that samples with a larger strut diameter noticeably yields a higher density. The effects of layer thickness to the density of the lattice blocks were also visible. At a larger layer thickness, a higher density was recorded.

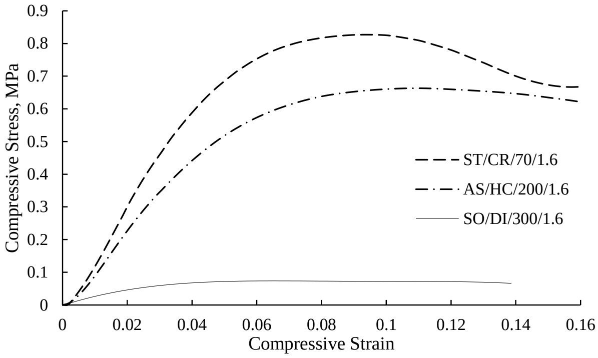
**Table 3:** Mass and density of lattice blocks

| **Lattice ID** | **Mass, M (g)** | **Density, M/V ($kgm^{-3}$)** |
|---|---|---|
| St/Cr/70/1.6 | 2.13 | 266.25 |
| As/Di/70/2.0 | 2.82 | 352.50 |
| So/Hc/70/2.4 | 3.44 | 430.00 |
| St/Di/200/2.4 | 3.17 | 396.25 |
| As/Hc/200/1.6 | 2.02 | 252.5 |
| So/Cr/200/2.0 | 2.85 | 356.25 |
| St/Hc/300/2.0 | 1.73 | 216.25 |
| As/Cr/300/2.4 | 2.50 | 312.50 |
| So/Di/300/1.6 | 1.13 | 141.25 |

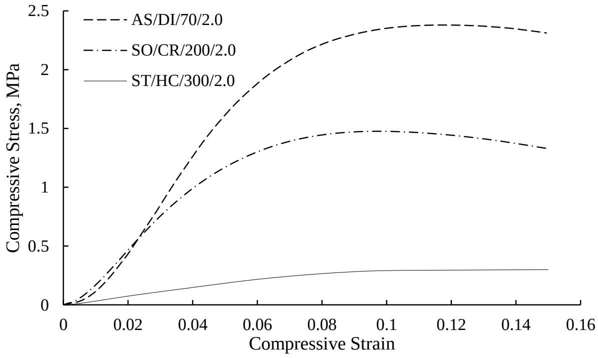
From the results, a sample with 70 μm layer thickness recorded the highest density of 430.00 $kg/m^3$. This is due to larger amount of filament deposited to fill up the closer thickness between the layers and therefore, increasing the density of the lattice block.

The stress-strain curve from the compression test of the samples with the same strut diameter of 1.6 mm, 2.0 mm and 2.4 mm are presented in Figure 3. The stress-strain curve shows that for all strut diameters, the samples went from elastic region and grows into steady plateau region. This rise is due to emergance of plastic hinges at the nodal locations of the structures [13]. Great linearity in the elastic region is by virtue of the periodical arrangement of the BCC structure [14].

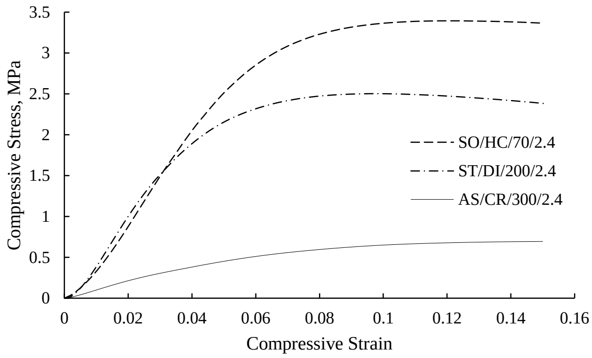
The stress-strain curve pattern of the lattice block in this study shows a stretch-dominated behavior which according to Rehme, indicating a great relative strength [3].



1.6 mm strut diameter



2.0 mm strut diameter



2.4 mm strut diameter

**Fig. 3:** Stress-strain curves for 1.6 mm, 2.0 mm and 2.4 mm strut diameter

From Figure 3, it is clearly shown that the gradient of the elastic stiffness increases as the layer thickness increase. The plateau region was noticeably higher at 70 µm layer thickness, followed by plateau region at 200 µm layer thickness. It can be seen that there is quite a great difference of maximum compressive stress between both layer thickness mentioned earlier with that of 300 µm layer thickness. Figure 3 shows that in all strut diameter, the 300 µm layer thickness exhibit the lowest strength. This is expected due to the feature of layer formation from the fastest printing mode. Figure 4 shows that the layer stacking of 300 µm layer thickness which is sloppy and not strongly connected to each other. This contributes to the reduction of strength.

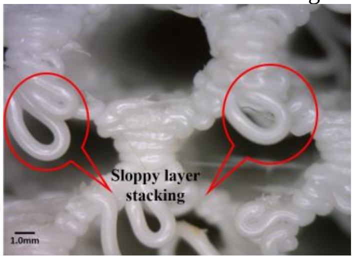


**Fig. 4:** A closed up view of sample with 300 µm layer thickness taken with DinoLite digital microscope which shows the sloppy layers stacking

Table 4 gives the specific stiffness and specific yield strength of the tested lattice structure. From the experiment, parameter combinations of So/Hc/70/2.4 and St/Di/200/2.4 give the greatest compressive strengths. Combination of these parameters also top the chart for the highest density as can be seen in Table 3 earlier. Therefore, it can be concluded that the density contributes to the strength of this structure. It can also be concluded that the reliable layer thickness of a good strength is from the 70 µm and 200 µm. The weakest combination of processing parameters would be the one with 300 µm layer thickness due to the layer formation which has been discussed earlier and explained in Figure 4 before.

**Table 4:** Experimental results

| Lattice ID | Specific Stiffness, (kPa/kgm$^{-3}$) | Specific Yield Strength (Pa/kgm$^{-3}$) |
|---|---|---|
| St/Cr/70/1.6 | 93.90 | 3117.37 |
| As/Di/70/2.0 | 75.66 | 6354.61 |
| So/Hc/70/2.4 | 135.67 | 7906.98 |
| St/Di/200/2.4 | 138.80 | 6511.04 |
| As/Hc/200/1.6 | 62.69 | 2653.47 |
| So/Cr/200/2.0 | 88.90 | 4210.53 |
| St/Hc/300/2.0 | 29.78 | 1063.58 |
| As/Cr/300/2.4 | 32.00 | 2272.00 |
| So/Di/300/1.6 | 28.32 | 566.37 |

Signal-to-noise ratio (S/N ratio) analysis identify the optimal process parameters by utilizing mechanical response data from Table 4. Graph of means plot for S/N ratio was produced and as shown in Figure 5. The higher S/N ratio indicates the optimum strength of samples. From Figure 5, the optimum layer thickness, print strength, print pattern and strut diameter are 70µm, almost solid, cross and honeycomb and 2.4 mm respectively. The suggested lattice ID with the optimized properties is As/Hc/70/2.4 or As/Cr/70/2.4.

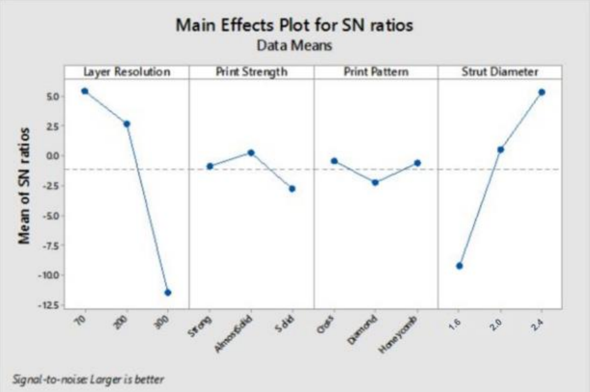


**Fig. 5:** S/N ratio analysis using MINITAB software

## 4. Conclusion

In this research, lattice structure material which was fabricated using FDM technique has been studied. The CubePro 3D printing machine was used which comprised of print pattern, print strength and layer thickness as its processing parameters. The combination of these parameters will influence the mechanical properties of the lattice structure block. Therefore the most apparent factors that affect the mechanical properties of the lattice block produced are the layer thickness. Besides that, the strut diameter of the designed lattice block is also influencing the mechanical behavior. It has been found that 70 µm and 200 µm layer thickness gives a better mechanical performance. From the result, it can be concluded that the suggested optimum lattice structure property is from the lattice ID of As/Hc/70/2.4 or As/Cr/70/2.4. The cross (Cr) and honeycomb (Hc) print patterns are the parameters that need to be decided during the fabrication of lattice structure, depends on the intended application of the material. This study can be an initiation for a further detailed research on FDM manufactured lattice structure analysis in the future.

## Acknowledgement

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