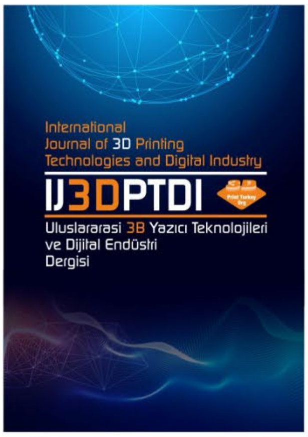


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# INVESTIGATING ENERGY ABSORPTION CAPABILITY OF ADDITIVELY MANUFACTURED CUBOCTAHEDRAL LATTICE STRUCTURES VIA TAGUCHI'S METHOD: EFFECTS OF PROCESS PARAMETERS

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# INVESTIGATING ENERGY ABSORPTION CAPABILITY OF ADDITIVELY MANUFACTURED CUBOCTAHEDRAL LATTICE STRUCTURES VIA TAGUCHI'S METHOD: EFFECTS OF PROCESS PARAMETERS

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## ABSTRACT

This research aims to investigate the influence of process parameters of fused filament deposition additive manufacturing technique on the energy absorption capacity of cuboctahedral lattice structures using Taguchi's method. Four process parameters (i.e., print temperature, print speed, layer thickness, and line width) were considered with three levels of parameter values for each, which resulted in nine combinations in Taguchi's L9 orthogonal array. The lattice structure was fabricated with each of nine combinations of process parameters and tested under a compression load to obtain the energy absorption experimentally. Signal-to-noise ratio analysis was conducted for the results obtained from the experiments of the nine Taguchi sets. Two more lattice specimens were fabricated with the parameter values which resulted in the best and worst energy absorption results and tested. The optimum values of the print temperature, print speed, layer thickness, and line width were determined to be 225 ºC, 30 mm/s, 0.12 mm, and 0.35 mm, respectively. The specific energy absorption (SEA) of the lattice specimen fabricated by using the optimum process parameter values presented 9.4% improvement compared to the highest SEA obtained from the lattices in the Taguchi's L9 array.

**Keywords:** Additive manufacturing, Cuboctahedral lattice, Energy absorption, Taguchi method.

## 1. INTRODUCTION

Applicability of truss-like lattice structures in different industries like medical, automotive, and aeronautics are now well-developed taking account of their success in specific absorbed energy, specific tolerable load, etc. This is because such structures are lightweight and have high stiffness compared to other cellular materials like honeycombs and foams [1]. Another factor in the success of these structures is the advancement of manufacturing technology, i.e., three-dimensional (3D) printing or additive manufacturing (AM). This technology facilitated the fabrication of complex lattice geometries, due to which a variety of designs and geometries can be manufactured [2].

The mechanical properties of lattice structures fabricated by AM are severely dependent on the process parameters (e.g., print speed and temperature) chosen during manufacturing. In this regard, various studies have recently been done to improve the performance of lattice structures by controlling the process parameters [3]. For example, Tang et al. [4] investigated the influence of process parameters of fused filament fabrication (FFF) AM technique on the mechanical properties of lattice structures. They reported that the tensile strength and elastic modulus enhance first and then decline with the increase of the printing temperature. Maximizing the compressive strength of Polylactic acid (PLA) lattice structures was investigated by Dixit et al. [5], resulting in a layer thickness of 0.1 mm, infill density of 100%, and printing speed of 40 mm/s.

Taguchi's methodology is a statistical design of experiment method, which can enhance the quality of manufacturing in several engineering applications, whereby different designs and parameters can be investigated. In this method, Orthogonal Array (OA) design, as a sort of fractional factorial design, is utilized to reduce the number of experiments by selecting subsets of combinations of different factors in several levels. This method was utilized to study the effect of FFF processing parameters on the strength of built parts [6]. They used a four-factor three-level (L9) Taguchi array. This method with an L16 algorithm was employed in the study conducted by Dong et al. [7]. They optimized the FFF process parameters used in fabricating lattice structures to improve the quality. The effects of four process parameters on the quality of built struts were investigated at different levels, reflecting the most effective ones as the fan speed and layer thickness for the inclined and horizontal struts, respectively.

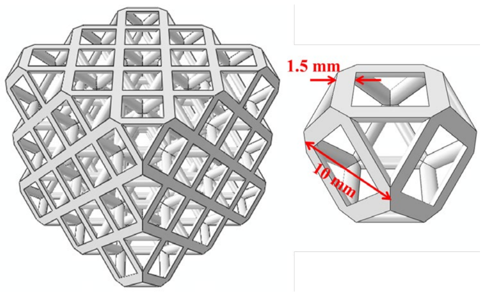
Cuboctahedral lattice has recently been proposed to have a characteristic in transition between the bending- and stretch-dominated lattices. The stretch-dominated lattice structures are known to have higher mechanical properties such as stiffness and strength compared to the bending-dominated lattices. Although the cuboctahedral lattice type has a bending-dominated characteristic, its compressive moduli and strength properties are shown to be competitive with the stretch-dominated lattice structures such as the octet lattice [3]. Besides, a bending-dominated characteristic is known to be preferable for better energy absorption performance of a lattice since the bending characteristic can allow for a smooth deformation behavior in the plastic region[8]. However, the energy absorption performance of the cuboctahedral lattice was not investigated in the literature. Furthermore, the existing study for cuboctahedral lattice [3] did not investigate the fabrication of this lattice with AM techniques. Because such lattices are very difficult to fabricate with traditional manufacturing methods on small scales (micro- or millimeters), AM is preferred for fabricating lattice structures. Hence, the effects of AM process parameters on the energy absorption capacity of the cuboctahedral lattice structure should also be investigated.

In this study, specific energy absorption (SEA) of cuboctahedral PLA lattice structures fabricated through the AM technique called FFF was investigated to address the aforementioned issues. Hence, this study aims to improve its SEA performance further by identifying the optimum process parameter values when manufactured by the FFF technique. To reduce the number of experiments, a four-factor three-level Taguchi methodology (L9) was utilized. Based on the experimental SEA results, the most effective process parameter and the best value of each one were extracted. Moreover, verification tests were done to verify the technique in use.

## 2. MATERIALS AND METHODS

### 2.1. Lattice structure and fabrication

The lattice structure used in this study is of a 3×3×3 cubic pattern with a unit cell size of 10 mm and a strut diameter of 1.5 mm. The cuboctahedral lattice structure specimen and its unit cell are shown in Figure 1. The lattice structures were manufactured with an FFF 3D printer (Creality CR-6 SE) using PLA material.




(a) (b)

**Figure 1.** An illustration of a Cuboctahedral, (a) 3×3×3 lattice structure, (b) unit cell.

### 2.2. Design of experiment

Taguchi's method is a design of experiments (DOE) method, which is utilized to improve the quality of the fabricated parts with a reduced number of experiments compared to the other DOE methods. This method is widely used in various engineering applications [8] as well as for problems including nonlinear plastic deformation and damage of materials [9]. Furthermore, the Taguchi method was used to improve the energy absorption of lattice shells under compressive loading [10]. Because it is preferred in the literature for problems that have similar aims to this study, it is chosen as an appropriate DOE method to use in investigating the effect of process parameters on the energy absorption of cuboctahedral lattices in this study.

Taguchi's three-level four-factor L9 ($3^4$) methodology was utilized in this study. By using this methodology, the number of experiments is reduced from 81 (full factorial) to 9, which increases the speed of data extraction. The sets of the combination of different levels of each factor used to fabricate the different lattice structures are gathered in Table 1. These sets are fixed for Taguchi's L9 algorithm; the letters shown by A, B, C, and D reflect the factors or process parameters and the numbers 1, 2, and 3 indicate the levels of each parameter.

**Table 1.** Experimental runs with an L9 ($3^4$) orthogonal array.

| Run | A | B | C | D |
|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 |
| 4 | 2 | 1 | 2 | 3 |
| 5 | 2 | 2 | 3 | 1 |
| 6 | 2 | 3 | 1 | 2 |
| 7 | 3 | 1 | 3 | 2 |
| 8 | 3 | 2 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |

The four factors or process parameters including Print Temperature (°C), Print Speed (mm/s), Layer Thickness (mm), and Line Width (mm) were investigated in three different values as listed in Table 2.

**Table 2.** Process parameters used in the study.

| Factor | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Print Temp. (°C) | 215 | 220 | 225 |
| Print Speed (mm/s) | 30 | 45 | 60 |
| Layer Thickness (mm) | 0.12 | 0.2 | 0.28 |
| Line Width (mm) | 0.35 | 0.40 | 0.45 |

Three repeated samples of the lattice structure were 3D printed for each of the nine parameter sets (i.e., for Runs 1-9). An image of the fabricated cuboctahedral lattice (i.e., for Run 4) is shown in Figure 2.

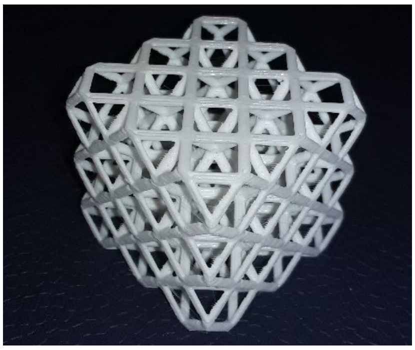
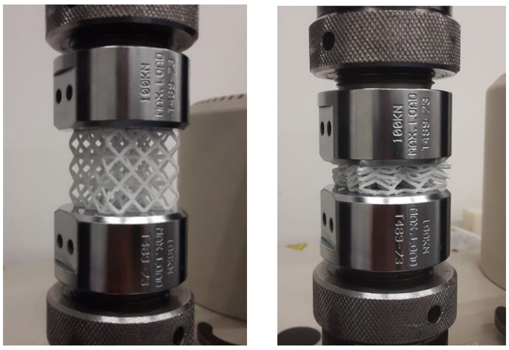


**Figure 2.** Fabricated cuboctahedral lattice.

## 2.3. Compression tests

For the Taguchi method with L9 ($3^4$), nine experiments with three repetitions were conducted as per Taguchi's design of experiment (DOE). Compression testing was performed with a universal testing machine (Instron 600 LX, USA) as shown in Figure 3, based on ASTM D1621 – Compression Testing of Rigid Cellular Plastics with a crosshead speed of 2 mm/min [11,12].



(a) (b)

**Figure 3.** Compression test of a lattice specimen (a) at the start point, and (b) at the densification point.

The data of the tests were recorded as load-displacement curves. This data was also utilized to calculate the values of absorbed energies. The extraction of absorbed energy from load-displacement curves is conducted by

$$E_i = \int_a^b f . dx \qquad (1)$$

where $f$ *and* $x$, show the load and displacement, respectively. Also, $i$ indicate the number of the Run ($i$=1, …, and 9). The values $a$ and $b$, are respectively referred to as the displacement at the start of loading (i.e., equal to 0) and the displacement at the densification point.

The energy absorption is divided by the mass of each lattice structure to calculate the SEA value given by

$$SEA_i = \frac{E_i}{M_i} \qquad (2)$$

where $E_i$ and $M_i$, indicate the absorbed energy and mass of each structure, respectively.

**2.4. Statistical Analysis by Signal-to-Noise (S/N) Ratio**

In the Taguchi method, the terms signal (S) and noise (N) are respectively referred to as the desirable (mean) and undesirable (standard deviation) values. Hence, S/N ratios are utilized to show the quality characteristic differing from the desired output. The reason for this deviation is the presence of some uncontrollable factors called noises, which can be grouped into external factors like human errors, manufacturing defects, and product degradation [13].

Regarding the design objective and process parameters in use, three different quality characteristics can be utilized; the-larger-the-better (Eq.3), the-smaller-the-better (Eq.4), and the-nominal-the better (Eq.5) [14].
The formulation for each is respectively given as follows:

$$S/N = -10\log_{10}\left(\frac{\sum_{i=1}^{N} {}^{1}/{}_{y_i^2}}{N}\right) \quad (3)$$

$$S/N = -10\log_{10}\left(\frac{\sum_{i=1}^{N} y_i^2}{N}\right) \quad (4)$$

$$S/N = 10\log_{10}\left(\left(\frac{\bar{y}}{s}\right)^2\right) \quad (5)$$

$$\bar{y} = \frac{\sum_{i=1}^{N} y_i}{N}$$

$$s = \frac{\sum_{i=1}^{N} (y_i - \bar{y})^2}{N-1}$$

In this study, the main aim is to improve the amount of SEA values. Hence, with the help of the-larger-the-better quality characteristic [15], the S/N ratio was implemented to determine and rank the effectiveness of the process parameters involved.

## 3. RESULTS AND DISCUSSION

### 3.1. Energy absorption results

The load-displacement curves obtained from the compression tests are shown in Figure 4 for the fabricated specimens for 9 different process parameter sets. The responses related to the confirmation tests (i.e., Conf. Best and Conf. Worst) were plotted in the figure, as well.
The SEA values, calculated from these load-displacement curves using Eq. (1) and (2), are listed in Table 3 for each experiment. The values related to the confirmation tests (i.e., Conf. Best and Conf. Worst) were included in Table 3, as well.

### 3.2. S/N ratio results

The S/N ratio was calculated for the SEA results based on the-larger-the-better case given by Eq. (3). The calculated S/N ratio values for each value of three levels of four parameters in Table 2 are listed in Table 4. The rank value in Table 4 shows the effect of each of the four parameters on the SEA results. As seen in Table 4, the layer thickness has a rank value of 1, which means it is the most effective parameter for improving the SEA result of the lattice structure. The least effective parameter is found to be the print speed because it has a rank value of 4. The second and third effective process parameters were observed as the line width and print temperature, respectively.

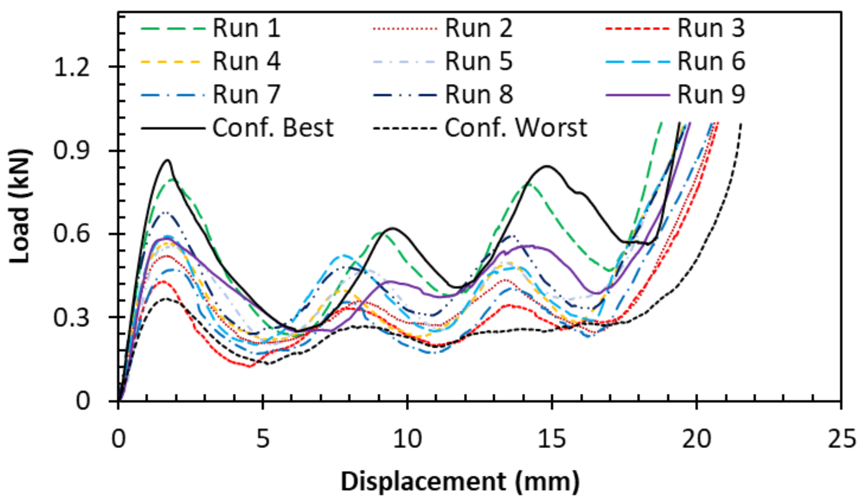



**Figure 4.** Load-displacement responses of each experiment (i.e., Run), extracted from the compression tests.

**Table 3.** The results of the experiments.

| Sample | Print Temp. (°C) | Print speed (mm/s) | Layer thickness (mm) | Line width (mm) | Mean SEA (J/g) |
|---|---|---|---|---|---|
| **Run 1** | 215 | 30 | 0.12 | 0.35 | 2.810 |
| **Run 2** | 215 | 45 | 0.20 | 0.40 | 2.187 |
| **Run 3** | 215 | 60 | 0.28 | 0.45 | 2.179 |
| **Run 4** | 220 | 30 | 0.20 | 0.45 | 2.289 |
| **Run 5** | 220 | 45 | 0.28 | 0.35 | 2.369 |
| **Run 6** | 220 | 60 | 0.12 | 0.40 | 2.460 |
| **Run 7** | 225 | 30 | 0.28 | 0.40 | 2.119 |
| **Run 8** | 225 | 45 | 0.12 | 0.45 | 2.607 |
| **Run 9** | 225 | 60 | 0.20 | 0.35 | 2.530 |
| **Conf. Best** | 225 | 30 | 0.12 | 0.35 | 3.073 |
| **Conf. Worst** | 220 | 45 | 0.28 | 0.40 | 1.902 |

It is worth noting that the delta value for each process parameter given in Table 4 is calculated in terms of S/N values extracted for three different levels (as gathered in Table 4) by subtracting the smallest value from the largest one. Then, based on the delta value, the rank of each process parameter is calculated. In other words, the higher the delta value, the higher the rank of the relevant process parameters. For example, the layer thickness has the highest delta value and therefore, its rank is 1, which means it is the most effective parameter.

The S/N ratio data in Table 4 are also plotted for each parameter in Figure 5. The layer thickness plot in Figure 5 shows that the S/N ratio decreases with the increase of the layer thickness. Because the-larger-is-better case was considered to calculate the S/N ratio, the decrease of the S/N ratio indicates that increasing the layer thickness leads to a decrease in the SEA result of the lattice structure.

However, the trends of the plots in Figure 5 are not uniform for the print temperature and line width. It is seen that the print temperature of 220ºC and the line width of 0.4 mm reflected the lowest values of SEA because the lowest S/N values were obtained for these parameter values.

The least effective process parameter, which was found to be the print speed with a rank value of 4 in Table 4, can be seen to have almost a linear plot in Figure 5. That means the print speed does not change the SEA measurably. However, by increasing the print speed from 30 mm/s to 45 or 60 mm/s, the SEA value slightly declines. Also, it is worth noting that the worst value for the line width was found at 0.40 mm.

### 3.3. Confirmation Test

Based on the results obtained from S/N ratio analyses, two more sets were manufactured, and compression tested to calculate the SEA values. Two sets of process parameters' combinations including levels that lead to the best and worst SEA result were utilized to fabricate the lattice specimens, which were named Conf. Best and Conf. Worst, respectively.

The parameter values that gave the best S/N ratio values (i.e., the best SEA values), which is called Conf. Best, were obtained as follows: The print temperature, print speed, layer thickness, and line width are 225 ºC, 30 mm/s, 0.12 mm, and 0.35 mm, respectively. The parameter values, which give the worst S/N ratio results and form the Conf. Worst, were 220 ºC, 45 mm/s, 0.28 mm, and 0.40 mm, respectively. The cuboctahedral lattice structures were manufactured with three repetitions with these two parameter value combinations and subsequently compression tests were done on them in a condition the same as the previous ones (i.e., Runs 1-9).

Load-displacement responses of the compression tests of the new lattice specimens are shown in Figure 4. The corresponding SEA values were calculated as 3.073 J/g and 1.902 J/g as listed in Table 3 for the Conf. Best and Conf. Worst, respectively.

**Table 4.** Response Table for S/N Ratios.

| Level | Print Temp. (°C) | Print Speed (mm/s) | Layer Thickness (mm) | Line Width (mm) |
|---|---|---|---|---|
| 1 | 7.512 | 7.563 | 8.372 | 8.176 |
| 2 | 7.501 | 7.537 | 7.351 | 7.046 |
| 3 | 7.636 | 7.549 | 6.926 | 7.427 |
| Delta | 0.135 | 0.026 | 1.446 | 1.130 |
| Rank | 3 | 4 | 1 | 2 |

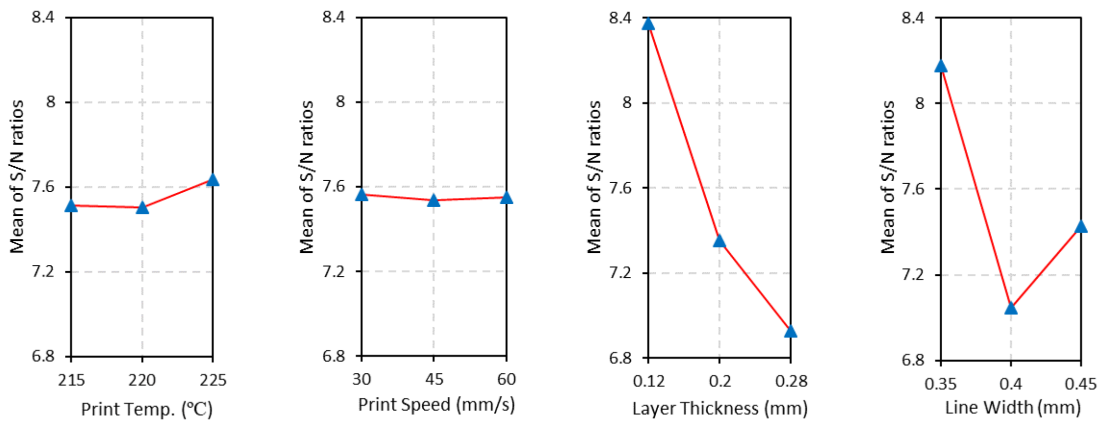



**Figure 5.** Mean effects plot for S/N ratios.

A comparison was made between the SEA values calculated for the new structures (i.e., Conf. Best and Conf. Worst.) and the structures with the highest and lowest SEA in the 9 Taguchi set (i.e., Run 1 and Run 7, respectively). It was found that the Conf. Best lattice structure reflects a 9.4% improvement in the SEA result compared to its highest value in 9 sets (i.e., for Run 1). A reduction of 10.2% in SEA was obtained for Conf. Worst compared with the results of the lattice structure with minimum SEA in 9 sets (i.e., for Run 7).

In other words, combining the parameter values, which gave the best S/N ratio values in Figure 5, resulted in a higher SEA result compared to the results for the parameter sets used in the Taguchi method as seen in Table 3. Similarly, the combination of the parameter values, which gave the worst S/N ratio values in Figure 5, gave a lower SEA result compared to the results for the parameter sets used in the Taguchi method. These results confirm that by using the Taguchi method and calculating the S/N ratio values for each parameter, the best and worst combinations of the parameter values can be determined correctly.

## 4. CONCLUSIONS

The energy absorption capacity of cubic 3×3×3 Cuboctahedral lattice structures manufactured from PLA via the FFF technique was investigated through three-level four-factor L9 Taguchi's method. Four different process parameters were investigated and the most effective one was found as layer thickness followed by line width, print temperature, and print speed. By using the combination of the best and worst values for each process parameter, the lattice specimens were fabricated and tested. The calculated SEA results proved that the combination of the parameter values that give the best and worst S/N ratio values for each parameter gives the best and worst SEA results, respectively. Thus, it was concluded that the calculated S/N ratio results for each parameter can be used to identify a combination of different parameter values to improve the SEA performance of the cuboctahedral lattice structure fabricated by the FFF technique. Furthermore, the SEA results of cuboctahedral PLA lattice structures highlight the importance of lightweight and mechanically efficient designs.

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