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Application of Lattice Structure in Weight Optimization

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Abstract: In this study parameters of lattice structure were analyzed for weight optimization. Lattice structure has various geometrical parameters such as percentage infill, cell thickness, cell type and orientation of cell. These parameters influence the mechanical properties of the component. These four independent parameters influence the functionality of component. Each parameter has three different levels which lead to large number of experimental combinations. Taguchi Method of Design of experiments is used to minimize the experiments which affect the time required and cost of experimentation. L9 orthogonal array is used to obtain suitable combination of lattice parameters as per functional requirements. MINITAB 19.0 is used to carry out statistical calculation. Analysis of variance is applied to get contribution of each parameter in weight optimization. Optimization of weight is carried out for minimum deflection and stress values. These complex lattice structures are modeled in ANSYS Space Claim 19.0. Using 3D printing technique prototypes are manufactured for experimentation. ABS and PLA materials are used to manufacture these structures. Experimentation is carried out on Universal Testing Machine. These experimental results were validated with Ansys simulation results. Experimental analysis concludes with best suitable combination of lattice parameters and contribution of each parameter in weight optimization.

Keywords* —*Lattice structure, Optimization, Design of Experiments, Taguchi Method, Additive Manufacturing, ANOVA

I. INTRODUCTION

Cellular Materials such as foam, Honeycomb, and Lattices are used in application where tailored mechanical properties are required. It has been used for various lightweight applications in the area of aerospace, automotive and Bio-medical [1]. The availability of additive manufacturing technology has eased the fabrication limitation of lattice structures. Additive Manufacturing describes the technology of generative production process. It is the process of manufacturing in which physical objects are made using layer by layer selective fusion, sintering and polymerization of a material. Different geometrical factors affect the mechanical properties of these structures.

Taguchi and Konishi developed statistical method of orthogonal array (OA) known as Taguchi Method [2]. Its application as Manufacturing processes, Biotechnology, Chemical Industries, Marketing and Advertising etc [3]. Taguchi method helps statistician and engineers to receive the goal and improved parameters. The method will reduce scrap, defects and lower cost of production and experimentation [4]. Taguchi Approach is to design robust systems that are more reliable and consistent [5].

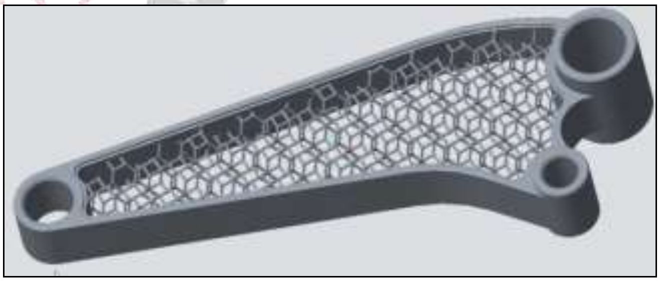

Figure 1 Lattice structure used for weight optimization

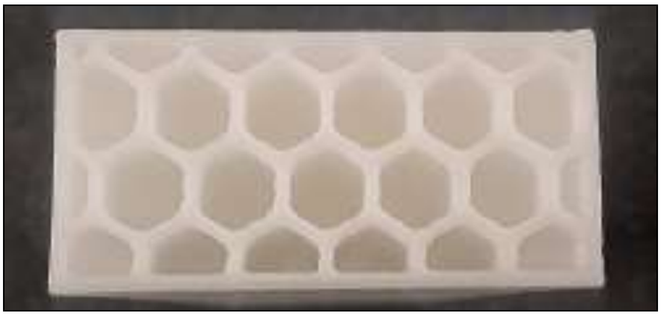

Figure 2 Cross section of Honeycomb structure

Above figure 1 shows weight optimized component with the help of lattice structure modeled in CREO 5.0 and figure 2 shows 3d printed honeycomb structure.

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II. Lattice Structure

Gibson and Ashby describe the cellular structure as “An assembly of cells with solid edges and/or faces, packed together so that they fill space” [9]. Some Natural Cellular structures exist in nature is cork, bee honeycomb, sponge, wood, coral. Like in many other cases, humans learned from nature, recognized the potentials of cellular structures having excellent properties at a relatively low mass and tried to copy them with their own means. For a better understanding man-made cellular material should be divided into stochastic structures and designed periodic structures, as well as in two dimensional and three-dimensional shapes.

A. Honeycombs (2D, stochastic, periodic)

B. Foams (3D, stochastic)

C. Designed Lattice Structures (3D, periodic)

Cellular materials mentioned have been utilized for centuries in a wide variety of applications and are common in natural materials such as wood, bone, sponge, and coral. These can be stated as a structure that consists of a connection of solid plates or struts which form Network of the edges and faces of cells. Recently these materials have been specifically designed to fulfill multi-functional material requirements in light weighting, thermal insulation, energy absorption and heat transfer [10]. Even though altering parameters of manufacturing processes allow for some amount of control over pore shapes and sizes, they remain restricted to producing randomly organized structures. Compared to other types of cellular structures including foams and honeycombs lattice structures are more flexible to achieve a wide range of different desired physical properties [11], such as high stiffness weight ratio, low thermal expansion coefficient, negative Poisson ratio and high heat dissipation rate through active cooling. Due to its outstanding performance, lattice structures have been used in a broad spectrum of applications.

III. Design of Experiment

The design of experiments is considered as one of the broadest and far-reaching approaches in the product as well as process development. It gives predictive knowledge of multiple variables and complex process with few acceptable trails. Optimization of an experimental process has following main approaches to the design of experiments.

A. Full Factorial Design

A full factorial design involves design consisting of two or more factors, each with a discrete possible level and it takes all the possible combination of all the levels of an experiment [6]. The sample size is the product of several levels of each experiment. For example, if three process parameters are involved in a process with levels as two, three and four respectively then the number of experiments in factorial design will be 2x3x4=24. Similarly, for two levels with k parameters number of experiments are 2^k and for three levels of k parameters, it will be 3^k.

B. Taguchi Method

Taguchi method is a highly fractional design which reduces the number of experiments to be carried out to the acceptable level. Array selector is used to determining the number of experiments to be carried out. S/N ratio and ANOVA gives importance of each parameter on process outcome. Taguchi method has been applied to optimization problems. Standard orthogonal array selector is given in the table shown below for various parameters and corresponding levels to get the desired outcome.

Full factorial designs are the most conservative of all design types, unfortunately because the sample size grows exponentially with the number of factors, full factorial designs are often too expensive to run. Taguchi method of design is less conservative but more efficient and cost-effective.

Table 1 Orthogonal Array Selector

	NUMBER OF LEVELS			
	2	3	4	5
2	L4	L9	L16	L25
3	L4	L9	L16	L25
4	L8	L9	L16	L25
5	L8	L18	L16	L25
6	L8	L18	L32	L25
7	L8	L18	L32	L50
8	L12	L18	L32	L50
9	L12	L27	L32	L50
10	L12	L27	L32	L50
11	L12	L27		L50
12	L16	L27		L50
13	L16	L27		
14	L16	L36		
15	L16	L36		
16	L32	L36		
17	L32	L36		
18	L32	L36		
19	L32	L36		

With the help of Table 1 number of experiments to be carried out for the problem is shown. The number of parameters and their respective number of levels determines the number of experiments to be carried out. Array to be used is mentioned in Table. For six parameters with three levels full factorial method suggest 729 experiments to obtain the best combination of parameters but in case of Taguchi method, it requires 18 experiments to be carried out to find the required optimum results. Steps followed in Taguchi method are as shown in figure 3 [8]. these four phases were used to carry out entire research work.

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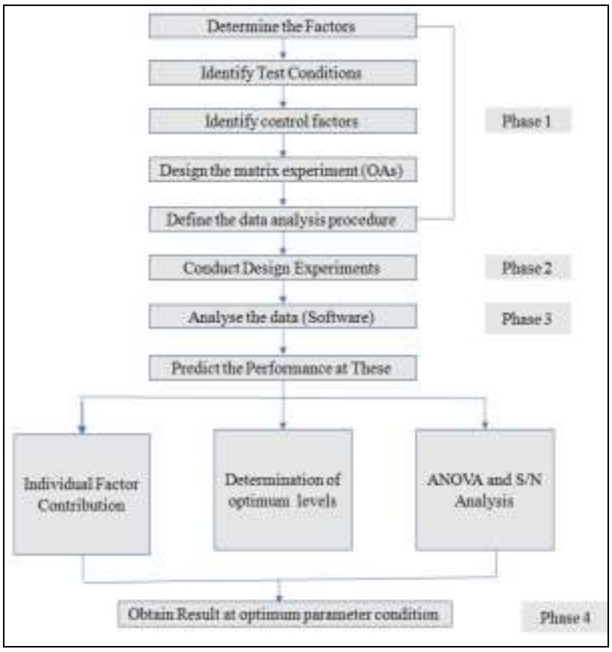

Figure 3 Steps in Taguchi Method

IV. PARAMETRIC ANALYSIS USING TAGUCHI METHOD

There are various parameters in 3D Lattice structure which are responsible for weight optimization. According to the Taguchi Method following steps are carried out.

A. *Identification of the main Function*

The beam as seen in following figure 4 is loaded under three point Bending test as shown in figure 5. There is roller support and load of 1000 N applied at the center. Material used for the beam was ABS and PLA. There are various parameters in 3D Lattice structure which are responsible for optimization of deformation, like Lattice type, Infill percentage, Wall thickness, Lattice orientation. The Objective is to find which parameter influences the Deformation the most and to find the best suitable combination for optimal deformation.

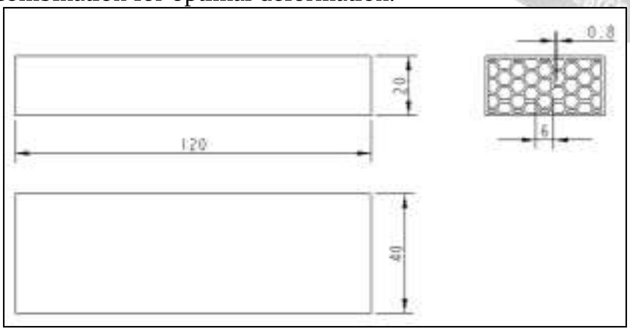

Figure 4 Detail Drawing of specimen

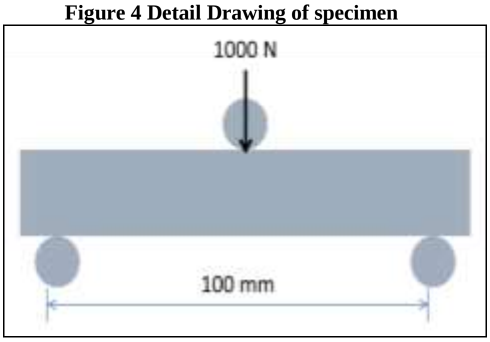

Figure 5 Loading Condition of specimen

B. *Identification of Objective Function*

In a different type of Experiments, there are three types of object functions smaller is better, Nominal is better and larger is better. S/N ratio Calculation Formulae are given below for this study objective function is smaller is better for deformation.

Objective Function: Smaller the Better

C. *Control Factors and their levels*

The factors and their levels were decided for conducting the experiment, based on the available parameters of cellular structure independent 3 parameters and 3 levels were selected as shown in table 2.

Table 2 Control factors and their levels

Parameters	Levels		
Lattice Type	Hexagonal	Square	Triangle
Infill %	75	50	25
Thickness	0.6	0.8	1.0

Cellular structure parameters are given below in figure as Lattice cell Type, Infill percentage, Cell thickness. Figure 6 shows geometrical parameter cell wall thickness and shell thickness.

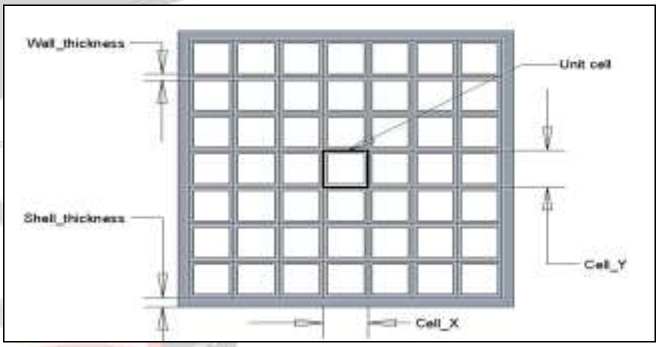

Figure 6 Lattice parameter specified cell thickness

Lattice structures are classified as 2D and 3D lattice structure, this experimental analysis mainly concentrated on 2D lattice structure. Lattice types are shown in figure 7 as hexagonal lattice, square lattice, and triangular lattice.

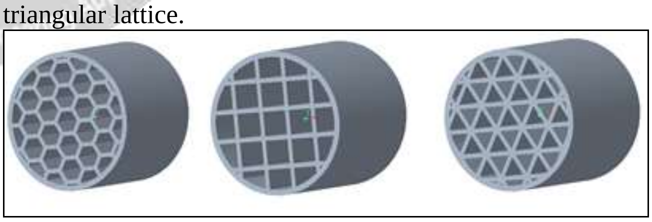

Figure 7 Lattice Type: a) Hexagon b) Square c) Triangle

Percentage infill stands for shell volume filled by material. The Size parameters are linked. Changing the infill will change Length and changing Length will change infill. Changing the Thickness will also change the infill percentage. Figure 8 shown below consists of models with different infill percentage.

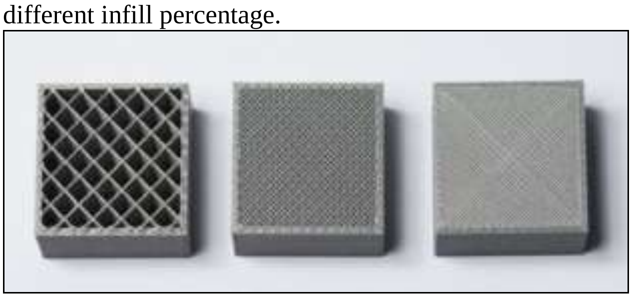

Figure 8 Percentage Infill a) 25% Infill b) 50% Infill c) 75% Infill

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D. Orthogonal Array Selection

To select an appropriate orthogonal array for conducting the experiments are to be computed. The most suitable orthogonal array is L9 array as shown in Table 3. Therefore; total 9 experiments must be carried out.

Table 3 Orthogonal Array Selector

	PARAMETERS							
L	1	2	3	4	5	6	7	8
E	2	L4	L4	L8	L8	L8	L8	L12
V	3	L9	L9	L9	L18	L18	L18	L18
E	4	L16	L16	L16	L16	L32	L32	L32
L	5	L25	L25	L25	L25	L50	L50	L50

L9 orthogonal array gives nine experimental combinations of three parameters with their three levels. Table 4 shows different combinations of parameters. With the help of these nine combinations different geometries are formed using ANSYS SpaceClaim. Advantage of using ANSYS SpaceClaim is it avoids further need of de-featuring and gives simplified methods for lattice creation and optimization.

Table 4 Experimental Combination L9 Array

Experiment Number	Lattice Type	Infill %	Thickness (mm)
1	Hex	75	1.0
2	Hex	50	0.6
3	Hex	25	0.8
4	Square	75	0.6
5	Square	50	0.8
6	Square	25	1.0
7	Triangle	75	0.8
8	Triangle	50	1.0
9	Triangle	25	0.6

Nine different geometries with different parametric combinations are shown in below. These complex structures are modeled in ANSYS 19.0 and cross section view is as shown in figure 9 and figure 10. Geometries shows impact of parameters on volume filled with material.

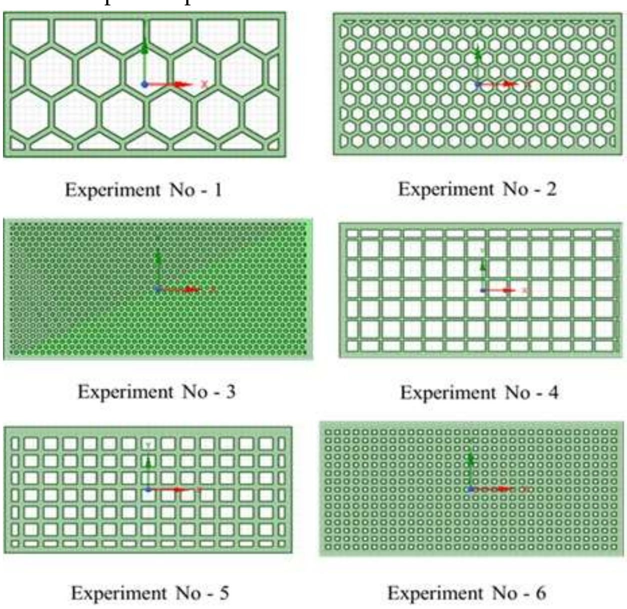


Figure 9 Geometry Modeled in ANSYS SpaceClaim

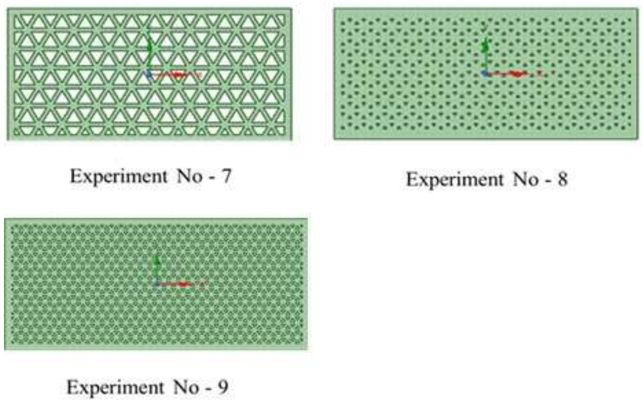
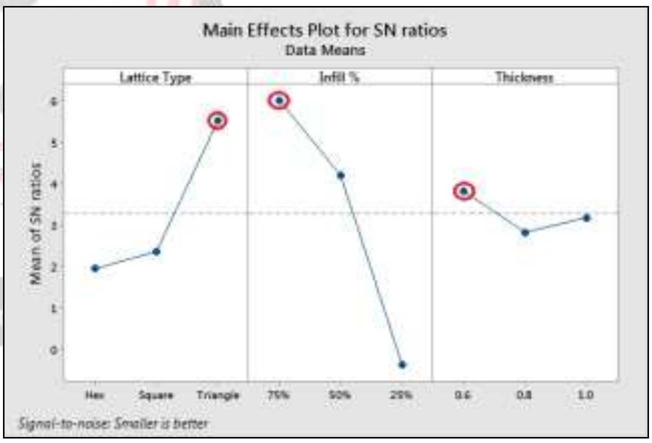


Figure 10 Geometry Modeled in ANSYS SpaceClaim

E. Signal to Noise Ratio

Signal to noise ratio depends on requirement of objective function. Formulae and significance of each condition are followed to derive results.

For objective function as larger is better goal is to obtain maximized response, in such case data characteristics is positive, For objective function as Nominal is best goal is to obtain the response and we want to base the signal-to- noise ratio on standard deviations only, in such case data characteristics is positive. Data characteristics is positive, negative or zero. For objective function as smaller is better goal is to minimize the response, in such case data characteristics is negative. Statistical calculations are carried out in MINITAB 19.0 Software.



Graph 1 Main effect plot for S/N ratio

The Graph 1 gives optimum parameter combination to get a smaller value of deformation. Main effect Plot of S/N ratio gives the selection of parameters. Results were drowned for the same. Statistical analysis of Response of mean and S/N ratio is carried out in MINITAB 19.0. From the graph lowest mean value for each parameter has been selected to obtain results given below in Table 5. Table shows the optimum combination of parameters and corresponding deformation of specimen.

Table 5 Desired Optimum Parameters and corresponding deformation

Lattice Type	Infill Percentage	Thickness (mm)	Deformation (mm)
Triangle	75	0.6	0.39

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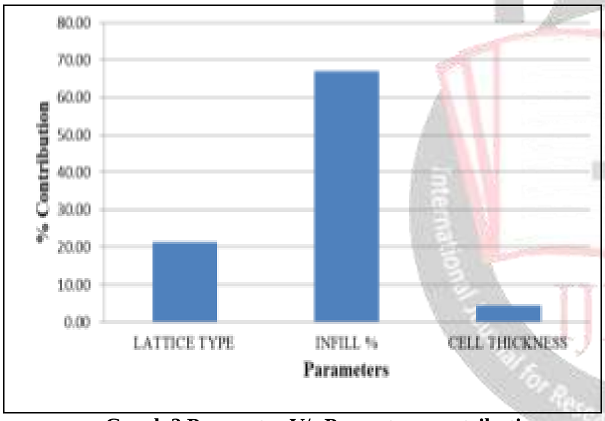
F. Analysis of Variance

Table 6 Statistical data in Calculation of ANOVA

Source	DF	Adj SS	Adj MS	P-Value	Percentage contribution
Lattice Type	2	0.18	0.09	0.25	21.24
Infill %	2	0.57	0.28	0.09	67.07
Cell Thickness	2	0.03	0.01	0.62	4.40
Error	2	0.06	0.03		7.29
Total	8	0.85			100.00

Analysis of Variance (ANOVA) provides the information about importance of the effect of each control parameter on the quality characteristics of functional requirement as deformation. The total variation in the result is the sum of variation due to various control factors, their interactions and due to experimental error. It can be derived from the table 6 that ANOVA for raw data and S/N data is applied to find the significance of parameters and measures or calculate their effect on the performance characteristics in product or process. Graph 2 shows percentage contribution of each parameter. Percentage infill has maximum of 67% contribution.



Graph 2 Parameter V/s Percentage contribution

V. ADDITIVE MANUFACTURING

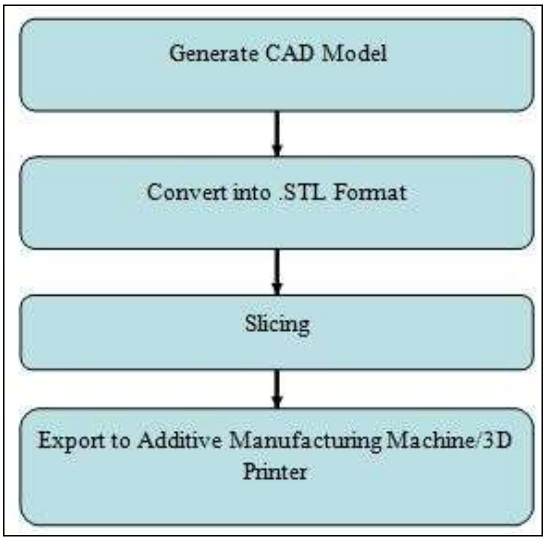


Figure 11 Process flow in Additive Manufacturing

To manufacture the component using Additive manufacturing, we need to follow simple steps as shown in Figure 11. Firstly we have to generate CAD model using any modeling software and then convert it into STL format. In STL format the CAD model is converted into numbers of facets having data which includes the vectors of position of each vertex and normal vectors. Then the STL format file is feed to Slicing tool. In slicing tool the codes are generated, which is used to step by step generation of part in additive manufacturing machine. Thus, here the part generated is shown in figure12.

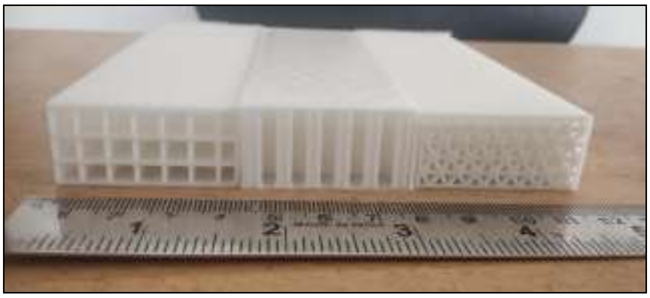


Figure 12 3d printed specimens

VI. EXPERIMENTATION

Total four test specimens were prepared for three point bending test on universal testing machine. Each test specimen have different lattice structure i.e. square, triangular, hexagonal and hexagonal lattice with orientation. These entire specimens were made of PLA material and manufactured using 3D printing method. parameter combination is shown in table 7.

Table 7 Parameter combination for lattice structure

Sr No	Lattice Type	Infill %	Thickness
1	Square	25%	0.8
2	Triangle		
3	Hexagonal		
4	Hexagonal with Orientation		

All test specimen have 25% infill percent and uniform thickness of 0.8mm. Cross sectional view of test specimens are shown in figure 13.

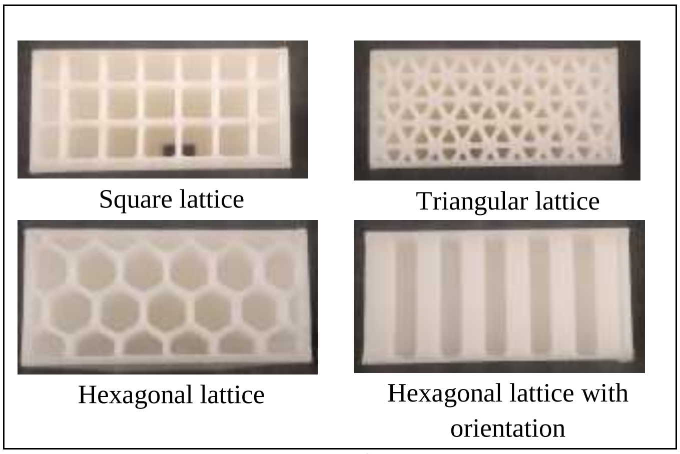


Figure 13 Samples used for experimentation

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Figure 14 Universal testing machine

Compressive and tensile strengths are used to test specimen using Universal Testing Machine (UTM). In this paper UTM is used to perform three point bending test. Three point bending test is a compression test where specimen is supported across its length using two supports at each end. There is no support used at the middle of specimen below it. Then specimen is pressed down from above in the middle of its span until specimen breaks or achieves specific value of deformation. Loading condition for experimentation is as shown in figure 16 and figure 14.

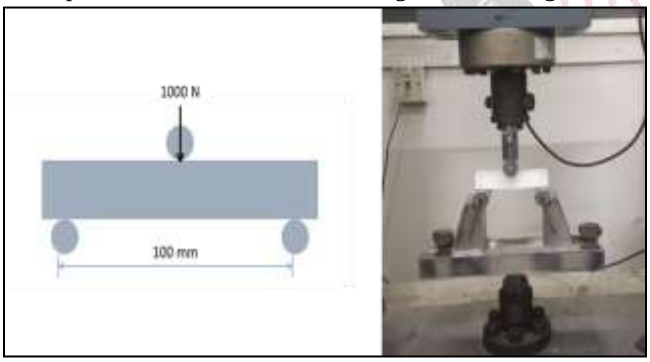

Figure 15 Loading condition for three point bending

VII. Graphs and Results

A. Result from simulation

After deciding the number of parameters and level we formed the L9 array means nine numbers of experiments as per Taguchi method. For nine different experiments that is nine different variety of Lattice structure in the beam were prepared using the CAD software. The beam was set to suitable boundary condition and the force of 1000 N applied at centre of beam and the simulation was done. Hexagonal/ Brick Meshing were done with minimum two bricks occupied in the minimum thickness in the beam. The results were found for maximum Von-mises stress and maximum deformation. Result of deformation and stresses were plotted and values for different combinations were listed. The following table 8 shows the values for each Experiment.

Table 8 Results from simulation

Experiment Number	Lattice Type	Infill %	Thickness (mm)	Deformation (mm)
1	Hex	75	1.0	0.5323
2	Hex	50	0.6	0.7318
3	Hex	25	0.8	1.313
4	Square	75	0.6	0.5337
5	Square	50	0.8	0.6518
6	Square	25	1.0	1.27
7	Triangle	75	0.8	0.4405
8	Triangle	50	1.0	0.493
9	Triangle	25	0.6	0.6842

After the simulation pictorial results were plotted for stresses and deformation. sample of pictorial Results are shown in figure 16 and figure 17. pictorial result shows the location and values of maximum as well as minimum stress and deformation.

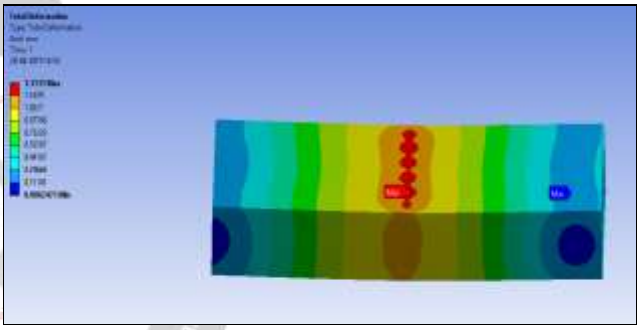

Figure 16 Deformation for hexagonal lattice

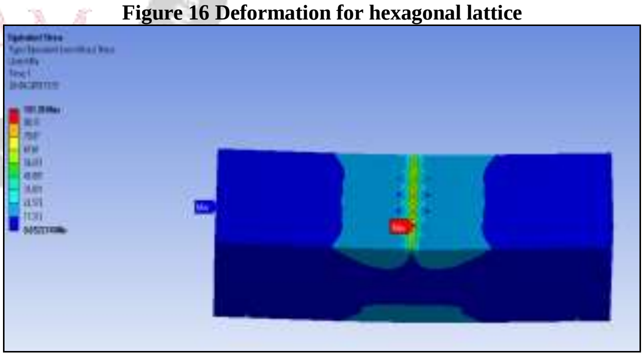

Figure 17 Stress in hexagonal lattice

B. Optimum deformation result

Table 9 shows the optimum combination of parameters and corresponding deformation of specimen. optimum functionality condition of lattice parameters is derived as triangular with 75 percentage of infill and 0.6 mm of cell thickness.

Table 9 Optimum Parameters and corresponding deformation

Lattice Type	Infill Percentage	Thickness (mm)	Deformation (mm)
Triangle	75	0.6	0.39

C. Percentage Contribution (ANOVA result)

ANOVA shows percentage contribution of each of the three parameters on the functional characteristics. For functional requirement Percentage infill has maximum of

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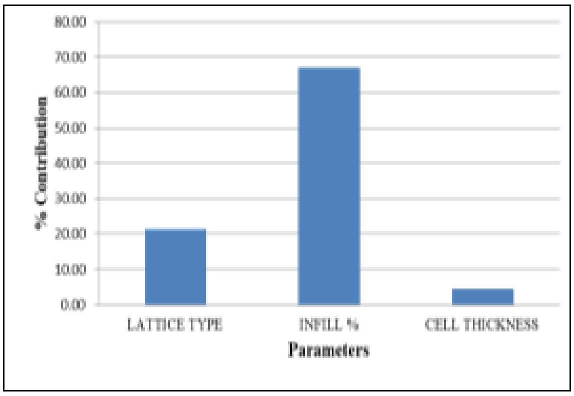
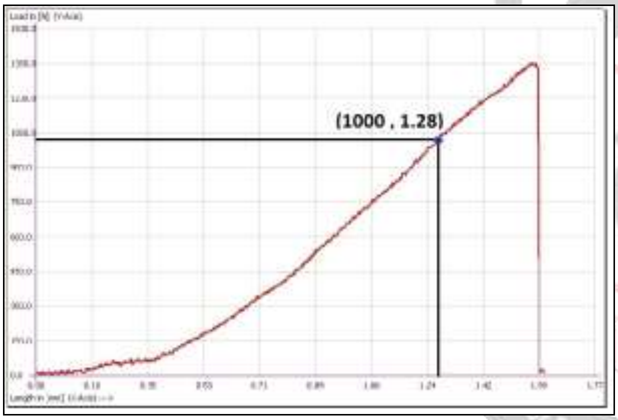
67% contribution. Graph 3 shows percentage contribution of each parameter.



Graph 3 Parameter V/s Percentage contribution

D.Result from experimentation (UTM Testing)

Total four test specimens were tested for three point bending test on universal testing machine (UTM). Each test specimen have different lattice structure i.e. square, triangular, hexagonal and hexagonal lattice with orientation. All test specimen had 25% infill percent and uniform thickness of 0.8mm. values for breaking load and deformation were drawn from experimentation on universal testing machine (UTM).



Graph 4 Load Vs Deformation (UTM Result)

From Graph 4 experimentation shows deformation of 1.28 mm and simulation gives deformation of 1.313mm at load 1000N. Hence the simulation results matches the actual problem with 97.48 % accuracy.

Table 10 Result from Experimentation

No. ⇨	**1**	**2**	**3**	**4**
Lattice Type	Square	Triangle	Hexagonal	Hex orientation
Infill %	25	25	25	25
Thickness (mm)	0.8	0.8	0.8	0.8
Breaking Load (N)	1924.9	1329.09	1952.94	1808.3
Deformation (mm)	1.28	1.59	1.86	3.08
Mass (gm)	41	67	41	40
Weight (N)	0.4022	0.6572	0.4022	0.3924
Breaking Load/Weight	4785.8	2022.14	4855.52	4608.3

Breaking load per unit weight were calculated from the breaking load and weight values. breaking load per unit weight values are listed in table 10. It is derived from table that Hexagonal Lattice structure is best suited under perpendicular loading condition compared to other Lattice type and orientation. Lattice cell orientation perpendicular to the loading direction gives better strength than lattice cell orientation parallel to direction of loading.

VIII. Conclusion

This paper illustrates the application of the Lattice structure in optimization. The following conclusions can be drawn based on the above experimental results of this study

Specimen with Hexagonal structure is best suited under perpendicular loading condition compared to other Lattice type and orientation. Lattice orientation perpendicular to the loading direction gives better strength than lattice orientation parallel to direction of loading.

In Process/Product development of cellular structure problem to obtain tailored mechanical properties Taguchi method is suitable as per this study. Taguchi method applied on the simply supported beam for three parameters and three level problems. It concludes that for optimum functionality condition lattice parameters as triangular with 75 percentage of infill and 0.6 mm of cell thickness is best suited.

Infill Percentage has more contribution in functional requirements than other parameters as shown by analysis of variance (ANOVA) with 67%. For functional outcomes as von-mises stress and deformation infill percentage is considered as most important parameter.

Specimen with Hexagonal lattice structure and lattice structure with perpendicular orientation are compared and it is seen that loading in perpendicular to the hexagonal orientation is preferred as it can bare more load to weight than other structure.

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References

[1] Dr. David Rosen, Dr. Scott Johnston, Marques Reed and Dr. Hongqing Wang, "Design of General Lattice Sturcture for Light Weight and Compliance Application" pp 1-14

[2] Taguchi G and Konishi "Taguchi Methods, orthogonal arrays and linear graphs, tools for quality american supplier institute" vol.1, pp. 18-35.

[3] Rao, Ravella Sreenivas, C. Ganesh Kumar, R. Shetty Praksham & Phil J. Hobbs, "Taguchi Methadology as a

 DOI : 10.35291/2454-9150.2020.0572

Statistical Tool for Biotechnological Applications: A critical Appraisal" Vol 4, pp 510-523

[4] Box G. and S. Bisgaard "Statistical tools for improving design" Vol 110, pp 32-40

[5] Byrne D. M., S. Taguchi, "The Taguchi Approach to Parameter Design" Vol 20 pp 19-26 1987

[6] Srinivas Atherya and Dr Y. D. Venkatesh, "Application of Taguchi Method for Optimization of Process parameters in improving the surface roughness of lathe facing operation", Mumbai, India. vol. 1.pp.13-19.

[7] Vinitkumar K. Modi and Darshan A Desai, "Review of Taguchi Method, DOE and Analysis of Variance for quality improvement through optimization in Foundry," Gujurat, India. Vol 5, pp. 184-193, Jan 2018.

[8] W. T. Foster, "Basic Taguchi DOE" National Association of Industrial Technology Conference Pitsburg PA 2000

[9] S. N. R. Kantareddy, B. M. Roh, T. W. Simpson, S. Joshi, C. Dickman, E. A. Lehtihet, "Saving weight with metallic lattice structures design challenges with a real-world example," Solid Freeform Fabrication,2016.

[10] Deniz Hara, Gökhan O. Özgen, "Investigation of weight reduction of automotive body structures with the use of sandwich materials," 6th Transport Research Arena April 18-21, 2016.

[11] Elza Thomas Ukken, Beena B.R., "Review on structural performance of honeycomb sandwich panel," International Research Journal of Engineering and Technology (IRJET), Volume:04, Issue:06, June 2017

 DOI : 10.35291/2454-9150.2020.0572