Determining the Factors Responsible for Affecting Impact Strength of a Carbon Fibre 3-D Printed Specimen Using Design of Experiments

Shubham Parekh[1], Pawan Bhandari, Ph.D.[1] and Praneel Acharya, Ph.D.[2]
[1]Department of Automotive & Manufacturing Engineering Technology,
[2]Department of Mechanical Engineering,
Minnesota State University
Mankato, MN 56001, USA
Shubham.parekh@mnsu.edu; pawan.bhandari.2@mnsu.edu; praneel.acharya@mnsu.edu

Abstract

The utilization of carbon fiber 3D printed specimens is progressively expanding across various applications that need exceptional levels of strength and stiffness. Nevertheless, the impact strength of these specimens may be influenced by several parameters, including carbon fiber content, infill pattern, density, printing speed, and layer thickness. This research study uses the design of experiments (DOE) methodology to examine the parameters that influence the impact strength of carbon fiber 3D printed specimens. A statistical model has been established to forecast the impact strength of carbon fiber 3D printed specimens, taking into consideration the elements. The study's findings indicate that the impact strength of carbon fiber 3D printed specimens is mostly influenced by the infill density in comparison to other parameters. The impact strength is significantly influenced by the interaction effects of layer thickness, infill pattern, and infill density. The statistical model created in this research may be used to ascertain the most suitable amalgamation of variables to get the intended level of impact strength for a certain application. This phenomenon has the potential to enhance the overall performance, longevity, and safety attributes of many items.

Keywords
Design of Experiments, Carbon Fibre, Impact Testing, 3-D Printing, Interaction Effects.

1. Introduction
Carbon fiber is a lightweight yet durable material that is composed of carbon atoms bonded together in a crystalline structure. It is known for the composite material known as polylactic acid (PLA) and is characterized by its ability to combine the strength and stiffness often associated with carbon fiber, while also offering the user-friendly and versatile properties of PLA filament. The use of this material is widely favored in 3D printing applications that need exceptional levels of strength and stiffness, particularly within the aerospace, automotive, and sports equipment sectors. The strength of carbon fiber material in a 3D printed component may be influenced by many variables, such as the infill pattern and the thickness of each layer. Identifying the key determinants of impact strength from an extensive range of variables has significant importance. The use of Design of Experiments (DOE) is a methodology that enables the examination of various factors and their impact on a given result.

The use of Design of Experiment (DOE) is a statistical technique that enables the optimization of product or process design. The use of this method facilitates the examination of the impacts of multiple variables on a given response variable. The DOE methodology is founded upon the notion of randomization, whereby the parameters under investigation are systematically modified in a random sequence. This approach aids in mitigating the impacts of bias and confounding variables.
The DOE is often carried out in two phases, the first is the planning phase where the researcher focuses on the variables to be investigated and the response variable to be measured. Additionally, a statistical model is constructed by the researchers to forecast the response variable by considering the various aspects. During the experimental phase, the researcher carries out the experiment in accordance with the established statistical model. Subsequently, the researchers proceed to gather empirical evidence pertaining to the response variable, followed by a comprehensive

analysis of the acquired data in order to ascertain the influence of the variables on the previously mentioned response variable.

Determine the significant factors and the interaction effects between Infill Density, for affecting the Impact Strength of a 3-D Printed part.

1.1. Problem Statement

The opportunity explored in this study is to identify and quantify the significant factors, as well as to investigate the interaction effects among Infill Density, Infill Pattern, and Layer Thickness, with the aim of understanding their individual as well as combined influence on the Impact Strength of 3-D printed parts.

1.2. Research Questions

This study seeks to address the following research questions (RQs) through a controlled experimental design conducted within a university laboratory setting:

RQ1. Among the Infill Pattern, and Layer Thickness of selected material, what are the significant factors that impact the strength of carbon fiber 3-D printed specimens when using a 23 Factorial design with two replicates?
RQ2. Do any of the identified factors exhibit interaction effects?
RQ3. What are the specific levels of these factors that result in the maximum achievable (optimal) impact strength?

In addition to the above mentioned research questions, the key contributions of this work are as follows:

- Investigating the factors that have a significant contribution to the strength of 3D-printed carbon specimens.
- The use of statistical tools in coordination with experimentation will validate the theory.
- Exploring optimization tools to better understand the contributing factors to the strength of 3D-printed carbon specimens.

2. Literature Review

3D Printing is a type of additive manufacturing process where the material is heated to a certain temperature and then the required part is manufactured by adding layers of the material on top of each other. One of the many benefits of 3D-printed carbon fiber parts is the capacity to produce previously impractical complex designs. Because the material can be positioned precisely where it is needed for optimal strength, this enables the fabrication of lightweight components with improved structural performance, minimizing irrelevant weight and material waste. Conventional carbon fiber component production methods often involve tedious and lengthy procedures such as hand layup or filament winding, which can be time-consuming and might also limit design flexibility.

Every 3D printer requires a digital file to manufacture the parts. Computer Aided Design (CAD) models can be designed through various software such as SolidWorks, AutoCAD, etc. Once the CAD model is uploaded to the 3D printing machine, the machine then uses slicing software which divides the entire model into different layers. These layers are then printed on top of each other till the required part is made.

Depending on the machine, there are a wide variety of materials including plastics, metals, composites, etc. which can be used. Every 3D printing machine uses a nozzle to increase the temperature to a certain level at which the material used can be heated so that it can be molded into layers. High-end machines and techniques are used for metals as the required temperature can reach very high levels. However, the most common type of material used for 3D printing is composites. A mixture of two or more materials comprises composites. The idea behind this is to use the different properties of materials in one part. For strengthening the parts, typically Carbon Fiber or Glass Fibers are used. These have a variety of applications where a high weight-to-strength ratio is required. In recent times many automotive companies have started using 3D printed carbon fiber parts for their vehicles.

Carbon fiber materials possess a high structural strength and are used to provide strength and structural rigidity. It has been concluded that having a carbon fiber outer layer increases the Charpy Impact strength of a carbon fiber-reinforced plastic specimen by nearly 50% (B. Wang et al., 2021). There are several studies conducted on the weave structure and pattern of the carbon fibers and there are a few conclusions made on their effect on the mechanical properties of the specimen. In a study, it was concluded that while conducting impact testing on carbon fiber-reinforced plastics, the impact energy varies as the direction of the woven carbon fiber changes. They found out that parts having $0^{o}/90^{o}$

orientation of the fibers have the lowest impact energies while the specimens with 45º/50 º to 45º/45 º orientation of fibers have the highest impact energies. These results are opposite to that of tensile testing (Hong et al., 2013).

While focusing on the volume fraction of fibers, the findings of a study conducted by Kim, indicate that there exists a direct correlation between the fiber volume fraction increase and the consequent improvement in the impact strength of the composite. The maximum enhancement was observed when the fiber volume fraction reached 40% (Karaş et al., 2022). When carbon fiber is added to a specimen the mean length of the fiber decreases as the carbon fiber volume fraction increases. This is due to the fiber-to-fiber interaction. It was concluded here that due to this effect, the Charpy impact energy is reduced by the increase in fiber volume fractions (Fu et al., 1999). The aforementioned investigations have shown contradictory results, thereby a definitive conclusion about the influence of carbon fiber volume fraction on impact energy cannot be determined.

Beylergil et al. (2023) conducted a similar experiment using the Taguchi method where the optimum 3-D printing parameters were found. It was concluded that the infill density of 100% is most suitable along with other optimum parameters such as the extruder temperature of 260º C. Tanveer et al. (2019) conducted an experiment and found that infill density shows a mixed response for the tensile and impact tests. It was also mentioned that adding different layers with different infill densities reduces the weight by nearly half and also shows a considerable amount of decline in Charpy impact strength. Hence it was concluded that the the infill density is directly proportional to the impact strength of the specimen.

3. Methods

3.1 Impact Tests

Impact Tests are used to determine the amount of energy required to break the material. The Charpy impact test is a typical method for impact testing in which a standardized specimen is exposed to an impact force by a swinging pendulum. The energy absorbed by the material when it fractures or breaks is measured in the test. It can help optimize component designs, material selection, and process parameters by providing useful insights into the material's reaction to dynamic loads. The Charpy impact test has been extensively utilized for evaluating the impact resistance of carbon fiber composites that have been produced using various manufacturing methodologies, including 3D printing. The Charpy Impact Tester used in the experimental procedure is indicated in Figure 1.

Figure 1. Impact Tester. Image source *tercosweden.com (Terco, n.d.)*

3.2 ASTM D6110 Standard

ASTM D6110 standard for impact testing of a notched specimen was followed to validate the findings of the experiment. The notch design was according to the standards shown in Figure 2, *Notch Dimensions* shall be 45° with a radius of curvature at the apex of 0.25 mm.

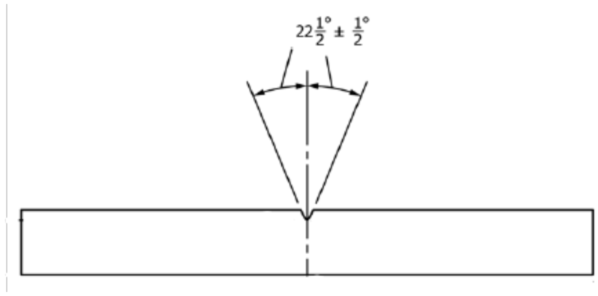

Figure 2: Notch Dimension for Specimen *(ASTM International, 2018)*

3.3 Machines and Material Used

1. MT3016 Impact Tester
   Maximum Impact Energy = 15 Joules (1 J= 1 Nm)
2. MarkForged Mark II 3-D Printer
   Variable infill thickness = 100µm to 200 µm
3. ColorFabb XT CF20 carbon fiber composite

3.4 Factors under Consideration

There are some variable factors in which the levels can be changed to get the maximum desired output. Some of these factors that were under consideration were :

- Infill Density
- Infill Pattern
- Layer Thickness
- Nozzle Temperature
- Print Speed

An experiment conducted by Tanveer et al. (2019) on the effects of infill density on the mechanical properties of a 3D-printed part, determined that increasing the infill density will increase the impact strength of the part. Agarwal et al. (2018) also concluded that the effect of the infill pattern is dependent on the infill density as increasing the infill density to 100% will result in a solid block. As a consequence, we have concluded that infill density is a crucial factor that must be considered. The High and Low levels of the factor were considered as 50% and 25%. This is because if the infill density is greater than 50%, then because of the dimension of our parts, the internal structure of the part will resemble to solid as there is a risk of material overlapping.

Another experiment conducted by Yeoh et al. (2020) determined that the mechanical properties of a 3D printed change with the infill pattern. The results show the variation in properties such as Stress, strain, tensile strength, hardness (Yeoh et al., 2020). The High and Low levels of the factor were considered as Gyroid and Honeycomb. This is because these two patterns have been responsible for increasing the mechanical properties the most with the gyroid being slightly better than the honeycomb.

Layer Thickness as a factor was selected because of the studies conducted by Abbas et al. (2018) In their experiment, the effects of layer thickness were observed on the impact strength of a 3D-printed part and concluded that layer thickness is the significant factor that increases the impact. The particular layer thickness determines the amount of layers, and increasing the number of layers results in increased structural integrity in the finished component. The quantity of layer thickness is dependent on the specific layer thickness. This is because of the strong bonding that may be achieved between layers when there is a significant temperature difference between them (Sood et al., 2010). Due to the limitations of the machine, the High and Low levels of the factor were considered as 150 µm and 100 µm.

Nozzle temperature and Print Speed as factors were eliminated because of the limitations of the machine. As the 3D printing machine available has a recommended working temperature range and varying it, could affect the machine negatively. And the machine does not offer variable print speed and because of that, the factor was eliminated.

Our Response Variable is the Total energy absorbed by the material until the fracture point is reached which is expressed in Joules (Table 1).

Table 1. Low and High values of the three factors under consideration

Factor	Low	High
Infill Density	25%	50%
Infill Pattern	Honeycomb	Gyroid
Layer Thickness	100 µm	150 µm

Part Used

A 3D model of the part was made using SolidWorks, and the dimensions were taken according to the Charpy Impact Testing machine. The parts were designed to fit the testing position in the machine. The dimensions of the parts were 77.47 mm * 20.32 mm * 6 mm. A 3D model of the part is shown below in Figure 3.

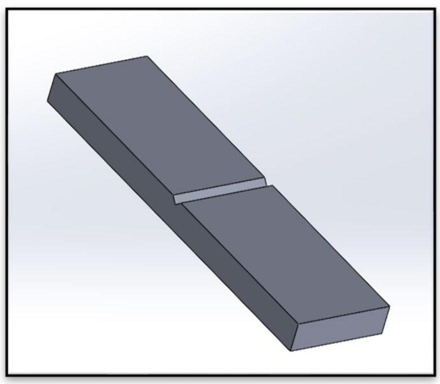

Figure 3. 3D model of part used for experimentation.

Experimental Setup

To ensure consistent experimental conditions, the sample is securely clamped in place using a fixed mechanical mechanism, as demonstrated in left of Figure 4. Additionally, in order to minimize errors arising from off-angle readings of the impact tester, all measurements are conducted at the same height for every experiment, as illustrated in the right of of Figure 5.

Figure 4. The figure on the left depicts the sample holder, while the figure on the right illustrates the direct energy measurements obtained from the impact tester, all of which are taken at the same height as the equipment.

4. Data Collection

Because of the 3 factors under consideration, 2^3 full factorial design was the best possible design which was created using Minitab. 2 replications of the experiment were done to reduce the cost of the experiment as well as maintain the variability of the runs. So, 16 runs are observed below in Figure 5. In the design phase, 0 represents the honeycomb structure and 1 represents the gyroid.

C1	C2	C3	C4	C5	C6	C7	C8
StdOrder	RunOrder	CenterPt	Blocks	Layer Thickness	Infill Density	Infill Pattern	Response (Energy)
2	1	1	1	150	25	0	1.7
9	2	1	1	100	25	0	2.0
3	3	1	1	100	50	0	2.3
4	4	1	1	150	50	0	2.4
14	5	1	1	150	25	1	1.9
8	6	1	1	150	50	1	2.5
15	7	1	1	100	50	1	1.8
16	8	1	1	150	50	1	2.3
5	9	1	1	100	25	1	2.1
7	10	1	1	100	50	1	1.8
13	11	1	1	100	25	1	2.1
6	12	1	1	150	25	1	1.9
1	13	1	1	100	25	0	2.1
11	14	1	1	100	50	0	2.3
10	15	1	1	150	25	0	1.8
12	16	1	1	150	50	0	2.3

Figure 5. Full Factorial Design

The cube plot shown below depicts the minimum and the maximum response and provides a better understanding of the data (Figure 6).

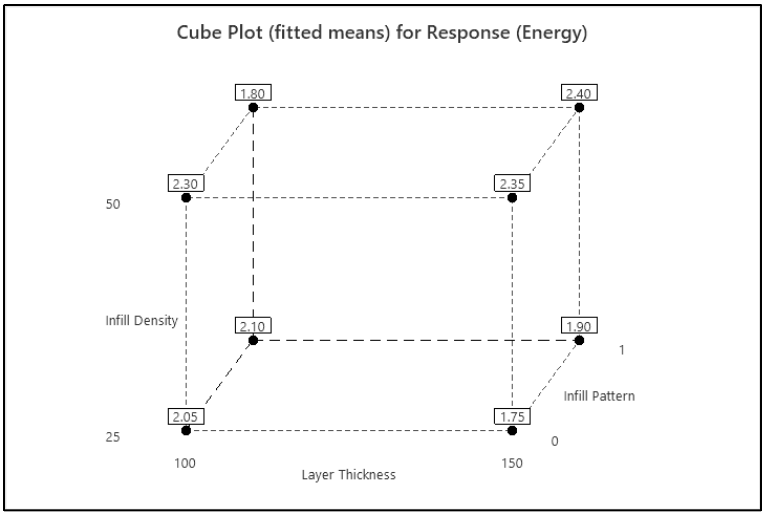

Figure 6. Cube Plot

5. Results and Discussion

5.1. Numerical Results

Factorial Design

The minitab output determines that from the main effects, only infill density is the significant factor along with all the 2-way and 3-way interaction effects. Infill pattern and Layer Thickness are not significant factors as per the Minitab output because the p-value is greater than the α value of 0.05. This can be confirmed in Figure 7.

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value
Constant		2.0813	0.0165	125.86	0.000
Layer Thickness	0.0375	0.0187	0.0165	1.13	0.290
Infill Density	0.2625	0.1313	0.0165	7.94	0.000
Infill Pattern	-0.0625	-0.0312	0.0165	-1.89	0.095
Layer Thickness*Infill Density	0.2875	0.1438	0.0165	8.69	0.000
Layer Thickness*Infill Pattern	0.1625	0.0812	0.0165	4.91	0.001
Infill Density*Infill Pattern	-0.1625	-0.0813	0.0165	-4.91	0.001
Layer Thickness*Infill Density*Infill Pattern	0.1125	0.0563	0.0165	3.40	0.009

Term	VIF
Constant	
Layer Thickness	1.00
Infill Density	1.00
Infill Pattern	1.00
Layer Thickness*Infill Density	1.00
Layer Thickness*Infill Pattern	1.00
Infill Density*Infill Pattern	1.00
Layer Thickness*Infill Density*Infill Pattern	1.00

Figure 7. Factorial Design Output

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	0.889375	0.127054	29.04	0.000
Linear	3	0.296875	0.098958	22.62	0.000
Layer Thickness	1	0.005625	0.005625	1.29	0.290
Infill Density	1	0.275625	0.275625	63.00	0.000
Infill Pattern	1	0.015625	0.015625	3.57	0.095
2-Way Interactions	3	0.541875	0.180625	41.29	0.000
Layer Thickness*Infill Density	1	0.330625	0.330625	75.57	0.000
Layer Thickness*Infill Pattern	1	0.105625	0.105625	24.14	0.001
Infill Density*Infill Pattern	1	0.105625	0.105625	24.14	0.001
3-Way Interactions	1	0.050625	0.050625	11.57	0.009
Layer Thickness*Infill Density*Infill Pattern	1	0.050625	0.050625	11.57	0.009
Error	8	0.035000	0.004375		
Total	15	0.924375			

Figure 8. Analysis of Variance

Figure 8. shows us that our experimental model is valid because of model's p-value being less than the α value of 0.05. The determination of significant variables may be made by examining the P-value obtained from Figure 8 and Figure 9. The ANOVA findings provide further confirmation that just one factor, namely infill density, has statistical significance. The observed results indicate that there is a strong interaction impact across all the parameters being examined. This implies that the impact of layer thickness and infill pattern on the response variable is not substantial, but their influence becomes apparent when combined with other variables. The regression equation used for the model is mentioned in Figure 9.

Regression Equation in Uncoded Units

Response (Energy) = 3.100 - 0.01300 Layer Thickness - 0.01800 Infill Density
+ 1.300 Infill Pattern + 0.000280 Layer Thickness*Infill Density
- 0.00700 Layer Thickness*Infill Pattern
- 0.0580 Infill Density*Infill Pattern
+ 0.000360 Layer Thickness*Infill Density*Infill Pattern

Figure 9. Regression Equation

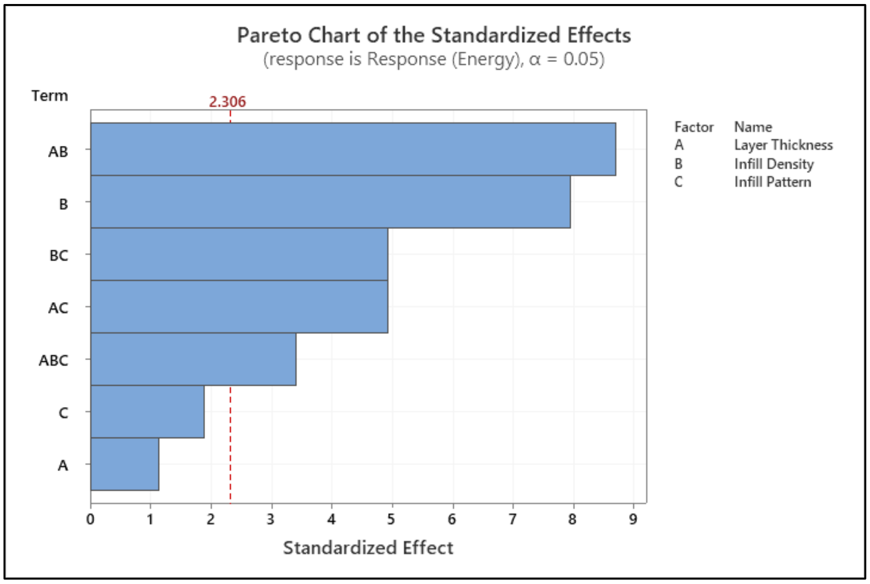

Figure 10: Pareto Chart

5.2. Results discussion

Statistical observations made in above section are contingent upon the assumption that the data follows a normal distribution. To validate the normality of our response data, residual plot as seen in Figure 10 was plotted. As seen in in Figure 11, histogram of residuals suggest that the residual are normally distributed. In addtion, the normal probability plot of residuals falls in line with some outliers. Our linear regression model assumes the error terms are independent, which can be confirmed by the randon order of the residuals around the residual line in the Versus Order graph. Upon examination of the Versus Fits scatter plot, it can be seen that the variability remains consistent on both sides. Therefore, it is reasonable to make the assumption of equal error variance.

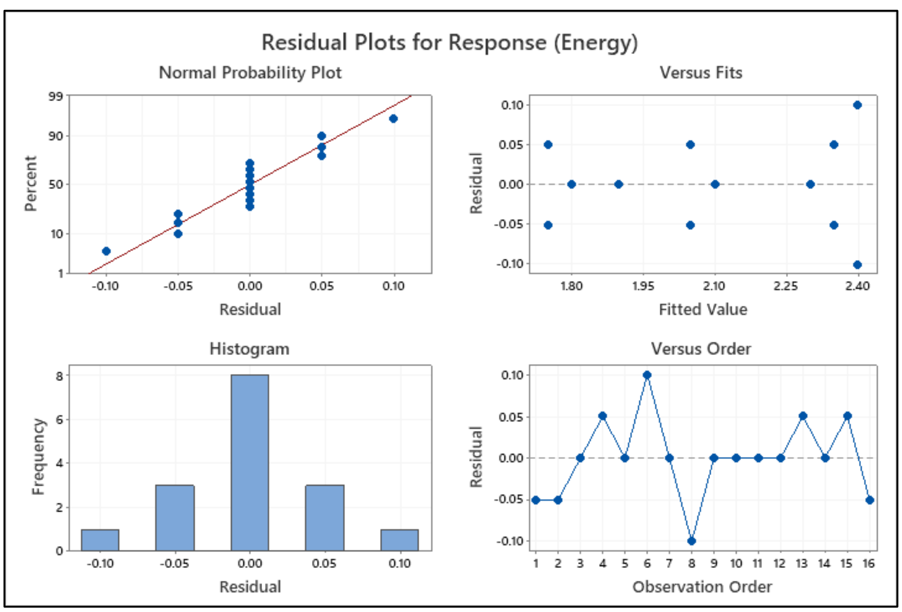

Figure 11. Residuals Plot

In addition to Figure 12, normal probability plot was plotted in Figure 12. In Figure 13, all points are in a straight line enclosed by an envelope with a 95% confidence interval. Based on the visual look of this graph, we can confirm with 95% confidence that the data follows normal distribution. In addition, since the P-value is greater than 0.05, we can say with 95% confidence that the data comes from the normal distribution.

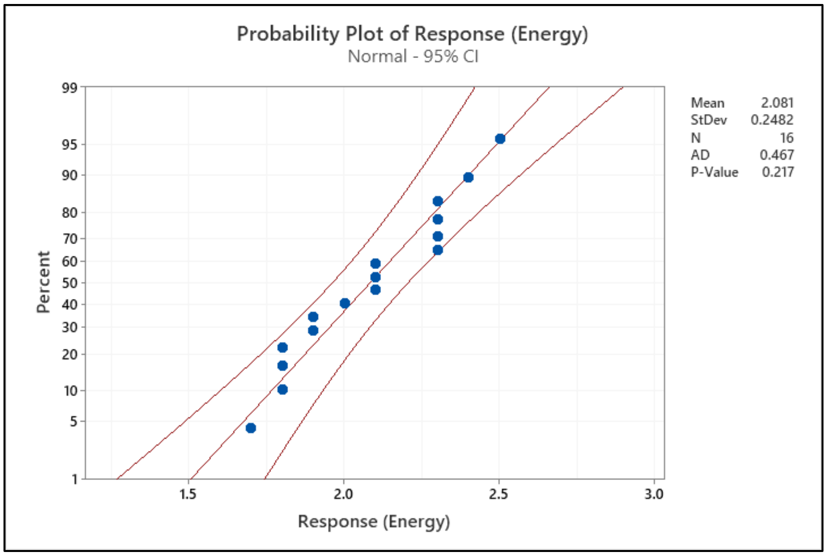

Figure 12: Normality Plot

From the main effects plot, we can see that infill density have the maximum slope, which signifies its highest effect on the response. Figure 14 shows that all the interaction effects have significant angle between them which confirms that all the interaction effects are affecting the response.

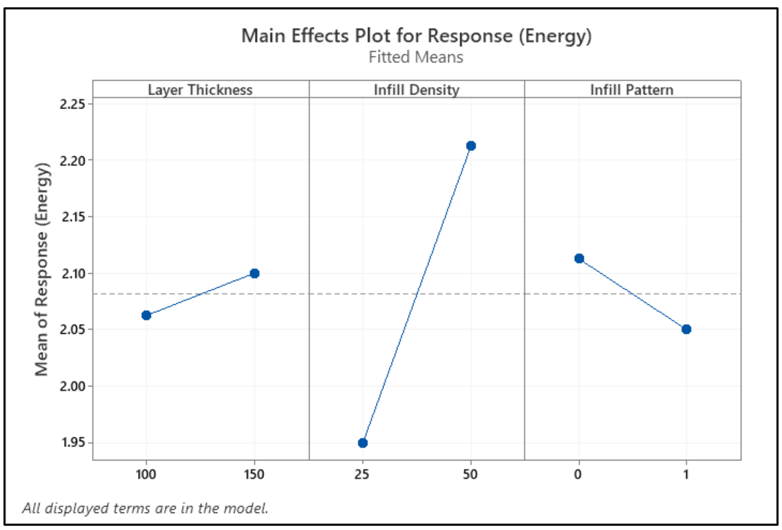

Figure 13. Main Effects Plot

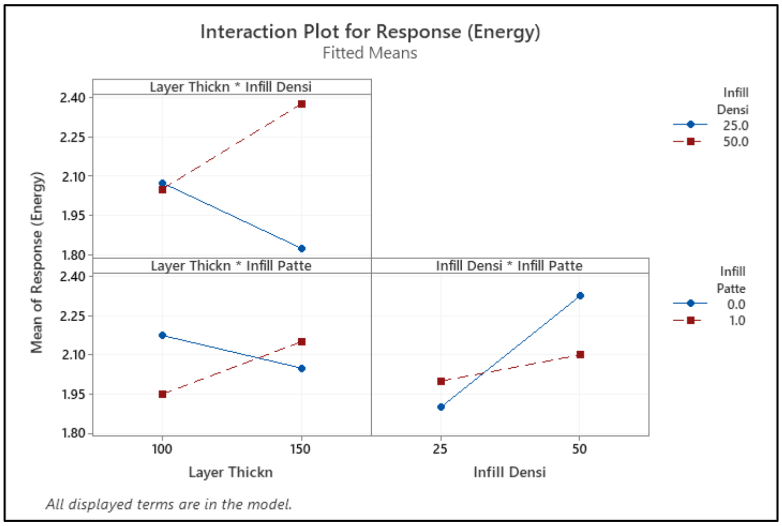

Figure 14. Interaction Plot

5.3. Response Optimization

Once we have developed the response model, optimization is carried out to better understand paprameters values to maximize the response. In order to do that following values are used for all inputs: Infill desinity between 25% to 50%, infill pattern 0 to 1, where 0 represents Honeycomb pattern and 1 represents Gyroid pattern, layer thickness in range of 100 µm to 150 µm. The values that are referred to as the low and high variables represent the three parameters under investigation in our experiment. By determining the optimal levels of these components, we can ascertain the conditions that provide the highest production. To better illusrtate the effect of parameters into response cotour plots as shown in Figure 15 and Figure 16 are used.

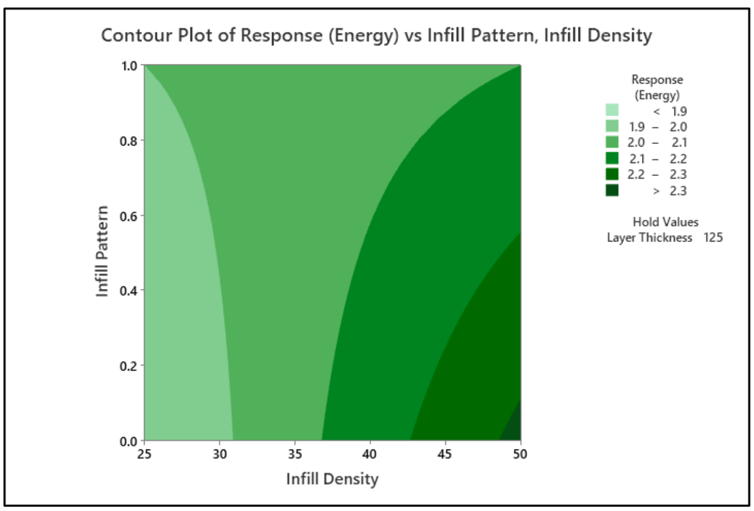

Figure 15. Contour Plot (Energy vs Infill Density and Infill Pattern)

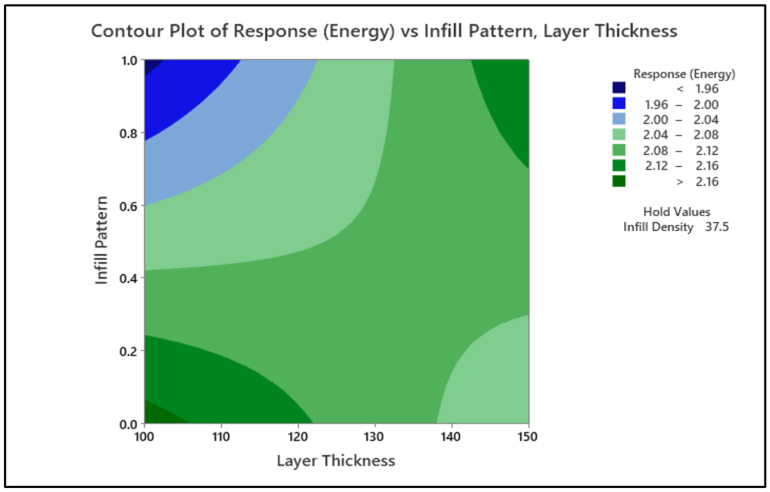

Figure 36: Contour Plot (Energy vs Infill Pattern and Layer Thickness)

Optimization of the response was done for getting the maximum response values by using the response optimization function in minitab, as seen in Figure 17. According to the findings shown in Figure 18 and Figure 19, it was found out that to get the maximum response variable, the layer thickness of 150 µm, infill density of 50%, and a Gyroid infill pattern is required. The graphical depiction of the result is shown in Figure 20.

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Response (Energy)	Maximum	1.7	2.5		1	1

Figure 47: Response Optimization (Parameters)

Solution

Solution	Layer Thickness	Infill Density	Infill Pattern	Response (Energy) Fit	Composite Desirability
1	150	50	1	2.4	0.875

Figure 18: Response Optimization (Solution)

Multiple Response Prediction

Variable	Setting
Layer Thickness	150
Infill Density	50
Infill Pattern	1

Response	Fit	SE Fit	95% CI	95% PI
Response (Energy)	2.4000	0.0468	(2.2921, 2.5079)	(2.2132, 2.5868)

Figure 19: Response Optimization (Prediction)

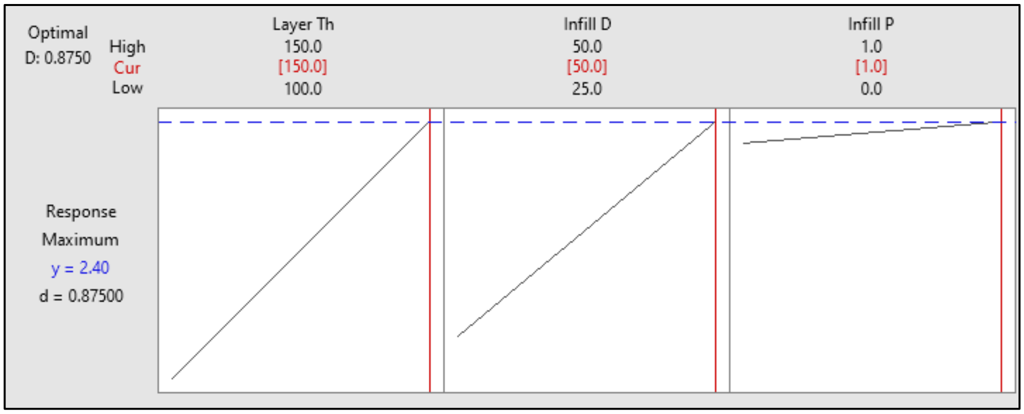

Figure 20: Response Optimization (graph)

5.4. Conclusion

Upon the successful completion of the experimentation and data analysis, three main key insights were observed:

1. With the experiment carried out, it is evident that Infill Density stands out as the sole main effect parameter with significant influence on the response. This significance is likely attributed to the fact that as density increases, approaching its maximum value of 100%, the part transitions to a completely solid state. Consequently, the importance of the other two factors hinges upon the chosen infill density.
2. Secondly, all of the two-way interaction effects, namely Layer Thickness - Infill Density, Layer Thickness - Infill Pattern, and Infill Density - Infill Pattern, prove to be noteworthy factors in affecting the response.
3. The experiment reveals that the maximum response value, indicating the maximum energy required to fracture the part, is achieved when employing a layer thickness of 150 µm, an infill pattern of gyroid, and an infill density of 50%. These findings collectively contribute to a comprehensive understanding of the experimental outcomes.

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Biographies

Shubham Parekh is an automobile engineering enthusiast on a journey for academic success and innovation. At Minnesota State University, Mankato, currently pursuing a master's degree in automotive engineering technology. Beginning with a strong foundation in automotive engineering through a bachelor's degree, Parekh has turned their interest in vehicles into hands-on expertise. They have participated in fascinating initiatives such as Formula Bharat and SAE Supra, where they have given their talents in vehicle design, prototypes, and manufacturing engineering. This real-world experience has fueled their desire to push the envelope in terms of making processes smarter and more efficient. Their interest inspired them to investigate Six Sigma and Lean techniques. With these tools, Parekh has grown skilled at optimizing operations, eliminating waste, and maintaining top-notch production quality. Aside from academics and projects, Parekh serves as the Director of Program/Activities at the IEOM (Industrial Engineering and Operations Management) student chapter at Minnesota State University, Mankato, where they play an important role in developing a culture of knowledge sharing and cooperation among their peers.

Pawan Bhandari, Ph.D. is an Assistant Professor in the Department of Automotive and Manufacturing Engineering Technology at Minnesota State University, Mankato, USA. He earned a B.S. and M.S. in Manufacturing Engineering Technology from Minnesota State University, Mankato, USA, and Ph.D. in Technology Management (Quality Systems) from Indiana State University, USA. Prior to joining academia, he worked as a Principal Health Systems Engineer at Mayo Clinic, Rochester, Minnesota where he provided end-to-end consulting to internal clients between department, region, and enterprise level. He was also an instructor in the Health Care Systems Engineering, at the College of Medicine, Mayo Clinic. Prior to joining Mayo Clinic in 2013, he worked as a Manufacturing Engineer. He is also a professional member of the American Society for Quality (ASQ) and IEOM. He is also an ASQ Certified Six Sigma Black Belt and ASQ Certified Quality Improvement Associate. His research interests are quality and process improvement, technology management, quality systems, performance improvement in healthcare, and applied business analytics which includes but is not limited to machine learning, Artificial Intelligence, and data science.

Praneel Acharya, Ph.D. is an Assistant Professor in the Department of Mechanical Engineering Technology at Minnesota State University, Mankato, USA. He earned his Ph.D. in Mechanical Engineering from South Dakota State University, USA. Prior to joining academia. His research interests are robotics, deep learning and optimization.