Optimization of 3D-Printing PETG for Biomedical Part Application Using FDM Parameters

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Abstract-*Additive Manufacturing is a process where components are produced through the successive addition of material layer by layer, which is completely different from conventional manufacturing techniques that involve material removal. In recent times, additive manufacturing has gained preference over traditional manufacturing approaches due to its improved precision, reduced production time, cost-effectiveness, and ability to produce high-quality products. In Fused Deposition Modeling, the performance of three-dimensional (3D) printed components is highly influenced by the selected process parameters. Therefore, proper optimization of these parameters is necessary to improve the characteristics of the manufactured product. The Fused Deposition Modeling (FDM) method is extensively utilized for fabricating components in different fields and shows significant potential in advancing orthopedic research by enabling the development of customized and easily accessible biomedical implants. The mechanical properties of implants fabricated through FDM mainly depend on the processing conditions, where layer thickness plays an important role. The influence of these parameters will be evaluated on tensile strength and flexural strength through experimental and statistical methods. The manufacturing parameters of three-dimensional (3D) printed composite bone plates will be optimized using an orthogonal experimental approach, and the effects of layer thickness, printing speed, filament feed rate, and biomedical material content on the tensile and flexural strength of the samples will be evaluated. Using Taguchi's mixed model fractional factorial design (L27), the experimental trials will be arranged, and the specimens will be produced through an FDM 3D printer, followed by the evaluation of tensile and flexural strength. Subsequently, the optimal combination of parameters will be determined using Signal-to-Noise (S/N) ratio analysis, while Analysis of Variance (ANOVA) will be conducted to identify the significant parameters and their effects on tensile and flexural strength.*

Keywords-3D PRINTING, Universal testing machine ASTMD638 Testing FDM and composite plastic material PEEK, Nylon, Corba fiber, PEKK, PLA, ABS, PETG

1. INTRODUCTION

Contrary to subtractive manufacturing, additive manufacturing, often known as 3D printing, is a method of fabricating items by connecting data from 3D models, and it is typically carried out layer by layer. The design and manufacturing processes can be improved in terms of speed and flexibility due to this technology. Additionally, conventional manufacturing techniques require significant time and cost to produce complex geometries; So, 3D printing machines are used in many different industries to make custom parts when designing something. However, the quick advancement of this technology has made it possible to create finished parts. The 3D printing process helps use less material, reduces work that requires a lot of effort, and lowers the total cost of making things.

Some other manufacturing industries, including those in the, medical aerospace, automotive, clothing food, electronic electric and, educational, prototype, civil engineering works architectural, chemical, building, and construction sectors, have most use fully because it make easy trail and error process and so many applications in 3D printing operation technology. Laser melting and FDM, which are types of Additive Manufacturing (AM), use different techniques like fused filament fabrication, stereolithography, direct jetting, photopolymer jetting, selective laser sintering, electron beam melting, and hybrid methods. Among the various 3D printing techniques, FDM is considered the most popular one because it is easy to use and doesn't cost as much as other methods.

Orthopedic implants include trauma, spinal, joint, patient-specific prostheses, and bone tissue engineering scaffolds. PLA is widely used in biomedical applications due to its biocompatibility and biodegradability for scaffolds and implant structures. To improve implant performance, researchers explore composite materials such as HA, PEEK, and PETG, which enhance biocompatibility, bone integration, and reduce inflammation risks during degradation.

II. LITERATURE REVIEW

Additive manufacturing, which is also called 3D printing, has become a significant part of the manufacturing process. This is because it can make complicated parts with very little waste of materials and in less time compared to traditional methods. Fused Deposition Modeling is considered one of the most commonly used methods in additive manufacturing because it is cost-effective, easy to operate, and works well with different types of thermoplastic materials.

Several researchers have investigated the use of composite materials and process optimization in FDM printing. **Balwant Singh and Raman Kumar** reviewed the use of polymer matrix composites in 3D printing and reported that adding reinforcing materials can significantly improve the mechanical performance and functionality of printed parts. Their findings highlighted the increasing importance of composite materials in engineering and biomedical applications [1].

Muammel M. Hanon studied how different settings used in FDM printing influence the strength and other physical characteristics of PLA parts. The study found that factors like layer height, infill density, and how the object is positioned during printing have a big impact. Proper adjustment of these parameters resulted in improved mechanical performance of the manufactured specimens [2].

Wenzhao Wang developed PLA/Nano-hydroxyapatite (n-HA) composite scaffolds for bone tissue engineering and observed improvements in both mechanical strength and biological compatibility. The study emphasized the importance of selecting suitable materials and structural designs for biomedical applications [3].

Xin Wang and colleagues provided a detailed review of polymer matrix composites used in additive manufacturing. Their research showed that material modification and process optimization play a crucial role in enhancing the strength, durability, and reliability of 3D-printed components [4].

Yahia Halabi applied Artificial Neural Networks (ANN) and optimization techniques to predict and enhance the mechanical properties of fiber-reinforced polymer composites. The results demonstrated that advanced computational methods can effectively identify optimal printing conditions and improve product performance [5].

Christine Le Performed experimental and numerical studies on 3D-printed bone plates exposed to bending loads.

The study demonstrated that machine learning techniques can be effectively applied to forecast mechanical behavior and support the design optimization process of biomedical implants [6].

Looking at the research that has been reviewed, it's clear that the settings used in FDM printing, like layer thickness, how much material is filled in, how fast the printer moves, and the pattern of the fill, all have a big impact on how strong and durable the printed parts are. Although extensive studies have been carried out on PLA and composite materials, studies focusing on the optimization of PETG for biomedical applications remain limited. Therefore, the present work aims to optimize the FDM printing parameters of PETG using the Taguchi method and evaluate the tensile, flexural, and compression properties of the fabricated specimens for potential biomedical applications

III. MATERIAL SELECTION AND MODELING

The Taguchi method is a widely used optimization technique that improves product quality and process efficiency by reducing the total number of experimental trials required. It uses a systematic experimental design known as orthogonal arrays to evaluate the effects of different process parameters. This method enables researchers to identify the most important factors and determine their optimal settings while saving time, cost, and resources. Because of its simplicity, reliability, and effectiveness, the Taguchi method is commonly applied in manufacturing, engineering, and quality improvement studies.

TABLE 1.PARAMETERS USED

Sl. No.	Parameters	Units	Leve1	Level 2	Level 3	Level 4	Level5
1	Layer Thickness	mm	0.2	0.2	0.2	0.2	0.2
2	Printing Speed (Constant)	mm/s	500	500	500	500	500
3	Infill Density	%	60%	40%	1%	20%	40%
4	Infill Pattern	-	Gyroid	Honey comb	Lightni ng	3D Honey comb	Concent ric

1) FACTORS

The mechanical characteristics and overall quality of FDM 3D-printed components are significantly affected by different printing parameters. Nozzle temperature determines the effective melting and deposition of filament throughout the printing operation. In this study, a nozzle temperature of 220°C was selected to provide proper material flow. The nozzle diameter, which manages the volume of extruded material, was maintained at 0.4 mm for all manufactured specimens. Infill density represents the amount of material contained within the printed component and directly affects its strength, weight, and material consumption; values between 1% and 60% were examined. Layer height, described as the thickness of each deposited layer, influences surface finish, printing time, and mechanical characteristics, and was varied from 0.1 mm to 0.3 mm. Printing speed indicates the movement rate of the nozzle during material deposition, and a fixed speed of 500 mm/s was followed throughout the investigation. Another significant parameter is printing orientation, which describes the placement of the component on the build platform and can greatly influence strength, dimensional precision, and surface characteristics. These parameters were chosen to examine their effect on the mechanical performance of FDM-printed composite specimens.

2) TAGUCHI CHART

The Taguchi chart is a useful visual tool that helps look at the results of experiments and find the best mix of process settings. It shows how different levels of parameters affect the result and helps researchers pick the best conditions for better performance. In this study, the Taguchi method was used to look at how different factors like layer thickness, infill density, and printing direction affect the outcome, while keeping the printing speed and nozzle temperature the same. A signal-to-noise ratio analysis was done to find the best settings that improve the mechanical properties and reduce differences in the experiment results. By selecting the optimal process conditions, the Taguchi method helps enhance product quality, improve process efficiency, and achieve more consistent and reliable performance in FDM 3D-printed components.

TABLE II. TAGUCHI CHART

SL NO	Layer Thick Ness	Printing	Infill Density	Infill Pattern
1	0.2	500	10%	Gyroid
2	0.2	500	20%	Gyroid
3	0.2	500	40%	Gyroid
4	0.2	500	60%	Gyroid
5	0.2	500	10%	Honeycomb
6	0.2	500	20%	Honeycomb
7	0.2	500	40%	Honeycomb
8	0.2	500	60%	Honeycomb
9	0.2	500	1%	Lightning
10	0.2	500	20%	3D Honeycomb
11	0.2	500	20%	Grid
12	0.2	500	40%	Gyroid
13	0.2	500	40%	Honeycomb
14	0.2	500	40%	Concentric

IV. ASTM STANDARDS

ASTM International is a worldwide recognized organization responsible for establishing standard testing methods and guidelines for materials, products, and manufacturing processes. These standards support the assurance of product quality, safety, reliability, and performance by offering uniform testing procedures. In engineering and manufacturing studies, ASTM standards are commonly implemented to obtain precise and comparable outcomes. In this study, ASTM standards were adopted during the fabrication and testing of the 3D-printed specimens to maintain the reliability of the experimental results. The application of these standards allows accurate assessment of material characteristics, confirms testing methods, and ensures that the fabricated components satisfy the necessary performance requirements.

A. TENSILE TEST ASTM D638

ASTM D638 is a standardized testing method applied to determine the tensile characteristics of plastic materials. It provides a uniform approach for testing specimens under tensile loading conditions to study their behavior when subjected to pulling forces. This test evaluates important mechanical characteristics such as tensile strength, elongation at break, and modulus of elasticity. These characteristics help determine the material's strength, stiffness, and overall performance under tensile loading, making ASTM D638 a widely used standard for material characterization.

B. FRACTURAL TEST ASTM D7264

ASTM D7264 is a standard method used to check how well polymer matrix composite materials bend and resist breaking under stress. This test is done by placing the sample in a setup where it is bent until it either bends too much or breaks. It gives key details about how strong the material is when bent, how stiff it is when subjected to bending, and how it behaves when forced to curve. These features help in checking how well composite materials can handle bending and whether they are good for use in engineering and structural projects.

C. COMPRESSION TEST ASTM D695

ASTM D695 is a standard testing procedure used to assess the compressive properties of rigid plastics and composite materials. During this test, the specimen undergoes compressive loading at a constant rate until deformation or failure takes place. The test offers essential information regarding the material's compressive strength, stiffness, and load-carrying ability.

Test Method	Method number
Tensile test	ASTM D638
Fractural test	ASTM D7264
Compression test	ASTM D695

V. MODELLING

1] 2D MODELLING IN CAD

A 2D CAD model is a computer-generated drawing used to represent the shape and dimensions of a component or product in two dimensions. It is created using Computer-Aided Design (CAD) software and consists of lines, curves, and geometric shapes that accurately define the design. 2D CAD models are commonly used in engineering, manufacturing, and technical documentation to communicate design details clearly and precisely. They offer important details regarding the dimensions, shape, and characteristics of a component, making them valuable for design, drafting, and manufacturing applications. Although 3D models are widely used today, 2D CAD drawings remain important for creating technical drawings and manufacturing documentation where a two-dimensional representation is sufficient.

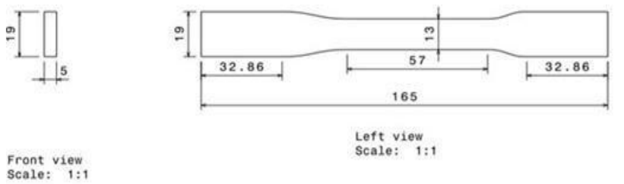
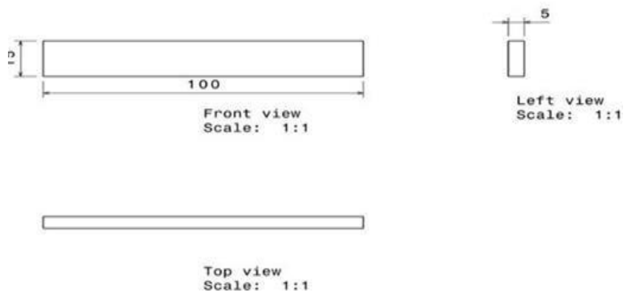


Figure5.1:Tensiletestspecimendrawing



2] 3D MODELLING IN CAD

3D modeling in CAD refers to the method of developing a three-dimensional digital representation of a component or product with the help of computer-aided design software. The procedure generally begins with a 2D sketch that represents the fundamental shape of the object. This sketch is later transformed into a 3D model by applying features such as extrusion, revolution, sweep, or loft. Additional features such as fillets, chamfers, holes, ribs, and patterns can be added to refine the design and meet functional requirements. 3D CAD models provide a realistic representation of the final product and are widely used for design visualization, analysis, prototyping, and manufacturing.

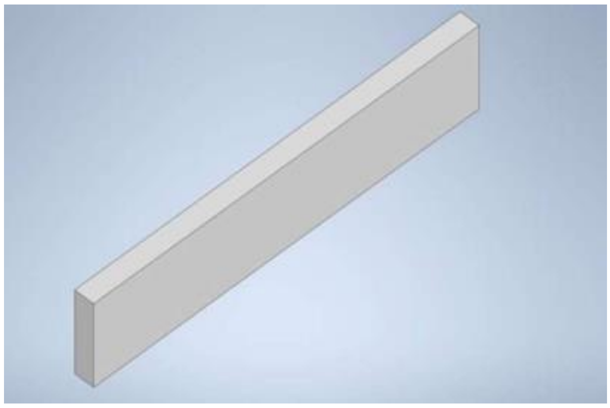


Fig2: Flexural and Compression Model

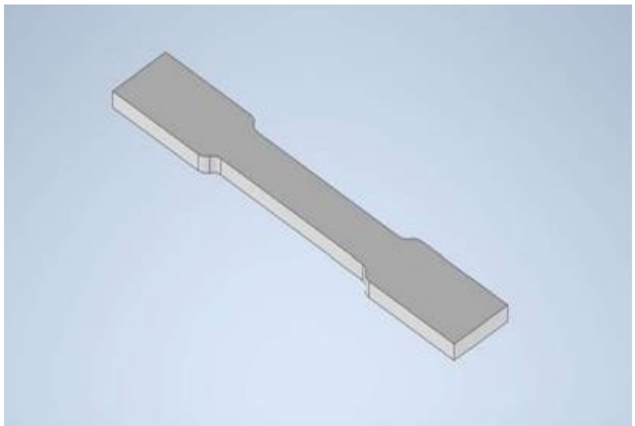


Fig3: Tensile Model

V. SLICING PROCESS

Cura is among the widely used software applications in 3D printing for preparing digital models prior to the printing process. It provides a simple and easy-to-use interface that helps users efficiently configure and control the printing operation. The primary purpose of cura is to divide a 3D model into fine layers and transform it into G-code, which includes the necessary commands for the 3D printer to fabricate the object layer by layer. The software also allows users to adjust essential printing settings, such as layer height, printing speed, infill density, and support structures. These features help improve print quality, optimize printing performance, and ensure successful fabrication of the final component.

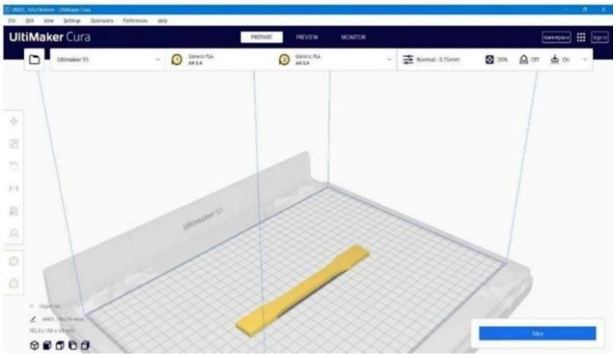


Fig:4 Slicing of Tensile Specimen

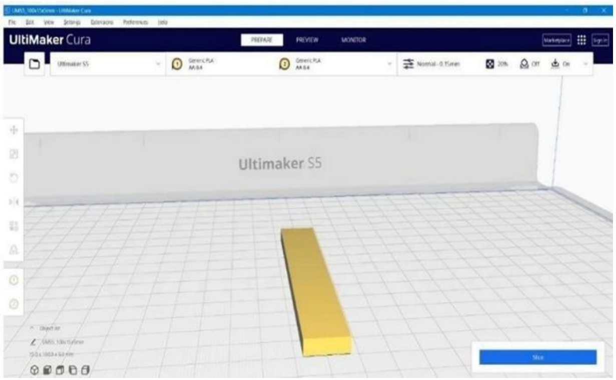


Fig5: Slicing of Flexural Specimen

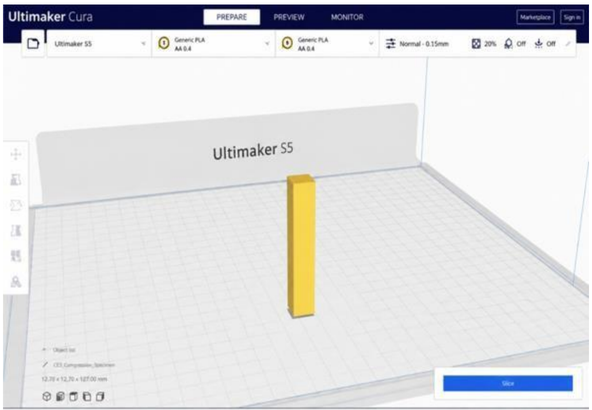
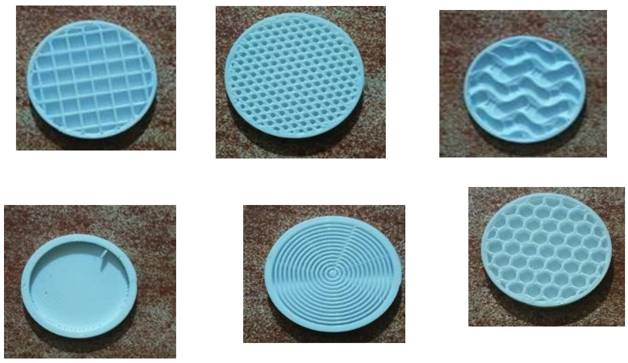


Fig6: Slicing of Compression Specimen

VII.PRINTING PATTERN

In 3D printing, the printing pattern is the set of layer lines visible on the surface of a printed object. These lines form because the printer builds the object one layer at a time by depositing material such as plastic filament. The appearance of the layer lines depends on printing settings like layer height, print speed, and nozzle size. Smaller layer heights usually produce a smoother surface, while larger layer heights make the lines more noticeable. The printing pattern plays an important role in determining the surface finish and overall quality of the printed part.

(i) Grid (ii) Concentric (iii)Honeycomb



(iv)Lighting(v)3DHoneycomb(vi)Gyroid

Fig7: Printing pattern

VIII. PRINTING FILAMENT

PETG (Polyethylene Terephthalate Glycol) is a commonly used material in FDM 3D printing because it is strong, durable, and easy to print. It combines the simple printing characteristics of PLA with the toughness of ABS, making it suitable for both functional and industrial applications. PETG is resistant to moisture and many chemicals, produces reliable parts, and has a low tendency to warp during printing. Due to its good mechanical properties and ease of use, PETG is widely used for manufacturing prototypes, engineering components, containers, and other practical products.

TABLE III. SPECFICATION OF MATERIAL

Chemical Structure	PETG belongs to the family of polyester. Chemical formula: $(C_{10}H_8O_4)_n$
Physical Properties	Density: 1.28 g/cm^3 Melting Point: 220°C - 270°C Bed Temperature (Tg): 75°C
Mechanical Properties	Tensile Strength: 48.6 Mpa Flexural Strength: 74 Mpa. Compression Strength: 71 HRM
Thermal Properties	Thermal Conductivity: 0.162 – 0.225 W/m-K

Fig8: Polyethylene terephthalate glycol (PETG) filament

1) PRINTING PROCESS

The 3D printing process starts by creating a digital model and converting it into G-code using slicing software. The printer is then prepared and the PETG filament is loaded into the machine. Printing settings such as nozzle temperature, bed temperature, and print speed are adjusted according to the material requirements. The printer builds the part layer by layer by depositing melted PETG material. Once printing is completed, the part is allowed to cool and is removed from the build plate. Finally, any support structures are removed and minor finishing is carried out to obtain the final printed component.

The 3D printing process using PETG starts with preparing and setting up the 3D printer properly. A heated print bed, usually maintained between 70°C and 85°C, helps the material stick well during printing. The PETG filament is loaded into the printer, and the required printing settings are adjusted using slicing software. The nozzle temperature is generally set between 230°C and 250°C, depending on the type of PETG filament and the printer being used. These settings help ensure smooth printing and produce strong, high-quality printed parts.

Proper bed leveling is important in PETG printing because it helps the first layer stick well to the print bed and reduces printing errors. PETG provides strong bonding between layers and maintains good dimensional accuracy during printing. However, it can sometimes produce thin strings of material, so the first layer should be checked carefully. Unlike PLA, PETG does not require much cooling, and a low-speed cooling fan is usually enough for small or detailed parts.

After printing is completed, the part is allowed to cool before being removed from the print bed. Additional post-processing techniques, such as support removal, sanding, or painting, can be carried out to enhance the appearance and surface finish of the printed component. To ensure proper printing performance, PETG filament should be kept in a dry environment to avoid moisture absorption. Because of its strength, durability, and easy printing characteristics, PETG is widely used for FDM 3D printing.

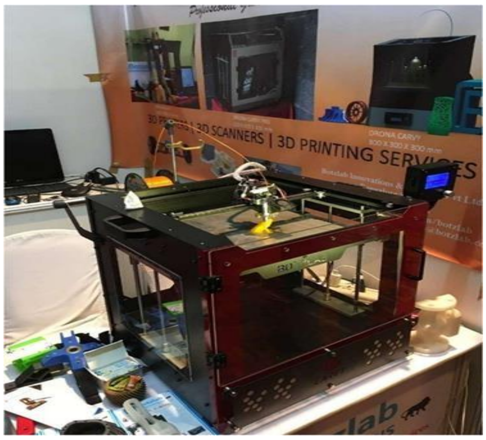


Fig9: 3D Printer used for additive manufacturing

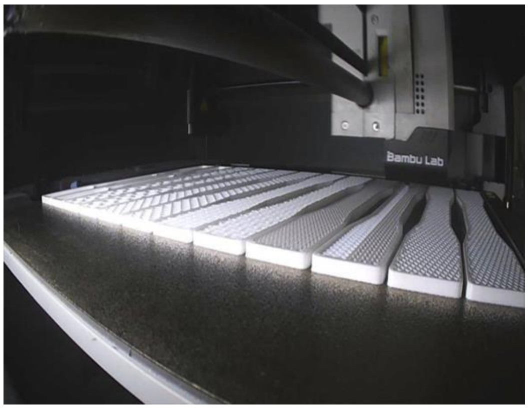


Fig10: Specimens are printing

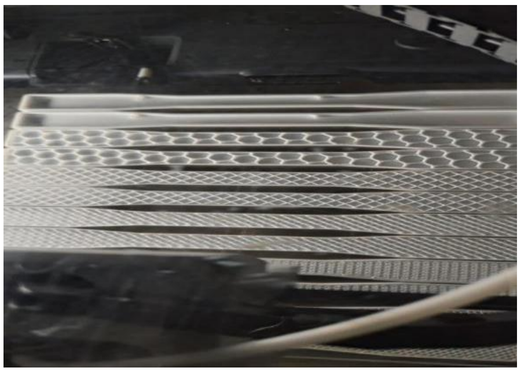


Fig11: Infilled specimens being printer

IX. EXPERIMENTAL

1) TENSILE TEST

The tensile test is conducted to determine the response of a material when exposed to stretching forces from opposite directions. In this procedure, a standard specimen is mounted in a Universal Testing Machine (UTM), where tensile force is gradually applied until the specimen breaks. During the experiment, the machine records the applied force and the amount of deformation. The collected data is used to evaluate important characteristics, including tensile strength, yield strength, stiffness, and elongation. Tensile testing helps in analyzing the strength and durability of materials.

Fig12: Universal testing machine

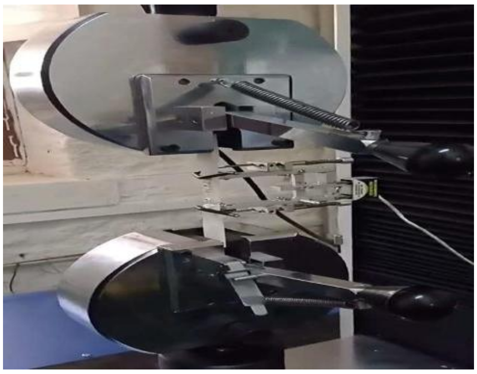


Fig13: Breaking of Tensile specimen

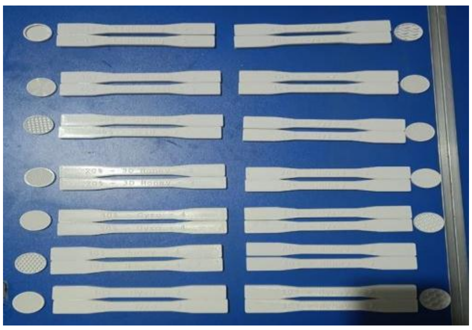


Fig14: 3D Printing tensile specimen

1). Tensile Test Result on (UTM)

TABLE IV. EXPERIMENTAL RESULT IF TENSILE TEST

Sl. NO	Walls	Printing Speed (mm/s)	Infill Density (%)	Infill Pattern	Tensile Strength (MPa)
1	2	500	10%	Gyroid	24.8
2	2	500	20%	Gyroid	31.5
3	2	500	40%	Gyroid	39.8
4	2	500	60%	Gyroid	46.2
5	2	500	10%	Honeycomb	23.5
6	2	500	20%	Honeycomb	30.1
7	2	500	40%	Honeycomb	38.4
8	2	500	60%	Honeycomb	44.9
9	5	500	1%	Lightning	28.7
10	2	500	20%	3D Honeycomb	22.149
11	2	500	20%	Grid	20.930
12	4	500	40%	Gyroid	22.202
13	4	500	40%	Honeycomb	23.474
14	3	500	40%	Concentric	24.481

2). FLEXURAL TEST

The flexural test, also known as the bending test, is conducted to determine a material's ability to resist bending under an applied external load. During this test, the specimen is supported at both ends while the load is exerted at the central region. With the gradual increase of load, the material starts bending, and its behavior is accurately recorded until significant deformation or fracture occurs. The test offers useful information regarding the material's flexural strength, stiffness, and overall structural behavior. Flexural testing is extensively applied in engineering and manufacturing fields to determine the suitability of materials for applications involving bending forces, including structural elements, machine components, and 3D-printed parts.

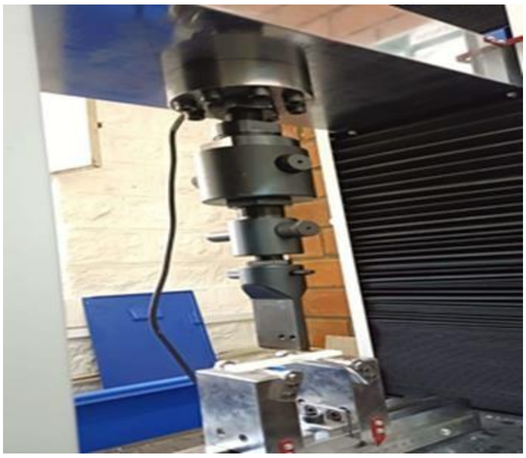


Fig15: Universal Flexural testing

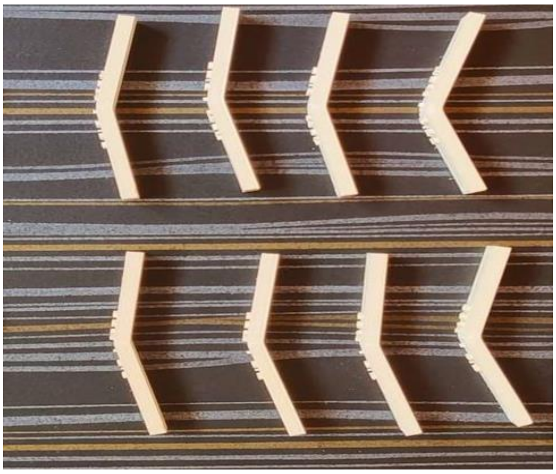


Fig16: Flexural specimen

TABLE V. EXPERIMENTAL RESULT OF FLEXURAL TEST

Sl. No.	Infill Pattern	Printing Speed (mm/s)	Walls	Infill Density (%)	Flexural Modulus (GPa)	Flexural Strength (MPa)	Flexural Behavior
1	Gyroid	500	2	10%	1.45	32.5	Brittle
2	Gyroid	500	2	20%	1.68	39.8	Semi-Ductile
3	Gyroid	500	2	40%	1.92	48.6	Ductile
4	Gyroid	500	2	60%	2.14	55.3	Highly Ductile
5	Honey comb	500	2	10%	1.38	30.1	Brittle
6	Honey comb	500	2	20%	1.61	37.4	Semi-Ductile
7	Honey comb	500	2	40%	1.86	46.1	Ductile
8	Honey comb	500	2	60%	2.08	53.2	Highly Ductile
9	Lightning	500	5	1%	1.22	34.2	Layer Crack
10	3D Honeycomb	500	2	20%	1.74	41.5	Ductile
11	Grid	500	2	20%	1.55	36.2	Semi-Ductile
12	Gyroid	500	4	40%	2.32	58.8	Highly Ductile
13	Honey comb	500	4	40%	2.25	56.4	Highly Ductile
14	Concentric	500	3	40%	1.97	51.7	Flexible

3). COMPTRESSION TEST

The compression test is done to see how a material behaves when it is pushed or squeezed. During this test, the specimen is placed between two plates on a Universal Testing Machine, and a load is slowly applied until the material starts to bend or breaks. The machine records the applied load and the amount of deformation throughout the test. The results help determine important properties such as compressive strength, stiffness, and the material's ability to withstand loads. Compression testing is commonly used to evaluate the strength and durability of polymers, composites, and other engineering materials.

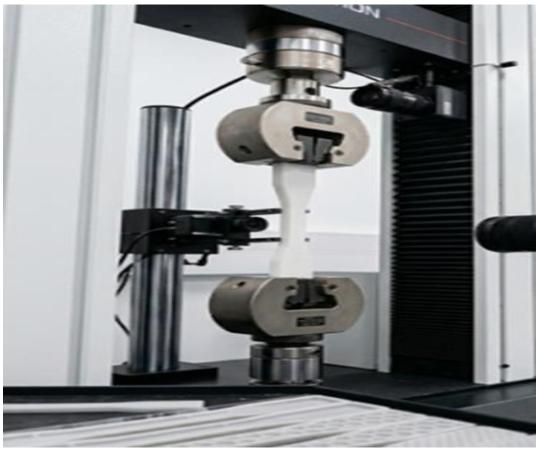


Fig17: Universal Compression testing machine

Fig18: Compression Specimen

TABLE V. EXPERIMENTAL RESULT OF COMPRESSION TEST

Sl. No.	Infill Pattern	Printing Speed (mm/s)	Walls	Infill Density (%)	Flexural Modulus (GPa)	Flexural Strength (MPa)	Flexural Behavior
1	Gyroid	500	2	10%	1.45	32.5	Brittle
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3	Gyroid	500	2	40%	1.92	48.6	Ductile
4	Gyroid	500	2	60%	2.14	55.3	Highly Ductile
5	Honey comb	500	2	10%	1.38	30.1	Brittle
6	Honey comb	500	2	20%	1.61	37.4	Semi-Ductile
7	Honey comb	500	2	40%	1.86	46.1	Ductile
8	Honey comb	500	2	60%	2.08	53.2	Highly Ductile
9	Lightning	500	5	1%	1.22	34.2	Layer Crack
10	3D Honey comb	500	2	20%	1.74	41.5	Ductile
11	Grid	500	2	20%	1.55	36.2	Semi-Ductile
12	Gyroid	500	4	40%	2.32	58.8	Highly Ductile
13	Honey comb	500	4	40%	2.25	56.4	Highly Ductile
14	Concentric	500	3	40%	1.97	51.7	Flexible

X. MAT LAB SIMULATIONS

MATLAB was used to study and display the tensile test results of PETG specimens printed with different infill patterns and densities. The software was used to create stress–strain graphs, making it easier to compare the mechanical performance of each specimen. By analyzing these results, it was possible to identify which printing parameters produced higher tensile strength and better overall material performance. MATLAB helped study how different printing settings affect the strength and how well the 3D-printed PETG parts work.

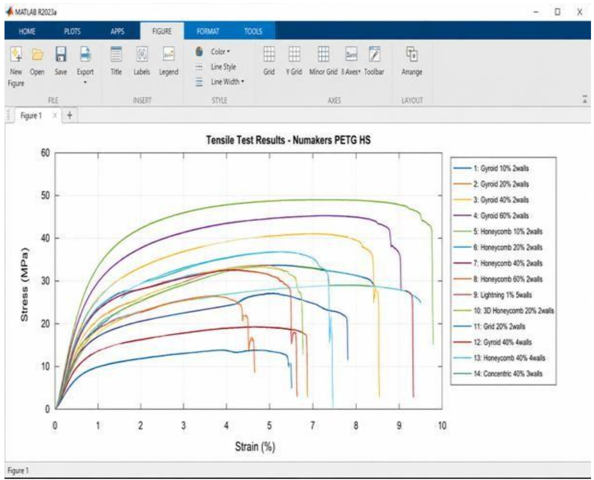

Fig19: Testing Result graph

MATLAB graph, each colored curve represents a different PETG specimen printed with varying infill patterns, infill densities, and wall settings. By comparing these curves, the tensile performance of each specimen can be evaluated.

Color Interpretation

The curves that reach higher stress values, such as the green and purple curves, indicate specimens with greater tensile strength and better ability to withstand applied loads. Curves in the middle range, such as yellow and light blue, represent specimens with moderate tensile performance. Lower curves, such as dark blue and orange, indicate lower tensile strength and a tendency to fail at lower loads. These results help identify the printing parameters that provide the best mechanical performance for the 3D-printed PETG specimens.

RESULTS

The specimens represented by the green and purple curves exhibited the highest tensile strength and showed better performance under the applied load. In contrast, the specimens represented by the blue and orange curves had lower tensile strength and failed at lower stress levels. This indicates that the printing parameters used for the green and purple specimens resulted in stronger and more durable PETG parts.

RESULTS AND DISCUSSION

This project examined the optimization and performance characteristics of 3D-printed PETG specimens fabricated through additive manufacturing. The mechanical characteristics of the specimens were assessed using tensile, flexural, and compression tests performed as per ASTM standards. Various printing parameters were studied to determine their influence on the strength and behavior of the fabricated components. The Taguchi method was applied to determine the optimal printing conditions while minimizing the required number of experimental runs. Furthermore, Artificial Neural Networks and Response Surface Methodology were implemented to forecast and optimize the mechanical characteristics of the specimens. The outcomes indicated that the proper selection of printing parameters considerably enhanced the tensile, flexural, and compressive strength of PETG specimens. Overall, the research confirmed that the integration of Taguchi, ANN, and RSM approaches is efficient in enhancing the quality and mechanical behavior of 3D-printed PETG components.

VARIATION OF EXPERIMENTAL DATA

1). TENSILE TEST RESULT

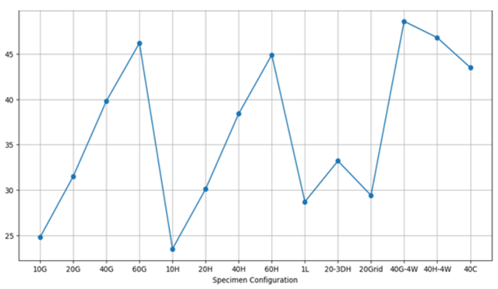

Fig20: Variation of Tensile Strength

The tensile strength of the printed specimens generally improved from 10G to 60G, showing better mechanical performance with changes in the printing configuration. The 10H specimen recorded the lowest tensile strength among all the samples. After this drop, the tensile strength increased steadily from 20H to 60H, followed by a small decrease for the 1L specimen. The highest tensile strength was achieved by the 40G-4W specimen, indicating superior performance compared to the other specimens. Although the 40H-4W and 40C specimens also showed good strength, their values were slightly lower. These results show that printing parameters and specimen configuration have a strong effect on tensile strength, with the 40G-4W specimen providing the best overall tensile performance.

2). FLEXURAL TEST RESULT

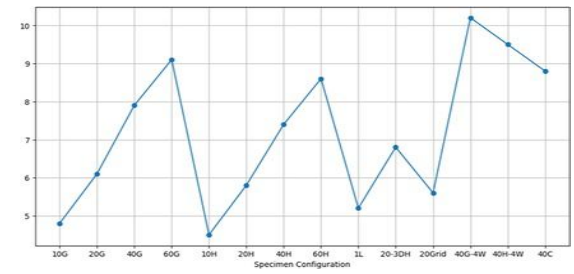

Fig21: Variation of Flexural Strength

The flexural strength of the printed specimens generally increased from 10G to 60G, showing an improvement in their ability to withstand bending forces. The 10H specimen showed the lowest flexural strength among all the samples. After this decrease, the flexural strength gradually increased from 20H to 60H and then slightly decreased for the 1L specimen. The highest flexural strength was obtained by the 40G-4W specimen, indicating the best bending performance. The 40H-4W and 40C specimens also showed good results, but their flexural strength was slightly lower. These results demonstrate that the printing configuration greatly influences the flexural properties, with the 40G-4W specimen achieving the highest overall bending strength and performance.

3). COMPRESSION TEST RESULT

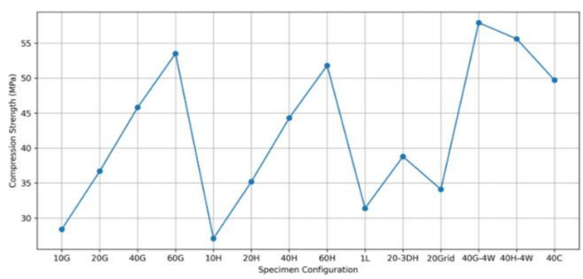

Fig22: Variation of Compression Strength

The compression strength of the printed specimens generally increased from 10G to 60G, showing an improvement in their ability to withstand compressive loads. The 10H specimen recorded the lowest compression strength among all the samples. After this decrease, the compression strength increased steadily from 20H to 60H and then slightly decreased for the 1L specimen. The highest compression strength was achieved by the 40G-4W specimen, indicating the best load-bearing performance. Although the 40H-4W and 40C specimens also showed good compression strength, their values were slightly lower. These results show that the specimen configuration has a significant effect on compression performance, with the 40G-4W specimen providing the highest compressive strength and overall best performance under compressive loading.

ANOVA PLOTS.

1). S/N PLOTS FOR TENSILE TEST

TABLE VI. RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS (TENSILE TEST)

Level	Layer thickness	Printing speed	Infill density	Infill pattern
1	25.67	26.14	26.60	26.36
2	26.70	26.92	26.12	26.64
3	27.22	27.03	27.23	26.69
4	27.48	26.97	27.02	27.37
Delta	1.81	0.90	1.02	1.00
Rank	1	4	2	3

The (S/N) analysis revealed that infill density has the strongest influence on performance, where Level 3 achieved the maximum S/N ratio and delivered the most stable results. Orientation also affected the performance of the specimen; however, its influence was lower compared to infill density. In contrast, layer height and printing speed displayed minimal changes in the S/N ratio, suggesting their limited contribution to the overall mechanical characteristics. Overall, the analysis verifies that infill density is the primary parameter influencing specimen quality and strength, followed by orientation, whereas layer height and printing speed show comparatively smaller effects.

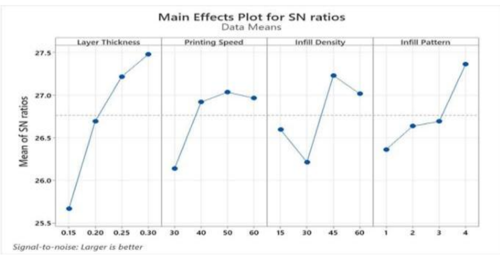

Fig23: Taguchi Analysis for ultimate tensile strength

2). S/N PLOTS FOR COMPRESSION TEST

TABLE VII. RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS (COMPRESSION TEST)

Level	Layer thickness	Printing speed	Infill density	Infill pattern
1	33.2	34.2	34.57	34.6
2	34.9	34.5	34.86	32.7
3	32.4	33.9	34.38	33.3
Delta	2.5	2.5	0.74	1.97
Rank	2	1	4	3

The signal-to-noise ratio analysis was done to check how different printing settings affect the compression strength of the 3D-printed samples. The results indicated that printing speed has the highest effect on compression performance, making it the most significant parameter. Feed rate also plays a significant role and has the second-highest effect on compression strength. The infill pattern has a moderate impact, while infill density has the least effect among all the parameters considered. Overall, the analysis indicates that controlling printing speed and feed rate is essential for achieving better compression strength and improving the overall performance of the printed specimens.

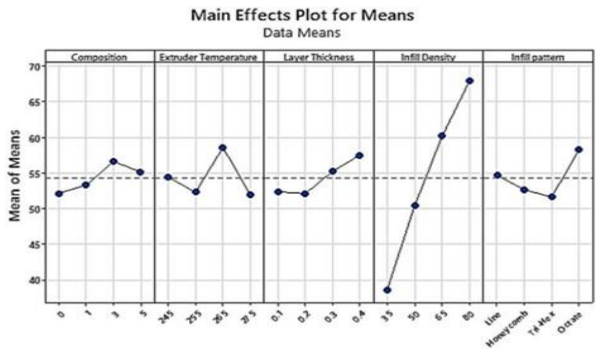

Fig24: Taguchi Analysis for ultimate Compression strength

3). S/N PLOTS FOR FLEXURAL TEST

TABLE VIII. RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS (FLEXURAL TEST)

Level	Layer thickness	Printing speed	Infill density	Infill pattern
1	11.09	11.32	11.57	11.25
2	11.34	11.70	11.86	11.38
3	11.89	12.00	11.38	12.03
4	12.22	11.52	11.74	11.89
Delta	1.12	0.69	0.47	0.78
Rank	1	3	4	2

The S/N ratio analysis was performed to investigate the effect of different printing parameters on the performance properties of the 3D-printed specimens. The findings showed that infill density produced the greatest impact on the response, identifying it as the most significant parameter. Layer height also contributes to specimen performance; however, its impact is lower compared to infill density. Printing speed shows a reduced influence, whereas orientation has the smallest effect among all the investigated parameters. Overall, the findings demonstrate that infill density is the key factor affecting the quality and Mechanical performance of the printed specimens, followed by layer height, printing speed, and orientation.

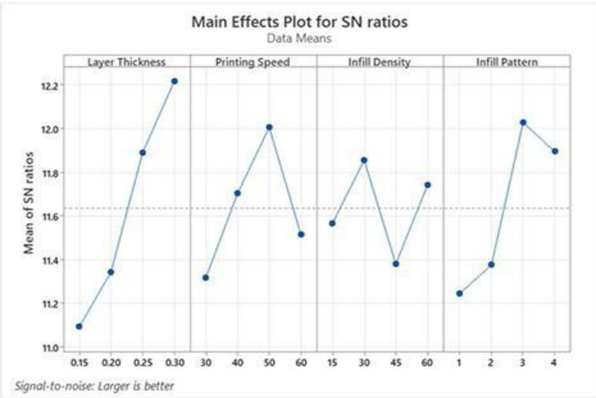

Fig25: Taguchi Analysis for ultimate Flexural strength

COUNTOUR PLOTS

Contour plots are graphs used to show how a response, such as strength or performance, changes with two different process parameters. They help identify the best combination of parameters that can produce the desired result. In Response Surface Methodology (RSM), these plots are created using a mathematical model developed from the experimental data. Contour plots make it easier to understand how different factors interact with each other and influence the response. When the mathematical model accurately represents the actual process, the contour plots provide reliable information for optimization and decision-making.

1). SURFACE PLOT FOR TENSILE STRENGTH

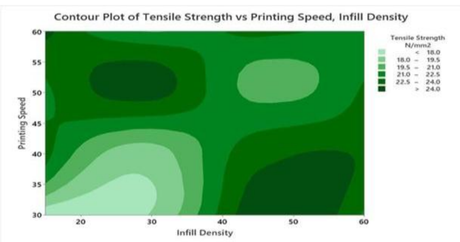

Fig 26: Printing speed vs infilled density

The contour plot shows that the performance of the printed specimen improves as both infill density and printing speed increase. Higher values of infill density and printing speed result in better response values, indicating improved mechanical properties. The best performance is achieved when both parameters are set at higher levels, suggesting that this combination provides the optimum printing condition for specimen.

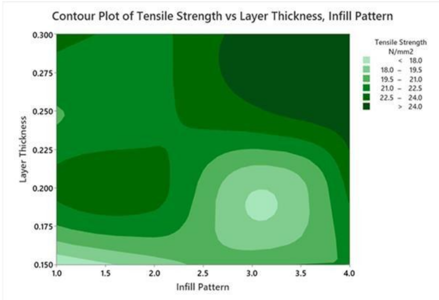

Fig27: Layer Thickness vs infilled Pattern

The contour plot indicates that the performance of the printed specimen improves as both the infill pattern and layer thickness increase. Higher response values are observed at larger layer thicknesses and higher infill pattern levels. The best result is achieved when the infill pattern is set to 4 and the layer thickness is 0.30 mm, showing that this combination provides the optimum printing condition for better mechanical performance.

2). SURFACE PLOT FOR FLEXURAL STRENGTH

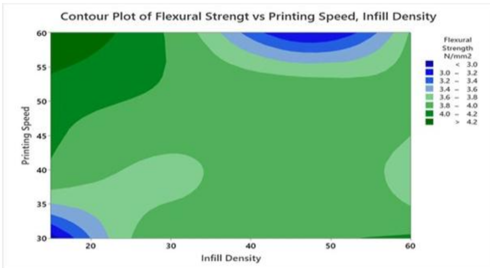

Fig28: Printing Speed vs Infilled Density

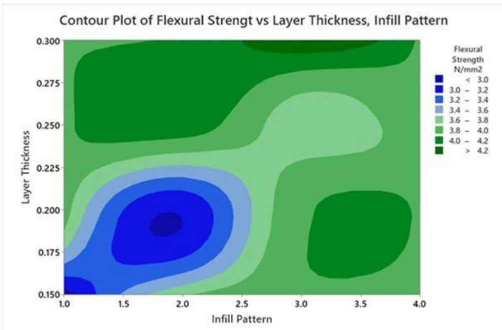

Fig29: Layer Thickness vs infilled Pattern

The specimen printed using the optimized printing parameters showed stronger bonding between the layers and higher flexural strength than the specimen printed with non-optimized settings. The optimized parameters helped reduce printing defects such as voids, weak layer adhesion, and layer deformation. As a result, the printed specimen demonstrated better strength, stability, and overall structural performance.

CONCLUTION AND FUTURE SCOPE

This research looked at how different settings used in FDM 3D printing affect the strength and other physical properties of PETG materials. The results from the tensile, flexural, and compression tests showed that the strength and general performance of the printed samples improved when the printing settings were properly adjusted. Among the parameters studied, infill density and infill pattern had the biggest effect on the mechanical properties. The Gyroid infill pattern worked best because it spread the load more evenly and made the structure more stable. The Taguchi method was used successfully to find the best printing settings while reducing the number of experiments needed.

Overall, the optimized PETG specimens demonstrated excellent strength, stiffness, and durability, making them appropriate for use in engineering, biomedical devices, and lightweight structural component applications. The study emphasizes the significance of choosing suitable printing parameters to manufacture high-quality and dependable 3D-printed components.

FUTURE SCOPE

Future research can concentrate on enhancing the strength and performance of 3D-printed PETG components through the application of advanced materials and improved optimization techniques. Methods such as Artificial Neural Networks, Machine Learning, and Response Surface Methodology can be implemented to precisely predict and optimize printing parameters. Additional investigations can also examine the utilization of composite materials and analyze characteristics such as fatigue life, wear resistance, and long-term durability. Furthermore, 3D-printed PETG can be applied in the development of personalized prosthetic devices, biomedical implants, and lightweight engineering components. The incorporation of sustainable and recyclable materials, smart sensors, and real-time quality monitoring systems can further enhance the efficiency, quality, and reliability of additive manufacturing processes.

APPLICATIONS

- Customized prosthetic limbs and orthopedic implants.
- Surgical guides and patient-specific medical models.
- Lightweight aerospace and automotive components.
- Functional prototypes and industrial machine parts.
- Jigs, fixtures, and tooling applications.
- Biomedical scaffolds and rehabilitation devices.
- Consumer products and customized household items.
- Educational and research applications in additive manufacturing.
- Sustainable manufacturing using recyclable PETG materials.
- Smart prosthetics and advanced biomedical devices.

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