

# Optimization of Tensile and Flexural Properties of PETG Filament in FDM 3D Printing Using Response Surface Methodology

Purnima Gupta<sup>1,\*</sup>, Ashish Sharma<sup>2</sup>, Pawan Kumar Arora<sup>3</sup>, Yogesh Shrivastava<sup>4</sup>

## Abstract

Now a days manufacturing trend has been changed from subtractive to additive. In additive manufacturing (3D Printing), layer by layer deposition occurs and final product can be obtained. The main advantages of additive manufacturing is to obtain customized product, complex geometry product. This research investigates the optimization of tensile and flexural Strength of PETG filament in Fused Deposition Modeling (FDM) 3-d printing by using of Response Surface Methodology (RSM). Specimens have been decided in accordance with ASTM standards for tensile and flexural checking out. Input parameters for the printer have been decided on based totally on literature evaluations and preliminary experiments. These parameters and their stages had been applied to layout an RSM-primarily based Design of Experiments (DoE). Following the DoE, specimens had been revealed and examined the usage of tensile and flexural trying out machines. The effects acquired were hired to expand mathematical fashions for tensile strength and flexural energy. These models facilitated the technology of contour plots, which were analyzed to recognize the dependency of output parameters on input parameters. Suitable tiers of enter parameters that yield specimens with most beneficial tensile and flexural electricity were recognized from the contour plots. Validation experiments confirmed the importance of the recognized parameter degrees, ensuring that they continuously produce specimens with perfect mechanical properties.

**Keywords:** Additive manufacturing, FDM, PETG, tensile strength, flexural strength.

## INTRODUCTION

Rapid Prototyping (RP) is a transformative technology that revolutionizes the manner designers and engineers create physical models from Computer-Aided Design (CAD) data [1-3]. This technique leverages numerous 3-d printing technology to assemble three-dimensional models layer by layer, using substances along with plastic, resin, or metal. Unlike traditional subtractive production techniques, where fabric is eliminated from a stable block, RP employs an additive process, sequentially including thin layers to construct the final item. One of the primary blessings of speedy prototyping is its ability to fast produce tangible prototypes, bearing in mind more advantageous layout visualization, testing, and validation. For example, physical fashions function superb visible aids for designers to speak their thoughts to stakeholders, which includes co-workers and clients. Engineers also can use these prototypes to behavior rigorous tests and

### \*Author for Correspondence

Purnima Gupta  
E-mail: purnimagupta57@gmail.com

<sup>1</sup>Student, Department of Mechanical Engineering, KIET Group of Institutions, Ghaziabad, Uttar Pradesh, India

<sup>2</sup>Faculty, Department of Mechanical Engineering, KIET Group of Institutions, Ghaziabad, Uttar Pradesh, India

<sup>3,4</sup>Faculty, Department of Mechanical Engineering, Galgotias College of Engineering and Technology, Gautam Budh Nagar, Uttar Pradesh India

Received Date: July 04, 2024

Accepted Date: July 16, 2024

Published Date: October 09, 2024

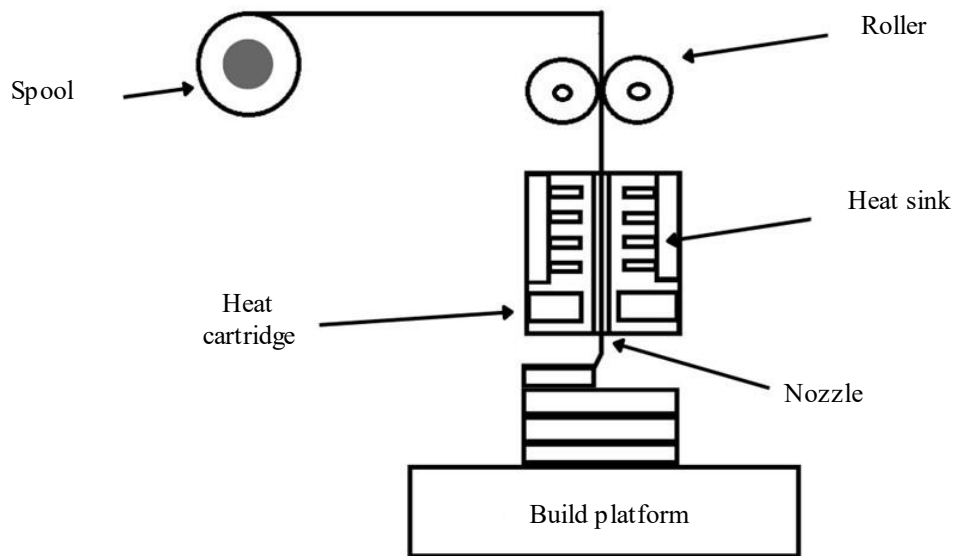
**Citation:** Purnima Gupta, Ashish Sharma, Pawan Kumar Arora, Yogesh Shrivastava. Optimization of Tensile and Flexural Properties of PETG Filament in FDM 3D Printing Using Response Surface Methodology. Journal of Polymer & Composites. 2025; 13(1): 39–58p.

validate their designs. For example, a mechanical engineer might use a prototype of a new turbine blade in a wind tunnel to measure performance elements inclusive of airflow performance and resistance or a civil engineer may create a scale version of a new bridge layout to check its structural integrity and reaction to various stress factors in a simulated environment or maybe an engineering professor would possibly use a 3-D-revealed version of a complex machine component to demonstrate its functionality and design ideas to students in a school room placing.

Several RP technology are commercially to be had, each with unique strengths. These encompass Stereolithography (SLA), which makes use of a laser to therapy liquid resin into stable layers; Selective Laser Sintering (SLS), which fuses powdered cloth the usage of a laser; Fused Deposition Modeling (FDM), which extrudes melted fabric through a nozzle to build layers; Digital Light Processing (DLP), just like SLA but the use of a virtual mild projector to treatment resin; and Binder Jetting, which deposits a binding agent onto a powder bed to shape strong elements [4-6]. These techniques are regularly together referred to as solid loose-form fabrication, laptop-computerized production, or layered manufacturing, emphasizing the layer-through-layer creation manner inherent to all RP technology. Despite its numerous blessings, speedy prototyping does have limitations, depending on the unique RP device. Additionally, growing metallic prototypes may be challenging, although advancements in era are expected to address this trouble inside the near destiny. For large production runs or less complicated gadgets, conventional manufacturing methods stay more comparatively cheap. However, the potential of RP to produce complicated internal systems and its continuous evolution make it a awesome generation with a growing effect on various industries. As the generation advances, it is possibly to become even extra fundamental to fields starting from aerospace to healthcare, supplying faster, greater value-effective answers for each prototype and production desires.

Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), is an additive production method that builds three-dimensional gadgets layer through layer, imparting a bendy and accessible technique for generating a wide array of designs [7-9]. Think of a 3D printer functioning like a sophisticated warm glue gun: it feeds a spool of thermoplastic filament, consisting of PETG or PLA, into a heated extruder that melts the fabric into a liquid nation. The molten plastic is then exactly extruded via a small nozzle, which follows a digital blueprint sliced into thin layers. As the print head movements throughout the build platform, it deposits fabric layer with the aid of layer. Once a layer is finished, the platform lowers, and the next layer is introduced, step by step constructing the final item. This technique's popularity is because of numerous benefits, such as its compatibility with numerous filament materials, every supplying exceptional residences which includes power, flexibility, and warmth resistance. Additionally, FDM printers are typically greater low priced and consumer-pleasant in comparison to other 3-D printing technology, making them best for hobbyists, instructional establishments, and small companies. FDM-published gadgets may be enormously strong and durable, suitable for practical prototypes and even some quit-use programs. Moreover, FDM offers sizable layout freedom, permitting the advent of complicated geometries with complex info, which include internal channels and cavities which are impossible with conventional production strategies. The FDM running principle has been shown in Figure. 1.

The packages of FDM printing are considerable and constantly increasing. This generation is specially popular for growing prototypes, allowing designers and engineers to check form, match, and function earlier than committing to large-scale manufacturing. FDM is an increasing number of used for low-volume manufacturing of specialized components, jigs, and furnishings, making it best for on-call for manufacturing or custom components. In academic settings, the affordability and ease of use of FDM printers offer college students with precious hands-on experience in layout, engineering, and 3-D modeling. FDM additionally empowers artists and architects to create particular and complicated objects, pushing the bounds of creativity. The capacity to create personalized objects with high customization caters to character desires and choices, adding every other layer of application to this era.



**Figure 1.** FDM working principle.

Polyethylene terephthalate glycol (PETG) chemical system (C<sub>14</sub>H<sub>20</sub>O<sub>5</sub>S) is a kind of copolymer and heat resistant plastic with the excellent properties of molding and well chemical resistance[10-13]. It is type of PET (Polyethylene terephthalate) which is characterised by low molding temperature to make it easily heat – bending and vacuum – formable into requisite shapes. In addition to these it also offer good chemical resistance with solvents and adhesives and offer good bond interface strength. PETG represents the advancement of the PET polymer. To synthesize the replacement, cyclohexane dimethanol and ethylene glycol in a molecular chain with a larger monomer will blend up which is imperative for avoiding PET crystallization. It is obtained with the help of two-step melt-phase polycondensation process. It is one of the simplest procedures where the two monomers are joined together simply with a little help from the formation of water. John Whinfield in cooperation with James Dickson, two scientist of Britain, are credited with the petrolysis of PET and the incorporation of PETG for the first time in the year 1941. This can be made through esterification where the glycols are heated with terephthalic acid to form poly ester. Altogether, they civilly constructed a long-chain molecule of PET that could transform into the fiber molecular with considerable dissolubility and melting point. By 1946 PET was adopted as the conventional material for the textile sector and in 1952 it was also employed in the meal packing segment and in 1976 PET is used for production of mineral water, carbonated drinks bottles.

Nevertheless, there are various weaknesses which include high crystallization temperatures, which in turn make it easy and opaque and start demanding for something that is more robust and reliable. Then emerged PETG, full form Polyethylene Terephthalate Glycol. For polyethylene terephthalate glycol-modified, or PETG, ethylene glycol in the molecular chain was replaced with a larger monomer and cyclohexane dimethanol ; which was used to halt the crystallization that goes with PET.

Raj et al. researched about influence of layer height, material density and extrusion temperature on the mechanical properties for PETG material on which he concluded tensile strength is more influenced by extrusion temperature, at max temperature, tensile strength was max and with min layer height. The optimal parameter was 225°C and 0.1mm layer height [14]. Kumaret al. reviewed the various parameters and what effect they have on the various mechanical properties of the 3d printed material. They came to the conclusion that more research has been conducted on the composite other than thermoplastics. And the various parameters have various impacts on the printed material. In context of the study the parameters such as infill pattern, print speed and extrusion temperature has significant impact on the various mechanical properties such as tensile strength, surface roughness as well as

dimensional accuracy while on the other hand the compressive strength was more impacted by the infill density, raster orientation and infill pattern. According to the study the printed parts have higher tensile and flexural strength when they are printed at 0 raster angle and high nozzle temperature. Similarly in the case of compressive strength the layer height is the deciding parameter when the layer thickness is high and infill density is less the print time taken will be less[15]. Ramesh et al. in their paper concluded that the different process parameters have different kinds of effects on the mechanical and thermal properties of the PETG material by taking the printing speed and temperature as variable parameters. The material selected was PLA and PETG and the comparison of both the materials. In order to reduce the complexity the diameter of the nozzle was taken as 0.4mm with the fixed parameters taken namely as infill density (20%), layer thickness (0.2mm), raster angle 450 and the bed temperature at 25°C. The study presented that the PLA filament showed more of an elastic behavior while the PETG filament presented itself brittle in nature. The melting point of the PETG filament was above 225°C. As the printing temperatures of both the materials increases there is an observed increase in viscosity which results in better fusion and decreased porosity. The study concluded that both the materials had asymmetry and that the tensile stress was less than the compressive stress. And as in the case of the PLA material the mechanical properties increase with the increase in the temperature. Whereas, for PETG material It was observed that the increase in the printing temperature as well as the print speed the properties were improved[16]. Bayas et al. conducted that the empirical evaluation on the 3d printed PETG material for properties such as the ultimate tensile strength, dimensional accuracy and the printing time. The layer thickness, infill percentage and the orientation of the specimen were the varying parameters. To obtain the maximum strength the honeycomb structure was used. And in order to reduce the number of specimens to be used the Taguchi L9's array was used. According to the evaluations made, As an increase in the layer thickness is observed the percentage elongation increases as well, and also the material can sustain large amount of load which indicates towards a higher tensile strength[17]. Tanveer et al. had done the variation in the infill percentage (50% and 100%) and the layer thickness (0.1mm and 0.3mm) focused on designing, validating and 3D printing the tensile specimen and by taking one end of the specimen fixed a static structural analysis was carried out on Ansys 16.2. by carrying out the analysis it was observed that with increased layer thickness and decrease in the infill percentage the tensile strength decreases. A percentage error of 5 was observed between the experimental and simulated results. The experimentally performed tensile and compressive test were validated by the static structural in Ansys [18].

The optimization of mechanical properties in Fused Deposition Modeling (FDM) 3D printing has been the subject of extensive research, particularly with regard to materials such as Polyethylene Terephthalate Glycol (PETG). PETG's recognition in additive production is attributed to its advantageous properties, which include sturdiness, chemical resistance, and simplicity of use. This segment reviews key studies which have explored the have an impact on of diverse printing parameters on the mechanical houses of PETG and different thermoplastics. Several studies have underscored the importance of printing parameters in determining the mechanical properties of 3D-revealed components. Sood et al. [19] investigated the outcomes of layer thickness, orientation, and raster angle on the tensile, flexural, and effect strengths of ABS parts, concluding that these parameters considerably have an effect on the mechanical overall performance. Although this study targeted on ABS, comparable standards follow to PETG, given the similar nature of these thermoplastics.

Research particular to PETG has found out the fabric's ability whilst processed beneath most appropriate conditions. Wang et al. [20] explored the outcomes of nozzle temperature and print pace on the tensile power of PETG, finding that higher nozzle temperatures normally beautify layer adhesion, thus enhancing tensile energy. However, immoderate temperatures can cause material degradation and reduced mechanical properties. Cicala et al. [21] performed a comprehensive examine on the influence of layer top, infill density, and print velocity on the mechanical homes of PETG. They observed that lower layer heights and better infill densities contribute to better tensile and flexural strengths because of elevated interlayer bonding and decreased porosity.

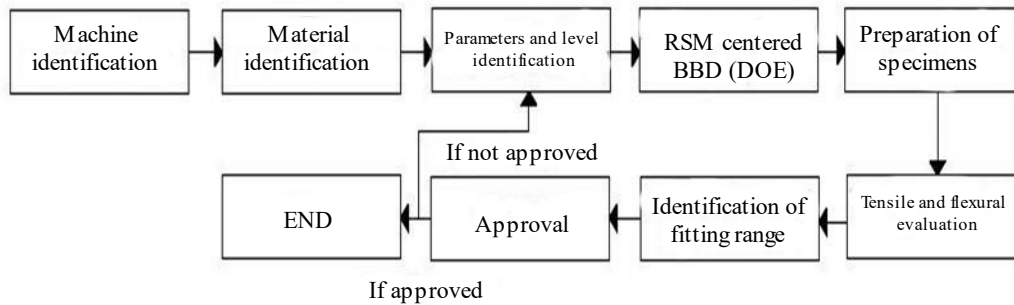
Response Surface Methodology (RSM) has been employed in numerous studies to optimize 3-D printing parameters. Raut et al. [22] applied RSM to optimize the tensile strength of ABS elements, demonstrating that RSM is a powerful device for identifying greatest printing conditions. This method permits for the exploration of interactions between multiple elements, offering a more complete information of their mixed effects. In the context of PETG, Hong et al. [23] used RSM to optimize the print settings for achieving maximum tensile power. Their observe highlighted the significance of parameter interactions and the advantages of the use of a systematic approach to parameter optimization. The use of contour plots derived from RSM models has validated useful in visualizing the relationships between input parameters and output responses. As established by means of Kumar and Singh [24], contour plots facilitate the identity of optimal parameter degrees by illustrating the consequences of various enter ranges. Validation of the optimized parameters via extra experiments is crucial for confirming the robustness of the findings. Studies consisting of that through Tofail et al [25], have shown that validation experiments not most effective verify the version predictions but also offer insights into the realistic applicability of the optimized parameters.

After effectively reviewing the various studies articles the authors have come to the belief that the parameters Nozzle Temperature (NT), Infill Density (ID) and Layer Thickness (LT) have the maximum giant effect on the tensile and flexural energy of the 3-d revealed specimen. The introduction of 3D printing has revolutionized manufacturing by using permitting the speedy and fee-effective production of complex geometries. Among the diverse 3-d printing technology, Fused Deposition Modeling (FDM) is in particular famous because of its accessibility, affordability, and flexibility. However, optimizing the mechanical residences of published parts remains a challenge, particularly whilst the usage of thermoplastic materials which include Polyethylene Terephthalate Glycol (PETG) [26]. PETG is broadly utilized in FDM because of its favorable traits, together with true mechanical energy, chemical resistance, and ease of printing. To maximize the mechanical performance of PETG-revealed components, it is critical to apprehend and optimize the method parameters that affect tensile and flexural residences. Previous studies have highlighted the importance of parameters including layer peak, printing velocity, nozzle temperature, and infill density. However, a systematic and complete technique to optimizing those parameters is needed to attain the high-quality feasible mechanical houses.

This examine employs Response Surface Methodology (RSM) to optimize the tensile and flexural homes of PETG filament in FDM 3-d printing. RSM is a strong statistical method used for developing, improving, and optimizing approaches. It presents a comprehensive know-how of the interactions among diverse input parameters and their outcomes on output responses. The experimental system involved printing specimens according to ASTM standards for tensile and flexural testing. The selection of enter parameters was based totally on an intensive literature review and initial pilot experiments. These parameters and their levels have been then used to create an RSM-based totally Design of Experiments (DoE). The printed specimens had been examined for tensile and flexural houses, and the results were used to expand mathematical models for tensile strength and flexural energy. Contour plots derived from the mathematical models were analyzed to examine the dependency of tensile and flexural strengths on the input parameters. This evaluation led to the identification of suitable stages of enter parameters that optimize the mechanical homes of PETG-printed elements. Validation experiments have been conducted to affirm the effectiveness of the diagnosed parameter tiers, confirming their importance in producing components with suitable tensile and flexural strengths. This research presents a systematic approach to optimizing the mechanical houses of PETG in FDM 3-D printing, contributing to the wider goal of enhancing the performance and reliability of 3D-printed additives in diverse packages.

## **PROPOSED METHODOLOGY**

The technique followed inside the gift work has been proven in the form of float chart as shown in Figure. 2.



**Figure 2.** Flow chart of proposed methodology.

The optimization of tensile and flexural residences of PETG filament in FDM three-D printing involves a established method divided into several levels. This method consists of the identification of the precise gadget and material, choice of key system parameters, layout of experiments the use of Response Surface Methodology (RSM), mechanical trying out, and validation of the consequences. The method is exact as follows:

### Phase 1: Identification of Machine, Material, and Process Parameters

#### *Machine identification*

The three-D printer chosen for specimen instruction is the CREATBOT F430. This system is thought for its excessive accuracy and capability to aid nozzle temperatures as much as 420°C, in conjunction with an routinely managed platform.

#### *Material identification*

The cloth selected for this observe is PETG (Polyethylene Terephthalate Glycol). PETG is desired due to its excessive sturdiness, moldability, and chemical resistance, making it suitable for experimental paintings in FDM 3D printing.

#### *Process parameters identification*

Based on vast literature reviews, the maximum full-size method parameters influencing the mechanical homes of PETG have been recognized as:

- Nozzle Temperature (N.T)
- Layer Thickness (L.T)
- Infill Density (I.D)

### Phase 2: Design of Experiments (DoE)

#### *Experimental design*

The Box-Behnken Design (BBD), targeted on Response Surface Methodology (RSM), is employed to generate a structured array of experiments. This design is chosen for its efficiency in fitting a quadratic version and its robustness in coping with the curvature assumed to be present within the device.

#### *Execution of experiments*

Each test, as mentioned with the aid of the BBD, is achieved three times to ensure repeatability and accuracy. Specimen instruction follows the experiment desk generated by way of the RSM-focused BBD.

### Phase 3: Mechanical Testing and Model Development

#### *Mechanical testing*

The revealed specimens are evaluated for tensile and flexural homes the use of a Servo Control Tensile Testing Machine at Galgotias College of Engineering and Technology. Tests are conducted in accordance with ASTM requirements (ASTM D638 for tensile trying out and ASTM D790 for flexural checking out).

### Data Analysis and Model Development

The results from the tensile and flexural tests are used to develop mathematical models within the RSM framework. These models describe the relationship between the process parameters (N.T, L.T, I.D) and the mechanical properties (tensile and flexural strength).

### Phase 4: Generation of Contour Plots and Optimization

#### Contour plot generation

Contour plots are created based on the developed mathematical models to visualize the effects of process parameters on tensile and flexural strengths. Two factors are varied at a time while the third is kept constant to observe the interaction effects.

#### Optimal parameter range identification

By analyzing the contour plots, optimal ranges for nozzle temperature, layer thickness, and infill density are identified. These ranges indicate the conditions under which the tensile and flexural properties are maximized.

### Phase 5: Validation Experiments

#### Validation of results

Pilot experiments are conducted using the identified optimal parameter ranges. The specimens are tested again for tensile and flexural strengths to validate the predictive accuracy of the models.

#### Comparison and confirmation

The results from the validation experiments are compared with the predicted values to confirm the effectiveness and significance of the optimized parameters.

## EXPERIMENTATION

In the present work the input parameters and levels selected has been listed in Table 1. The highest and lower-level value of the parameter is defined in the coded form as -1, 0 and +1 respectively.

**Table 1.** Input parameters and levels.

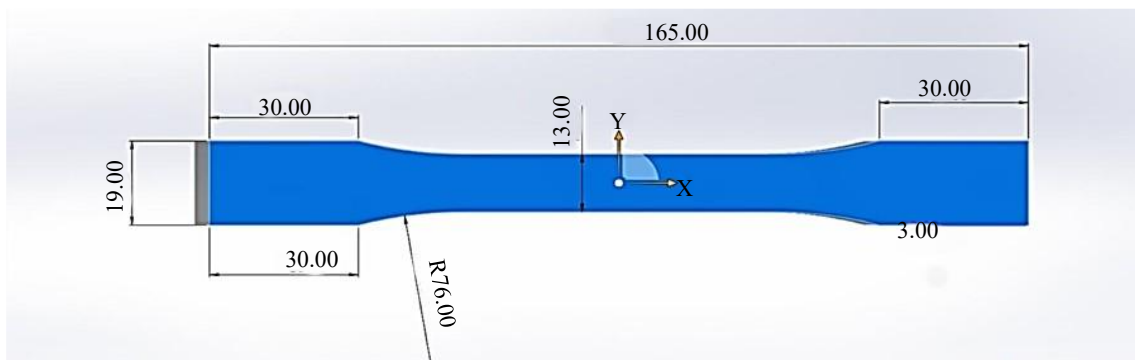
Factor	Symbol	Unit	Level		
			Low (-1)	Medium (0)	High (1)
Infill Density	ID	(%)	50	75	100
Layer Thickness	LT	(mm)	.10	.15	.20
Nozzle Temperature	NT	°C	220	230	240

The DoE has been created using the RSM based BBD method, the generated DoE has been listed in Table 2.

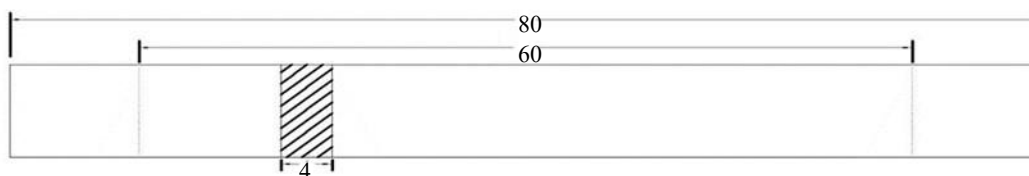
Following the DoE tensile and flexure test specimens have been printed. The Tensile specimens are prepared according to the ASTM (D638) and have the following dimensions as 165mm x 19mm x 3mm as shown in Figure. 3. Whereas, the Flexural specimen ASTM (D790) is used. The dimensions for the flexural specimen are 125mm x 12.7mm x 3.2mm as shown in Fig. 4. The CAD model of the specimen is prepared on the Solidworks software and the CAD file is then converted into the STL format for the purpose of printing. The slicing of the specimens is done on the UltimakerCura software according to the decided process parameters. PETG material is used for preparation of specimens. The printer used in present work has been shown in Figure. 5. Moreover, the printing of specimens have been shown in Figure. 6 as well as the printed test specimens for tensile and flexure test have been shown in Figures. 7&8, respectively.

**Table 2.** DoE based on BBD.

Run Order	Factors (Coded units)		
	ID	NT	LT
1	-1	0	1
2	0	1	1
3	-1	1	0
4	1	1	0
5	0	0	0
6	1	0	-1
7	0	-1	1
8	1	0	1
9	0	0	0
10	0	-1	-1
11	-1	-1	0
12	-1	0	-1
13	0	1	-1
14	0	0	0
15	1	-1	0



**Figure 3.** Line diagram of tensile specimen.



**Figure 4.** Line diagram of Flexure specimen.

**Testing of Specimens**

The testing of the specimens for the Tensile and Flexural strength is done on the Servo Control TENSILE Testing Machine. For the Tensile and flexural test the ASTM standard at break and yield is determined. The tensile test is conducted by fixing one end of the specimen to the fixed jaw of the machine and the other end to a moveable jaw and the load is applied till the specimen fracture. Whereas, for the flexural test the three-point bending apparatus is used the specimen is placed on a span(length-100mm) and the load is applied at the center of the specimen till the specimen is fractured. For the flexural test the speed was maintained at 5 mm/min and for the tensile test the speed was constant at 3 mm/min. Figure. 9 shows the UTM machine for tensile and flexure test. Figure. 10 shows the image of tensile specimen mounted in the machine. Figure. 11&12 shows the tensile specimen before testing and after testing, respectively.

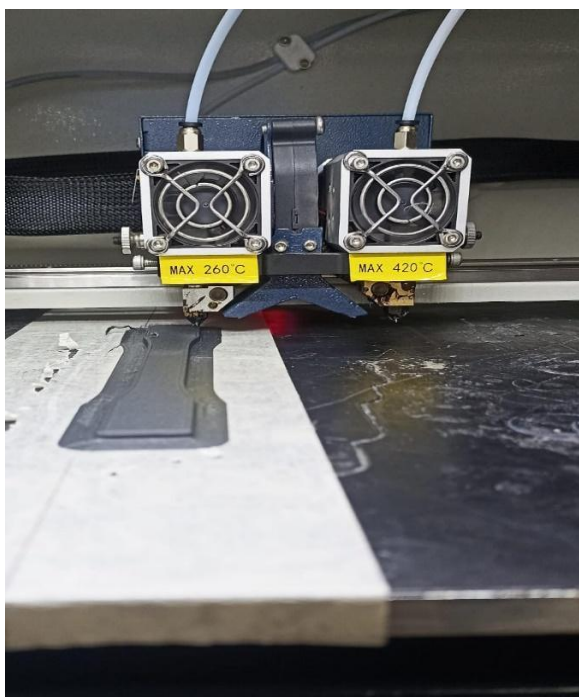
Similarly, Figure. 13 shows the image of flexure specimen mounted in the machine. Figure. 14&15 shows the tensile specimen before testing and after testing, respectively.



**Figure.5.** Creatbot F430 printer.



**Figure 6.** Printing of specimens



**Figure 7.** Tensile specimens



**Figure 8.** Flexure specimens



Figure 9. Servo control tensile testing machine



Figure.10. Tensile test of specimen.



Figure 11. Specimen before tensile test.



Figure 12. Specimen after tensile test.



Figure 13. Three-point bending apparatus



**Figure 14.** Specimen before flexure test.



**Figure 15.** Specimen after flexure test.

After testing the specimens the tensile strength and flexure strength of each specimen have been listed in Table 3.

**Table 3.** Experimental data obtained.

Run order	Factors (Coded units)			Tensile strength (MPa)	Flexural strength (MPa)
	<i>ID</i>	<i>NT</i>	<i>LT</i>		
1	-1	0	1	14.369	2.65
2	0	1	1	15.88	2.91
3	-1	1	0	15.2	2.8
4	1	1	0	17.23	3.1
5	0	0	0	16.19	3
6	1	0	-1	17.22	3.1
7	0	-1	1	16.23	3.1
8	1	0	1	17.543	3.2
9	0	0	0	15.876	2.93
10	0	-1	-1	16.456	2.7
11	-1	-1	0	14.105	2.5
12	-1	0	-1	15.046	2.6
13	0	1	-1	15.949	3
14	0	0	0	15.879	3
15	1	-1	0	17.023	3.3

---

## RESULT AND DISCUSSION

### Response Surface Methodology

Response Surface Methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes, originally developed by Box and Wilson in 1951. RSM focuses on the relationships between several explanatory variables and one or more response variables, making it particularly valuable when multiple input variables influence a performance measure or quality characteristic. The core idea of RSM is to use a sequence of designed experiments to obtain an optimal response, involving systematically varying input variables, collecting data, and fitting a response surface model to the data. This model can navigate the process space, identify optimal conditions, and gain insights into the process's behavior. Widely utilized in engineering, manufacturing, and the bodily sciences, RSM optimizes product designs and improves procedure overall performance. For example, in chemical engineering, RSM optimizes reaction situations to maximize yield or purity while minimizing fees and environmental impact. In production, it improves product nice and decreases waste by means of figuring out top of the line settings for diverse parameters.

Central to RSM is the layout of experiments (DOE), involving decided on experimental runs in which enter variables are systematically varied. Common designs like factorial designs, relevant composite designs (CCD), and Box-Behnken designs efficaciously estimate first- and second-order fashions. First-order models identify guidelines for improving response, even as 2d-order models approximate curved surfaces to locate best situations. After statistics collection, a reaction surface model, usually a polynomial equation, is fitted to explain relationships among input variables and response. Regression analysis estimates polynomial coefficients, minimizing variations between found and expected responses. The model generates response floor plots, visually depicting these relationships, helping in identifying most beneficial regions. Optimization strategies like gradient descent or the technique of steepest ascent find the best input settings, with validation ensuring reliability and robustness. RSM's systematic technique reduces experimental runs compared to standard techniques and complements know-how of variable-response relationships. Despite assuming a polynomial version, RSM is broadly used throughout industries, together with prescribed drugs, agriculture, and materials technological know-how. It optimizes drug formulations, enhances crop yield and quality, and develops new materials. As technology evolves, RSM's capabilities are expected to expand, solidifying its role in process optimization and experimental design.

### Analysis for Tensile strength Test

In tensile test analysis the factor ID (Infill Density) is significant because their P value is less than 0.05. But the factor NT (Nozzle Temperature) and LT (Layer Thickness) are insignificant for a given set of parameters that have been chosen for experiment because their P value is greater than 0.05. And all of the insignificant, either two way or square are insignificant as their P value is greater than 0.05. The coefficient of determination R-sq which basically shows the goodness of fit of a model has a value of R-sq= 95.41% which indicates the high significance of a model, as shown in Table 4.

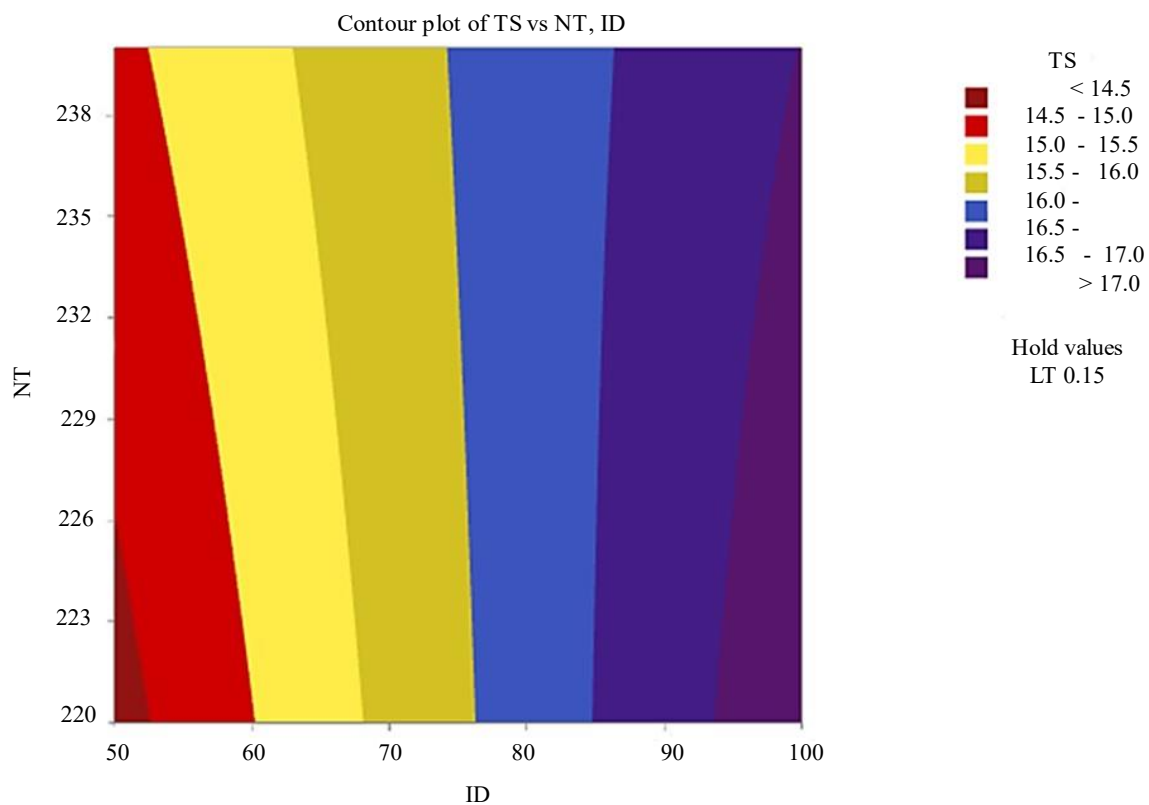
The above graph is plotted amongst Nozzle Temperature (NT) and Infill Density (ID). and its impact on Tensile Strength. The Layer Thickness is kept constant at 0.15mm. From the above graph it can be seen that the peak Tensile Strength is obtained when the Nozzle Temperature (NT) is between the range of 220-240C and the Infill Density between the range of 85%-100%.The reason being increasing the nozzle temperature provides better interlayer adhesion between the layer which offers better tensile strength. Similarly, lower nozzle temperature results in weak adhesion between the layers of the printed parts which result in lower Tensile Strength. As when the Infill Density is high then material density is increased and internal structure support is strong which results in higher Tensile Strength and low Infill Density provides less Tensile strength as there is less material present, so low internal support is observed.

**Table 4.** ANOVA for Tensile strength.

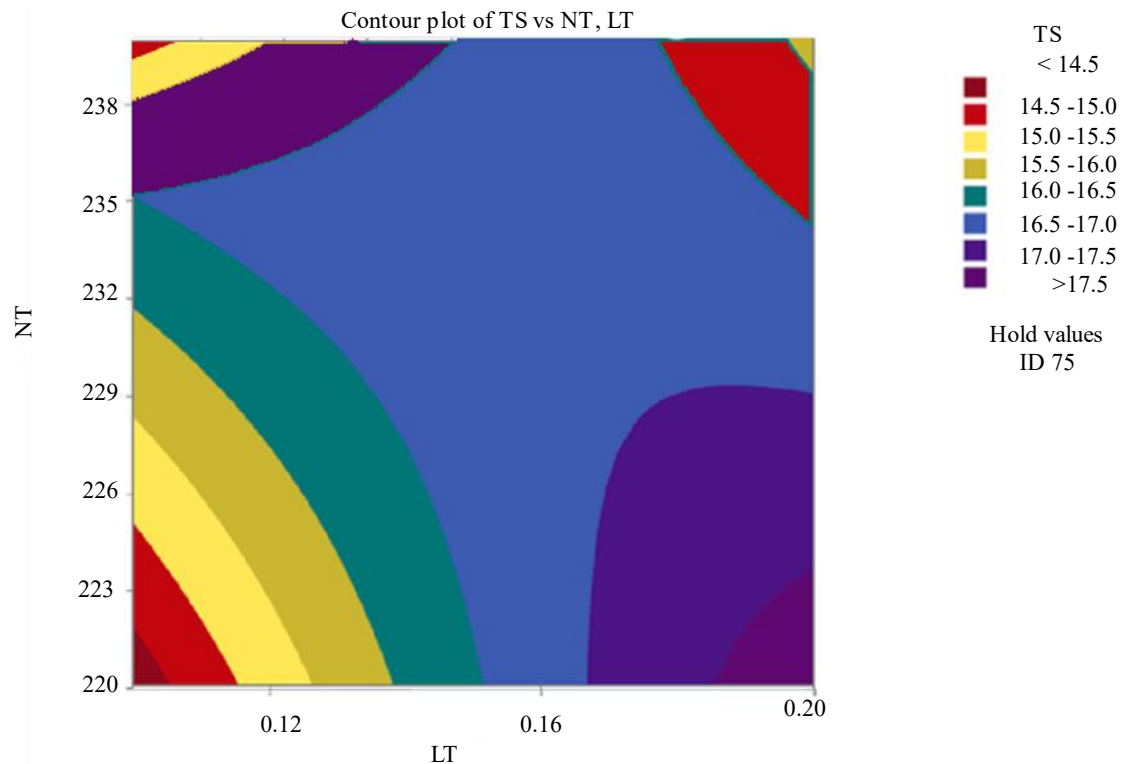
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	13.9032	1.5448	11.56	0.007
Linear	3	13.3284	4.4428	33.24	0.001
ID	1	13.251	13.251	99.15	0
NT	1	0.0248	0.0248	0.19	0.685
LT	1	0.0527	0.0527	0.39	0.558
Square	3	0.1215	0.0405	0.3	0.823
ID*ID	1	0.0287	0.0287	0.21	0.662
NT*NT	1	0.0001	0.0001	0	0.984
LT*LT	1	0.0842	0.0842	0.63	0.463
2-Way Interaction	3	0.4533	0.1511	1.13	0.421
ID*NT	1	0.1971	0.1971	1.48	0.279
ID*LT	1	0.25	0.25	1.87	0.23
NT*LT	1	0.0062	0.0062	0.05	0.838
Lack-of-Fit	3	0.6031	0.201	6.18	0.143
Pure Error	2	0.0651	0.0326		
Total	14	14.5714			

$SR-sqR-sq(adj) \quad R-sq(pred)0.36556995.41\% \quad 87.16\% \quad 32.77\%$  The generated model of tensile strength has been shown below.  $TS = -1 + 0.247 ID + 0.079 NT - 52.8 LT - 0.000141 ID*ID - 0.00004 NT*NT + 60.4 LT*LT - 0.000888 ID*NT + 0.200 ID*LT + 0.078 NT*LT$

This generated model has been used to generate the contour plots as shown in Figures 16 to 18.

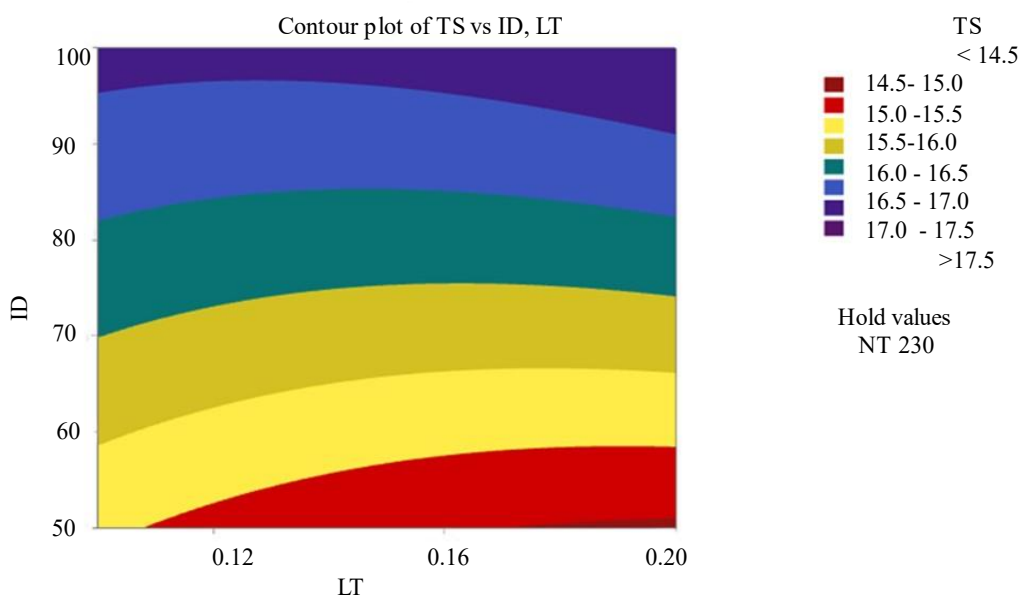


**Figure 16.** Contour plot showing variation in tensile strength with change in nozzle temperature and infill density



**Figure 17.** Contour plot showing variation in tensile strength with change in nozzle temperature and Layer thickness.

The above graph is plotted amongst Nozzle Temperature (NT) and Layer Thickness (LT), and its impact on Tensile Strength. The Infill Density is kept constant at 75%. From the above graph it can be seen that the peak Tensile Strength is obtained when the Nozzle Temperature (NT) is between the range of 224-240C and the Layer Thickness (LT) between the range of 0.17-0.20 mm. The reason for that is that the thicker layer has higher interlayer adhesion which results in stronger parts while the thicker layer may have improved strength in various orientations due to the inter-layer bonding characteristics.



**Figure 18.** Contour plot showing variation in tensile strength with change in Infill density and Layer thickness.

The above graph is plotted amongst Infill Density (ID) and Layer Thickness (LT). and its impact on Tensile Strength. The Nozzle Temperature (NT) is kept constant at 230C. From the above graph it can be seen that the peak Tensile Strength is obtained when the Infill Density is between the range of 96%-100% and the Layer Thickness (LT) between the range of 0.1-0.20 mm. The reason being thicker layer can influence the mechanical properties (Tensile strength) of the 3d printed parts i.e., thicker layers produce parts with strong interlayer adhesion that results in stronger print which results in improved Tensile Strength. While thinner layers may provide better strength in some specific orientations due to layer bonding characteristics.

From the above plots a suitable zone has been identified as shown in Table 5 and Table 6.

**Table 5.** Identified suitable range of input parameters for tensile strength

N.T (deg.C)	I.D (%)	L.T (mm)
220-240	85-100	-
224-240	-	0.17-0.20
-	96-100	0.1-0.2

**Table 6.** Intersection of the obtained range for tensile strength

N.T (deg.C)	I.D (%)	L.T (mm)
224-240	96-100	0.105-0.20

According to the experimental work it can be noted that when the respective parameters such as the Nozzle temperature (NT), Layer Thickness (LT) and Infill Density (ID) are in the ranges (224C-240C), (0.105mm-0.20mm) and (96%-100%), then the value of Tensile Strength obtained is above 17.5MPa. The reason being the Tensile strength is increased when thinner layers are used as they reduce the likelihood of debonding between the layers. Also, strong interlayer bonding at the molecular level is observed when the nozzle temperature is high because of increased flow of the material and better adhesion between the layers which in turn increases the value of the Tensile Strength. The specimens were printed on CreatBot F430 printer on the basis of the ranges obtained from the contour plot, the evaluation of the Tensile Strength was done on the Servo Control Tensile Testing Machine. After the evaluation the value of Tensile Strength obtained was 17.5MPa or above.

### Analysis for Flexure Strength

In analysis of Flexure test, ID (Infill Density) and LT (Layer Thickness) factors are significant because their P value is less than 0.05 and the interactions ID\*ID, LT\*LT, ID\*NT and NT\*LT are significant because their P value is also less than 0.05. But the factor NT is insignificant because of its p value which is greater than 0.05 considering the given set of parameters that have been chosen for experiments. And the interactions ID\*LT and NT\*NT are insignificant as their P value is greater than 0.05. The coefficient of determination R-sq which basically shows the goodness of fit of a model has a value of R-sq= 99.10% which indicates the high significance of a model, as shown in Table 7.

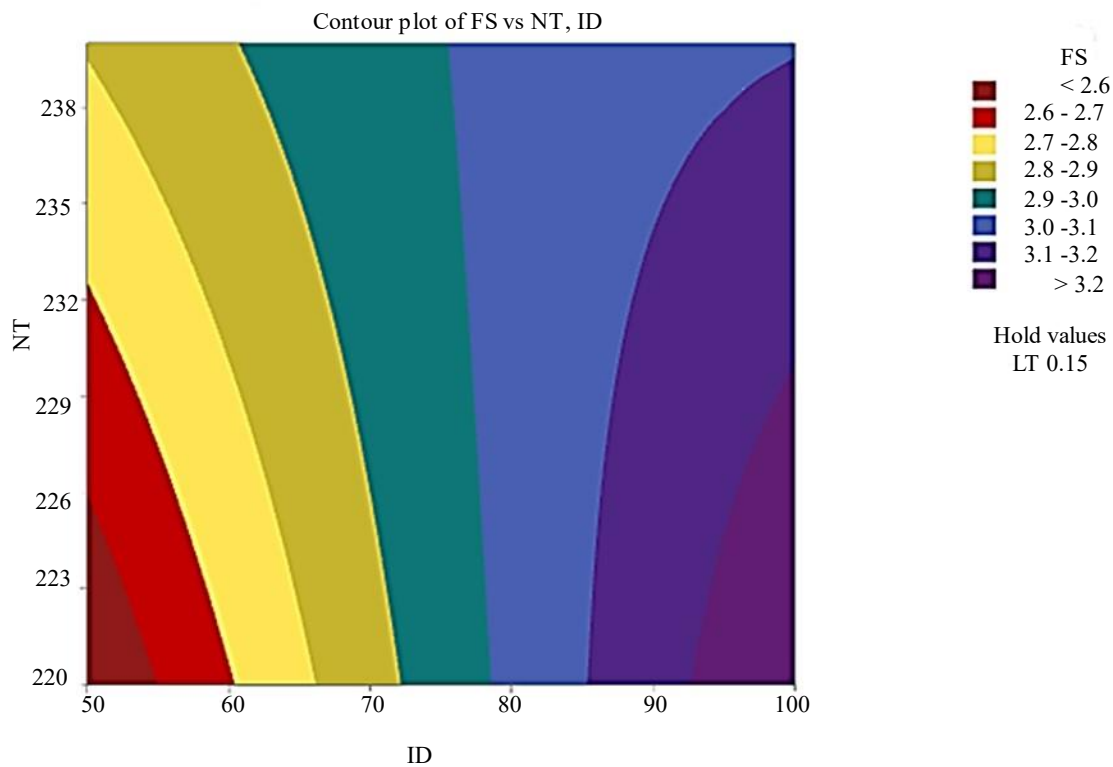
The above graph is plotted amongst Nozzle Temperature (NT) and Infill Density (ID). and its impact on Flexural strength. The Layer Thickness is kept constant at 0.15 mm. From the above graph it can be seen that the peak Flexural strength is obtained when the Nozzle Temperature (NT) is between the range of 220 C-239 C and the Infill Density between the range of 85%-100%. The reason being as the nozzle temperature increases the interlayer bonding gets stronger which results in better fusion between the layers of the printed parts. Similarly, if the nozzle temperature is low then interlayer adhesion is low which results in weak parts being produced. As the infill density increases more rigid parts are produced because the material density increases. Similarly, when the infill density decreases material usage and print time is reduced but the strength is compromised.

**Table 7.** ANOVA for flexure strength.

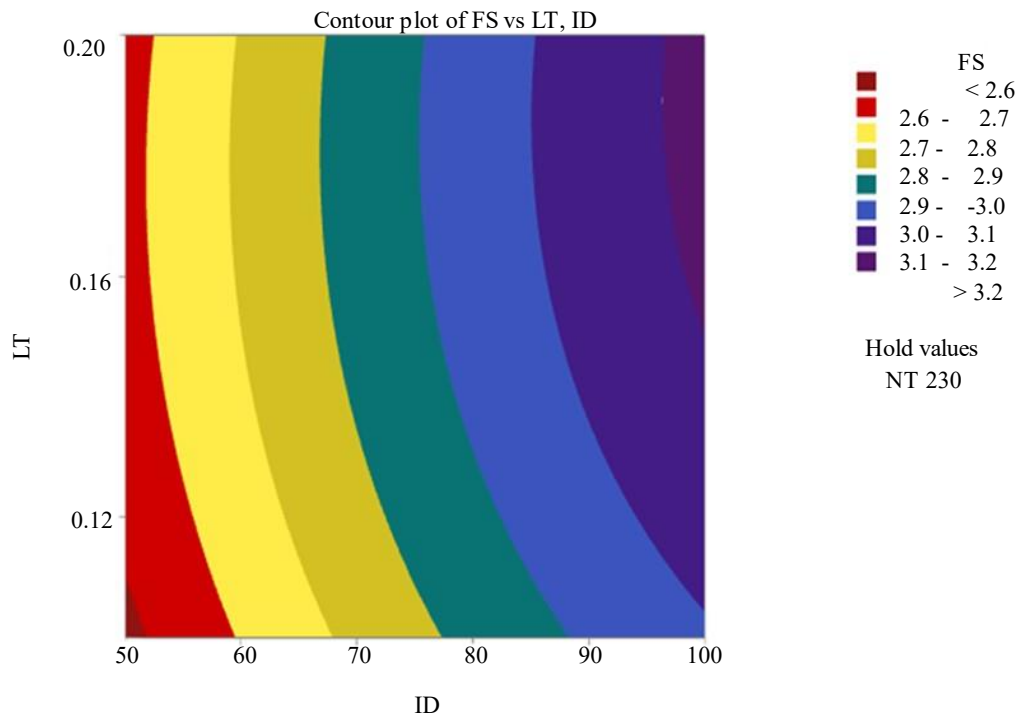
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.746568	0.082952	61.07	0
Linear	3	0.609775	0.203258	149.64	0
ID	1	0.577813	0.577813	425.38	0
NT	1	0.005513	0.005513	4.06	0.1
LT	1	0.02645	0.02645	19.47	0.007
Square	3	0.013643	0.004548	3.35	0.113
ID*ID	1	0.007756	0.007756	5.71	0.062
NT*NT	1	0.000126	0.000126	0.09	0.773
LT*LT	1	0.006933	0.006933	5.1	0.073
2-Way Interaction	3	0.12315	0.04105	30.22	0.001
ID*NT	1	0.0625	0.0625	46.01	0.001
ID*LT	1	0.000625	0.000625	0.46	0.528
NT*LT	1	0.060025	0.060025	44.19	0.001
Error	5	0.006792	0.001358		
Lack-of-Fit	3	0.003525	0.001175	0.72	0.626
Pure Error	2	0.003267	0.001633		
Total	14	0.75336			

$SR-sqR-sq(adj)R-sq(pred)0.0368556$  99.10% 97.48% 91.54% The generated model of tensile strength has been shown below.  $FS = -19.5 + 0.1352 ID + 0.1037 NT + 61.95 LT - 0.000073 ID*ID - 0.000058 NT*NT - 17.33 LT*LT - 0.000500 ID*NT + 0.0100 ID*LT - 0.2450 NT*LT$ .

This generated model has been used to generate the contour plots as shown in Figures 19 to 21.



**Figure 19.** Contour plot showing variation in tensile strength with change in nozzle temperature and Infill density.



**Figure 20.** Contour plot showing variation in tensile strength with change in Layer thickness and Infill density.

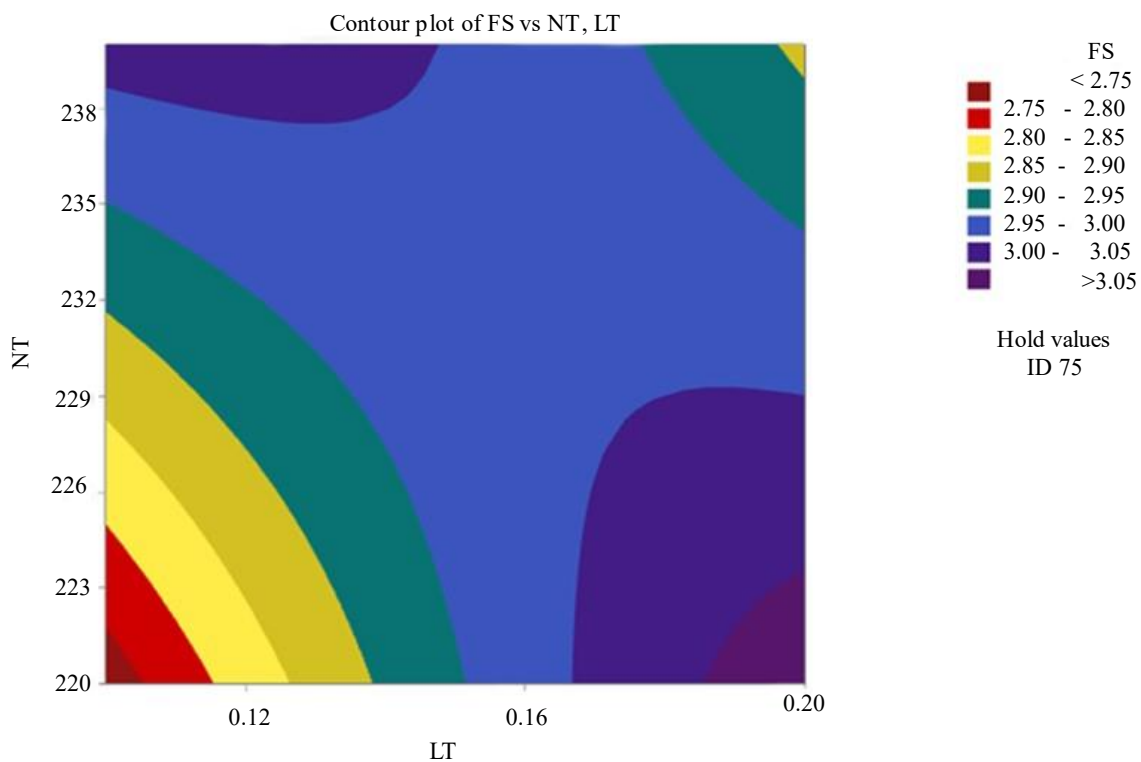
The above graph is plotted amongst Layer Thickness (NT) and Infill Density (ID), and its impact on Flexural strength. The Nozzle Temperature is kept constant at 230C. From the above graph it can be seen that the peak Flexural strength is obtained when the Layer Thickness (LT) is between the range of 0.10-0.20 mm and the Infill Density between the range of 98%-100%. The reason being having thicker layers reduces print time as the layer gets deposited quickly but there is a demerit that there is a loss of detail and poor surface finish is obtained. As for the thinner layers print resolution is better and better surface finish is obtained. On the other hand high Infill Density produces more rigid and stronger parts as the material density is more and lower Infill Density results in reduced print time and material usage but also sacrifices material strength and structural integrity.

The above graph is plotted amongst Layer Thickness (NT) and Nozzle Temperature (NT), and its impact on Flexural strength. The Infill Density is kept constant at 75%. From the above graph it can be seen that the peak Flexural strength is obtained when the Layer Thickness (LT) is between the range of 0.17-0.20 mm and the Nozzle Temperature between the range of 220-230C. The reason being having high Nozzle Temperature leads to better adhesion between the layers which result in improved mechanical properties such as Tensile Strength. Whereas, low nozzle temperature has a negative impact on flowability and viscosity which results in weak layer adhesion resulting in low tensile strength. On the other hand, having thicker layers leads to reduced print time and the layer gets deposited onto each other more quickly leading to poor print resolution and surface finish which has a negative impact on the Tensile Strength. Thinner layers provide better print resolution and increased surface finish providing higher Tensile Strength. From the plots a suitable range of input parameters have been identified that is pertaining to maximum flexure strength for the given range of input parameters, as shown in Table 8 and 9.

As for the Flexural Strength when the selected parameters namely, Nozzle Temperature (NT), Layer Thickness (LT) and Infill Density (ID) are in the following ranges, (220C-230C), (0.17mm-0.20mm) and (89%-100%) then the value of the flexural strength obtained will be above 3.2MPa. This is because, for good interlayer adhesion which provides high strength parts ideal nozzle temperature is necessary. If the nozzle temperature is kept too high then Temperature-Driven decay may be observed and if the

Nozzle Temperature is kept too low then proper adhesion between the layers would not take place leading to weak parts being produced. Similarly, if the layer thickness is kept high then number of layers required would be less and the printing time would also be reduced but it would comprise the Flexural Strength of the printed part and if the thickness of the layers is kept low then then the time to print the specimen would slightly increase but the distribution of stress is better, resulting in high Flexural Strength. For the Infill Density it is better if the Infill Density is kept high because it provides more internal support structure for the printed part resulting in high Flexural Strength.

Moreover, from the ranges of input parameters shown in Table 6 and 9 has been further used to identify a single intersection range as shown in Table 10.



**Figure 21.** Contour plot showing variation in tensile strength with change in nozzle temperature and Layer thickness.

**Table 8.** Identified suitable range of input parameters for flexure strength

N.T (deg.C)_	I.D (%)	L.T (mm)
220-239	85-100%	-
220-230	-	0.17-0.20
-	89-100	0.10-0.20

**Table 9.** Intersection of the obtained range for tensile strength

N.T (deg.C)	I.D (%)	L.T (mm)
220-230	89-100	0.17-0.20

**Table 10.** Single intersection range.

Parameter	N.T (deg.C)	I.D (%)	L.T (mm)
Tensile Strength	224-240	96-100	0.105-0.20
Flexure Strength	220-230	89-100	0.17-0.20
Intersection Range	224-230	96-100	0.17-0.20

In order to validate the obtained intersection range as shown in Table 10, more experiments have been performed as shown in Table 11.

**Table 11.** Validation Experiment.

Exp. No.	N.T (deg.C)	I.D (%)	L.T (mm)	Tensile strength	Flexure strength
1	225	100	0.18	17.5	3.28
2	230	100	0.18	17.6	3.23
3	230	100	0.20	17.6	3.22

From the validation experiments it has been found that the values of tensile strength and flexure strength are greater than or equal to 17.5 and 3.2, respectively. Which resembles that the obtained range is significant.

## CONCLUSION

This study successfully demonstrates the optimization of tensile and flexural properties of PETG filament in FDM 3D printing through a systematic approach utilizing Response Surface Methodology (RSM). By cautiously selecting key technique parameters such as nozzle temperature, layer thickness, and infill density based totally on comprehensive literature overview and pilot experiments, the studies establishes a sturdy basis for experimental design. The CREATBOT F430 3-d printer, acknowledged for its high precision and capability to address excessive nozzle temperatures, was identified as the most suitable device for specimen training. PETG filament was selected for its fine properties, inclusive of sturdiness, moldability, and chemical resistance, making it a perfect candidate for this look at.

The RSM-targeted Box-Behnken Design (BBD) become hired to generate a structured array of experiments, making sure an green and comprehensive exploration of the parameter area. Mechanical checking out of the broadcast specimens, performed according to ASTM standards, supplied reliable information on tensile and flexural strengths. Mathematical fashions evolved from the experimental facts facilitated the technology of contour plots, which have been instrumental in visualizing the effects of the technique parameters and identifying most beneficial levels. The intersection of these premier tiers found out the most favorable conditions for maximizing tensile and flexural strengths. Validation experiments showed the predictive accuracy of the RSM models, demonstrating that the optimized parameter ranges continually produce PETG-published parts with superior mechanical houses. The results from the validation experiments no longer only verified the version predictions but additionally highlighted the sensible applicability of the optimized parameters.

The findings of this study make a contribution considerably to the field of additive manufacturing with the aid of supplying a comprehensive methodology for optimizing the mechanical residences of PETG filament in FDM 3-d printing. The method targeted on this research can function a treasured manual for future studies and practical packages, ensuring that PETG-published components gain their most capability in terms of mechanical overall performance. This research underscores the significance of systematic optimization and empirical validation in advancing the competencies of FDM three-D printing technology.

## REFERENCES

1. Upcraft S, Fletcher R. The rapid prototyping technologies. *AssemAutom.* 2003;23(4):318-30.
2. Pham DT, Gault RS. A comparison of rapid prototyping technologies. *Int J Mach Tools Manuf.* 1998;38(10-11):1257-87.
3. Yan X, Gu P. A review of rapid prototyping technologies and systems. *Comput Aided Des.* 1996;28(4):307-18.
4. Ashley S. Rapid prototyping systems. *Mech Eng.* 1991;113(4):34.
5. Chua CK, Leong KF, Lim CS. *Rapid prototyping: principles and applications.* 3rd ed. Singapore: World Scientific; 2010.

6. Kamrani AK, Nasr EA, editors. Rapid prototyping: theory and practice. New York: Springer; 2006.
7. Bourell DL, Beaman JJ Jr, Klosterman D, Gibson I, Bandyopadhyay A. Rapid prototyping. Composites. 2001;383-7.
8. Solomon IJ, Sevel P, Gunasekaran J. A review on the various processing parameters in FDM. Mater Today Proc. 2021;37:509-14.
9. Comb J, Priedeman W, Turley PW. FDM® Technology process improvements. In: Proceedings of the Solid Freeform Fabrication Symposium; 1994; Austin, TX. p. 1-10.
10. Dudek P. FDM 3D printing technology in manufacturing composite elements. Arch Metall Mater. 2013;58(4):1415-8.
11. Szykiedans K, Credo W, Osiński D. Selected mechanical properties of PETG 3-D prints. Procedia Eng. 2017;177:455-61.
12. Dupaix RB, Boyce MC. Finite strain behavior of poly(ethylene terephthalate) (PET) and poly(ethylene terephthalate)-glycol (PETG). Polymer. 2005;46(13):4827-38.
13. Lacroix C, Bousmina M, Carreau PJ, Favis BD, Michel A. Properties of PETG/EVA blends: 1. Viscoelastic, morphological and interfacial properties. Polymer. 1996;37(14):2939-47.
14. Srinivasan R, Prathap P, Raj A, Kannan SA, Deepak V. Influence of fused deposition modeling process parameters on the mechanical properties of PETG parts. Mater Today Proc. 2020;27:1877-83.
15. Sheoran AJ, Kumar H. Fused Deposition modeling process parameters optimization and effect on mechanical properties and part quality: Review and reflection on present research. Mater Today Proc. 2020;21:1659-72.
16. Ramesh M, Rajeshkumar L, Balaji D. Influence of process parameters on the properties of additively manufactured fiber-reinforced polymer composite materials: a review. J Mater Eng Perform. 2021;30(7):4792-807.
17. Bayas E, Kumar P, Harne M. Impact of process parameters on mechanical properties of FDM 3D-printed parts: A comprehensive review. Eur Chem Bull. 2023;12:708-25. Tanveer MQ, Mishra G, Mishra S, Sharma R. Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts-a current review. Mater Today Proc. 2022;62:100-8.
18. Sood AK, Ohdar RK, Mahapatra SS. Parametric appraisal of mechanical property of fused deposition modelling processed parts. Mater Des. 2010;31(1):287-95.
19. Wang P, Zou B, Xiao H, Ding S. Effects of printing parameters of fused deposition modeling on mechanical properties, surface quality, and microstructure of PEEK. J Mater Process Technol. 2018;271:62-74.
20. Cicala G, Latteri A, Del Curto B, Vedrano S, Carfi Pavia F, Recca G. Engineering thermoplastics for additive manufacturing: A critical perspective with experimental evidence to support functional applications. J ApplBiomaterFunct Mater. 2018;16(3):186-95.
21. Raut S, Jatti VS, Khedkar NK, Singh TP. Investigation of the effect of built orientation on mechanical properties and total cost of FDM parts. Procedia Mater Sci. 2014;6:1625-30.
22. Hong S, Choi J, Kim H. Optimization of Process Parameters for the Tensile Properties of PETG Parts Using the Taguchi Method. Materials. 2020;13(12):2794.
23. Kumar R, Singh R. Investigations for mechanical properties of STL files for rapid prototyping. Mater Today Proc. 2016;3(6):1803-11.
24. Tofail SA, Koumoulos EP, Bandyopadhyay A, Bose S, O'Donoghue L, Charitidis C. Additive manufacturing: scientific and technological challenges, market uptake and opportunities. Mater Today. 2018;21(1):22-37.
25. Durgashyam K, Reddy MI, Balakrishna A, Satyanarayana K. Experimental investigation on mechanical properties of PETG material processed by fused deposition modeling method. Mater Today Proc. 2019;18:2052-9.
26. Lenth RV. Response-surface methods in R, using rsm. J Stat Softw. 2010;32:1-17.