

# Application Of Taguchi's Experimental Design And Range Analysis In Optimization Of FDM Printing Parameters For PET-G, PLA And HIPS

N. Mohammed Raffic, Dr.K.Ganesh Babu P.Madhan

**Abstract:** The present work aims to conduct optimization of Fused Deposition Modeling printing parameters for three different materials namely PET-G, PLA and HIPS which has less consideration than the conventionally adopted material ABS by various authors in the area of research in past decades for the assessment of specimen weight and fatigue strength. The FDM printing parameters such as Slice Height, Infill Density, Shell Thickness and Raster Angle are varied with three levels ( $3^4$ ) to create the experimental design matrix as per Taguchi's experimental design. Taguchi's S/N ratio method and Range Analysis are the analysis tools considered for obtaining the optimum parameter combination and significant factor over the output responses measured. From both the above mentioned methods it is observed that Infill density is the most significant factor which affects the specimen weight by contributing 92.14% , 88.86% , 63.52% and fatigue strength by 60.18% , 50.86% , 53.90% for PET-G, PLA and HIPS. PET-G is found to have more fatigue strength than PLA and HIPS. The specimens made out of HIPS are found to weigh less than other materials considered. The optimum parameter combination for both the responses are found to have good agreement in all the three materials considered. Inclusion of other input printing parameters associated with the process and adoption of various DOE methods and optimization techniques are suggested as further research directions from the present work to have a deep insight of the study concerned respectively

**Index Terms:** ANOVA, Fatigue Strength ,FDM , Range Analysis, Signal to Noise Ratio, Taguchi's Orthogonal Array.

## I. INTRODUCTION

The continuous growth and long time success of any industry in the market has a linear relationship with customer satisfaction it attains through its products and best services it provides. Optimization is a procedure adopted by engineers and scientists in order to reduce the variation occurring in a product by controlling the parameters and characteristics pertinent to product design and development. The input process parameters selected will have a serious effect over the final performance of a product or system with no doubt. Many methods like Taguchi's Orthogonal Array, Response Surface Methodology are generally adopted by authors to create the experimental plan and the experimental data is further analyzed to obtain the optimum parameter combination and also the significant parameter which has the maximum effect over the final response under study. Samir Kumar Panda [1] et.al has conducted studies to optimize the FDM input parameters such as layer thickness, build orientation, raster width, air gap and raster angle for ABS – P400. The authors have experimentally identified the various mechanical properties like mechanical, flexural and impact strength of FDM samples through the experimental plan developed by Central composite design. The experimental results obtained are further analysed using bacterial foraging technique for identifying the optimum parameter combination.

The authors have advised to avoid small raster angle which may result in stress accumulation in the direction of deposition and higher raster width may improve strong bond formation between the rasters. Vishwas M [2] et.al has optimized the FDM process parameters for materials such as ABS and Nylon by considering the input parameters model orientation, shell thickness and layer thickness. The taguchi's L9 orthogonal array experimental plan has been devised for conducting the experiments for identifying the ultimate strength and dimensional accuracy of the parts prepared by both ABS and Nylon using FDM Pramaan Mini machine. The results observed are further analysed through Signal to noise ratio method and it has been identified that both shell thickness and orientation angle are most impacted process parameters over the mechanical properties of both the materials. The optimum parameter combination has also been communicated for good achievement of dimensional accuracy of parts printed. John Ryan C. Dizon [3] et.al has made a detailed review on various additive manufacturing techniques commercially available in the market such as Fused Deposition Modeling, Stereo lithography, Digital Light Processing, Selective Laser Sintering, Polyjet Printing and Laminated Object Manufacturing their capabilities, advantages and applications in various sectors. The authors have finally made a conclusion by developing various reasonable questions by having deep insight into the technological capabilities, testing standards, open source software used and mechanical properties arrived through various research methods and the standards followed in conducting the mechanical tests for the evaluation of Tensile, Compressive , fatigue and impact. Anoop Kumar Sood [4] et.al has made a study to improve the dimensional accuracy of FDM processed parts using grey taguchi method by considering layer thickness, raster width , air gap and orientation. J.Santhakumar [5] et.al has made an attempt to enhance the impact strength of polycarbonate material processed by FDM by considering the four input parameters such as layer thickness, build orientation , raster angle and raster width through taguchi's experimental design . Imthiyaz Khan and Dr.A.A.Shaikh [6] has reported a review on FDM based parts to act as rapid tooling and discussed about stair case effect

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observed with FDM made parts. Wenzheng Wu [7] et.al has studied the influence of two different FDM parameters layer thickness and raster angle over the mechanical properties of PEEK material processed through FDM process and compared the results obtained of PEEK material with ABS. Szykiedans [8] et.al has studied few mechanical properties of PETG with and without glass fibre addition to study about tensile strength and elastic modulus of the material by varying the build orientation. Mahdi Kaveh [9] et.al have investigated the effect of FDM process parameters over dimensional accuracy and internal cavity for HIPS material processed through FDM process.

## 2. Fused Deposition Modeling

Fused Deposition Modeling (FDM) is a low cost thermoplastic based additive manufacturing process which has application in the making of prototypes and functional models. The Process is also known by its other names such as Fused Filament Fabrication (FFF), Material Extrusion (ME) in the market. The process has the involvement of numerous printing parameters and material options in general. The appropriate selection of parameters are highly essential to have quality print out of the FDM machine. Materials like Acronitrile Butadiene Styrene (ABS), Poly Lactic Acid (PLA), Poly Ethylene Terethalate-Glycol added (PET-G), High Impact Poly Styrene (HIPS), Polyamide (PA) and many other materials can be printed with less difficulty. The process works under the principle of extruding the raw material loaded in the form of a filament in a spool through a heated nozzle over a heated or unheated bed. The filament is added layer by layer to get the final shape of the output. The process starts with a cad model and ends up with a tangible solid object. The cad model prepared through solid modeling software has to be inputted in to the slicing software in form of .stl file for slicing the model in to individual layers. The slicing software has various options for controlling the FDM parameters such as Layer Thickness, Infill Density, Shell Thickness, Raster Angle, Printing Speed, Air Gap, Bed Temperature, and Nozzle Temperature. The sliced model with the prementioned parameters can be previewed before ordering the machine to print the object. The Slicing software also generates the G- code for the object generated through FDM process. The definitions of the FDM Printing Parameters considered in the present work are detailed below.

- Slice Height:** An important FDM parameter also known as Layer Thickness which may be defined as the height of the individual layer to be deposited one over the another to attain the final model. Lesser the value will result in more number of layers and increased strength.
- Infill Density:** It is defined as the amount to material to be filled inside the solid object normally expressed as percentage. Higher the value more the amount of material consumed by the model and also increases the weight and cost of the specimen
- Shell Thickness:** It is defined as the thickness of the top and bottom layers of the solid object which are visible to the observer.
- Raster Angle:** It is the angle made by the raster with respect to the horizontal which may be varied from 0 - +90.

The present work considers three FDM Printable materials such as PET-G, PLA and HIPS. The details about them are described below.

### a) Poly Ethylene Terethalate – Glycol Modified (PET-G)

A Standard thermoplastic which has excellent properties in terms of strength and temperature resistance offering improved impact resistance, chemical resistance and heat resistant compared to ABS/PLA. PETG is an excellent water and moisture barrier material, and is widely used for soft-drink bottles.

### b) Poly Lactic Acid (PLA)

PLA is a biodegradable thermoplastic which may be derived from renewable resources such as cornstarch, sugarcane, Tapioca roots or even potato starch. It finds application in food packaging, bags, disposable tableware, upholstery, disposable garments, hygiene products, diapers and surgical implants. [10]

### c) High Impact Polystyrene (HIPS)

HIPS is an engineering thermoplastic with dimensional stability, good impact resistance, excellent machinability and excellent aesthetic properties. HIPS is often specified for low strength structural applications such as housings and covers. It is easy to fabricate, paint and glue. Various studies on FDM process have been conducted by authors on different end output response measurements by considering different materials and process parameter combinations to understand their effect. [15-19] The specimens for the present work has been printed by utilizing the capabilities of Raise3D N2 Plus 3D printer which has a build volume of 305\*305\*610 mm (W\*D\*H) with a heated bed which can be used based upon the material printed. It consists of dual extruder for loading the raw filament and support material to get extruded through the heated nozzle. The machine works under the principle of Fused Deposition modeling. Idea maker is the slicing software associated with this machine to slice the solid model in to thin layers. The Figure1 shows the Raise3D N2 Plus FDM printer used in the current work.

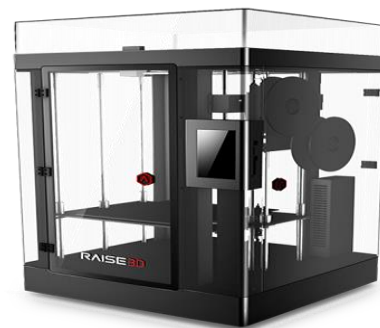
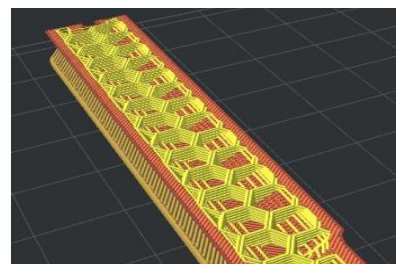
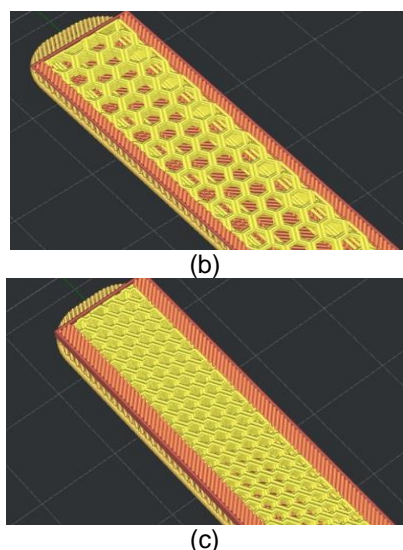


Figure 1 Raise3D N2 Plus FDM Printer



(a)



**Figure 2 Sliced specimen model with Infill Densities (a) 25% (b) 50% and (c) 75%**

The Figure 2 (a), (b), (c) shows the different views of the fatigue specimen filled with different infill densities. The Table 1 represents the details of various physical, mechanical, thermal properties and other material characteristics obtained from the filament manufacturer's data sheet.

**Table 1 Detail of Various Properties of FDM Materials**

Property / Characteristics	Unit	PET-G	PLA	HIPS
Density	g/cm <sup>3</sup>	1.27	1.24	1.04
Ultimate Strength	Mpa	53	65	32
Elongation at Break	%	18	6	50
Extruder Temperature	°C	230-250	190-220	230-245
Bed Temperature	°C	75-90	45-60	100-115
Glass Transition Temperature	°C	80	60	100
Filament Diameter	Mm	1.75	1.75	1.75
Color	-	Black	Green	White

### 3. Design of Experiments

Design of Experiments (DOE) is a systematic method to determine the influence of input parameters over a single or set of output responses. It clearly indicates the controllable and uncontrollable input process parameters over the output responses measured. Several methods such as Taguchi's Orthogonal Array (OA), Response Surface Methodology (RSM), Definitive Screening Design (DSD) etc., have been used by many researchers to create the experimental plan. The results obtained are generally statistically analyzed to know their significance and contribution percentage of input process parameters considered for study over the output responses. Authors Pavan Kumar Gurrula and Srinivasa Prakash Regalla [11] has utilized the concept of DOE in their work by considering three different FDM parameters to study the volumetric change in FDM parts by using the Face centered central composite cubic model design which provides a total of

20 experiments to be conducted. The authors have concluded that the factors horizontal and vertical direction have effect over the dimensional accuracy and curl than model interior. Madhuri Chaudhari [12] et.al has made a study to compare the characteristics of part built using FDM process by adopting Taguchi's L<sub>9</sub> orthogonal array for creating the experimental plan. Surface roughness, production time and cost are the output parameters measured by varying the input parameters such as layer thickness, infill density, orientation and post processing technique adopted for the parts built through FDM. The results obtained are further statistically analyzed through ANOVA to determine the significant factor. The authors have concluded their work by representing the parameter combination for better results. Fahraz Ali [13] has investigated the effect of seven process parameters on build time, material consumption, and surface Roughness by creating the experimental plan using Taguchi's L18 orthogonal array and the optimum process parameter combinations for better output characteristics are reported. Ashay Kohad, and Rajendra Dalu [14] has conducted review on the various optimization techniques followed in the optimization of FDM process parameters. Taguchi's Orthogonal array, Response Surface methodology, Grey relational analysis, Group Method Data Handling, I-Optimal Criterion, Teaching learning based optimization algorithm and full factorial design are the various techniques used for conducting optimization of FDM process parameters as reported by the authors. Table 2 represents the different FDM parameters which are varied at 3 levels.

**Table 2 Varying FDM Printing Parameters and Considered Levels**

S.No	FDM Printing Parameters	Symbol	Unit	Level 1	Level 2	Level 3
1	Slice Height	A	mm	0.15	0.2	0.25
2	Infill Density	B	%	25	50	75
3	Shell Thickness	C	mm	1	2	3
4	Raster Angle	D	Deg	0	30	60

The Table 3 shows the experimental design layout or plan consisting of 9 different experiments with varying combination of input process parameters in their coded and uncoded values. The code 1 denotes the lowest value of a factor followed by code 2 which denotes the middle value of a factor and the code 3 represents the highest level of a factor. Table 4 shows the other FDM parameters which are kept constant throughout the process of specimen printing.

**Table 3 Taguchi's Experimental Design Layout**

Test Run	Coded Values				Uncoded Values			
	A	B	C	D	A	B	C	D
R1	1	1	1	1	0.15	25	1	0
R2	1	2	2	2	0.15	50	2	30
R3	1	3	3	3	0.15	75	3	60
R4	2	1	2	3	0.2	25	2	60
R5	2	2	3	1	0.2	50	3	0
R6	2	3	1	2	0.2	75	1	30
R7	3	1	3	2	0.25	25	3	30
R8	3	2	1	3	0.25	50	1	60
R9	3	3	2	1	0.25	75	2	0

**Table 4 Constant FDM Printing Parameters**

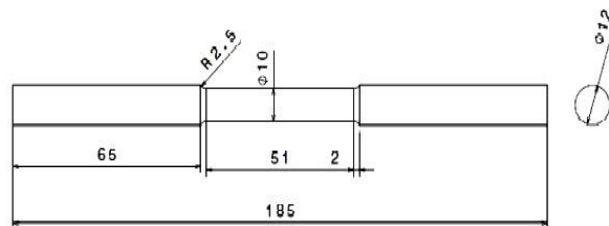
S.No	Parameter / Characteristic	Unit	Value
1	Nozzle Diameter	mm	0.4
2	Raster Width	mm	0.4
3	Printing Speed	mm/s	150
4	Internal Structure	-	Honeycomb
5	Air Gap	mm	0.1
6	Build Orientation	-	Flat
7	Filament Diameter	mm	1.75

**4. Experimental Setup**

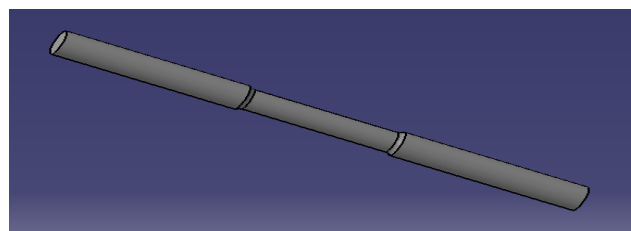
The present work utilizes the experimental setup available at the Strength of Materials laboratory to conduct a rotating bending fatigue test as shown in Figure 3. The experimental setup consists of two chucks opposite to each other to hold the specimen and the power for rotating the chuck is obtained from the D.C motor available in the setup. The setup has a facility to add weights ranging between 1 Kg to 100 Kg at the left end of the specimen to estimate its fatigue life or fatigue strength by applying different loads. The setup is equipped with a revolution counter to record the number of revolutions made by the specimen before failing or breaking into parts. The main drawback of the present setup is that the speed of rotation cannot be varied and the maximum diameter it can hold in the chuck cannot be more than 20mm and length of the workpiece than can accompanied cannot be greater than 200mm.

**5. Experimental Procedure**

The specimen for conducting the rotating fatigue test has an overall length of 185mm with a diameter of 12mm at the gripping section and 10mm diameter at the centre for a length of 51mm. A length of 25mm is inserted in to the chuck on both the sides to hold the specimen while rotating. The 3D model of the specimen is prepared using CATIAV5R20 as shown in Fig 5 and the 2D dimensional views are created using the drafting module as shown in Fig 4.

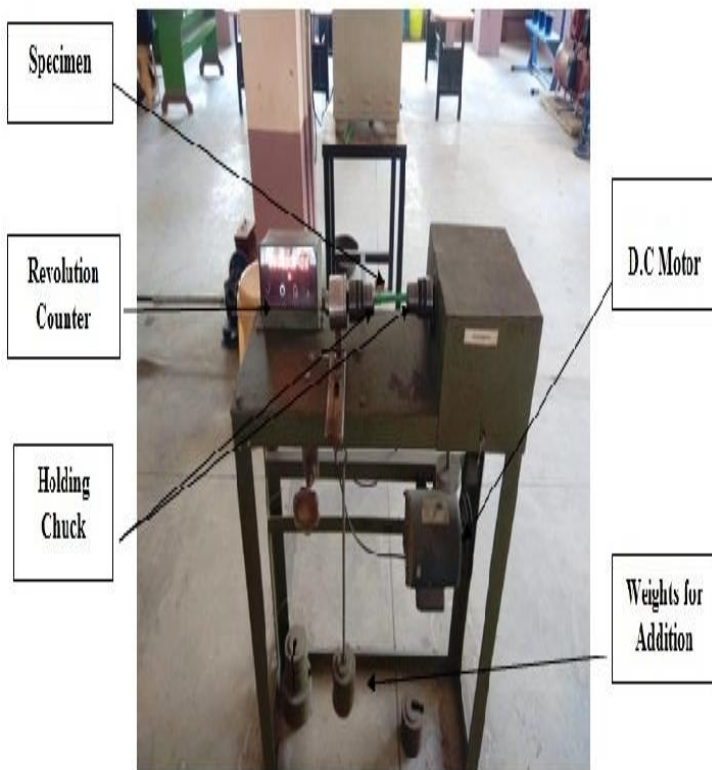


**Figure 4 2D View of Fatigue Specimen**



**Figure 5 3D Model of Fatigue Specimen**

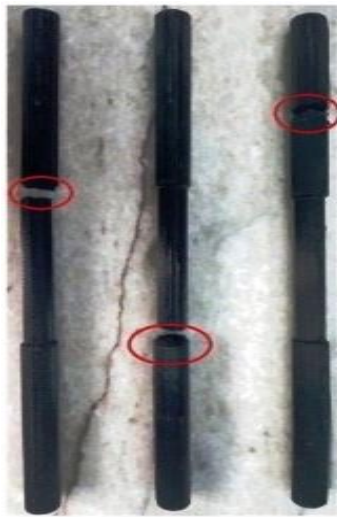
In the present study specimens are printed as per the experimental plan for all the three different materials considered for experimentation. The specimen is fixed one at a time in the chuck and a load of 4 Kg is added to the weighing pan before starting the motor. The chuck rotates due to the power supplied by the D.C motor with the applied load and the revolution of the specimen is recorded by the revolution counter until the specimen rotates without any notice of failure. The specimen undergoes breaking of two parts because of the applied load and the machine is switched off to remove the specimen once the breakage occurs. The no of cycles the specimen has rotated before failure is considered to be the Fatigue life or Fatigue strength of the material. In total 27 specimens made out of three different materials are subjected to experimentation and the corresponding values are recorded for further analysis. The location of the breaking area in the specimen is highlighted for reference in Figure 6, 7, 8. – (a),(b),(c)



**Figure 3 Rotating Bending Fatigue Test Experimental Setup**



(a)

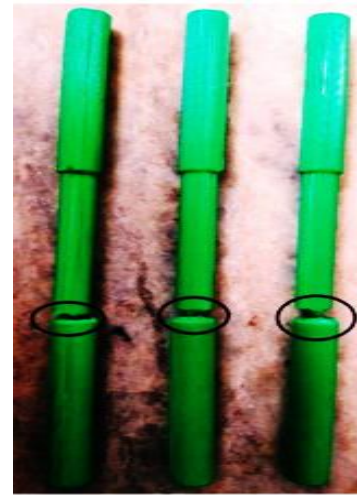


(b)

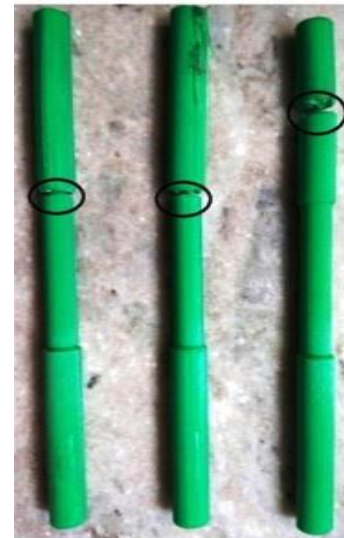


(c)

**Figure 5 Failed PET-G Specimens ordered from 1-9**



(a)



(b)



(c)

**Figure 6 Failed PLA Specimens ordered from 1-9**



(a)



(b)



(c)

Figure 7 Failed HIPS Specimens ordered from 1-9

## 6. Results and Discussion

The experimental data obtained through the experimental work is further analyzed using MINITAB 17.0 Software and Table 5 represents the experimental values obtained towards specimen weight while printing the fatigue specimen and its corresponding signal to noise ratio.

### 6.1 Effect of Input Parameters on Specimen Weight

Table 5 Experimental Values for Specimen Weight and Corresponding S/N Ratio

Test Run	Specimen Weight (gms)			S/N Ratio		
	PET-G	PLA	HIPS	PET-G	PLA	HIPS
R1	10	8	7	-20	-18.06	-16.9
R2	14.5	13.5	6	-23.23	-22.61	-15.56
R3	20	18	15.5	-26.02	-25.11	-23.81
R4	11	11	8.5	-20.83	-20.83	-18.59
R5	15.5	15	12	-23.81	-23.52	-21.58
R6	18	18	14	-25.11	-25.11	-22.92
R7	13	12	10	-22.28	-21.58	-20
R8	14.5	13	11.5	-23.23	-22.28	-21.21
R9	19.5	18	15	-25.8	-25.11	-23.52

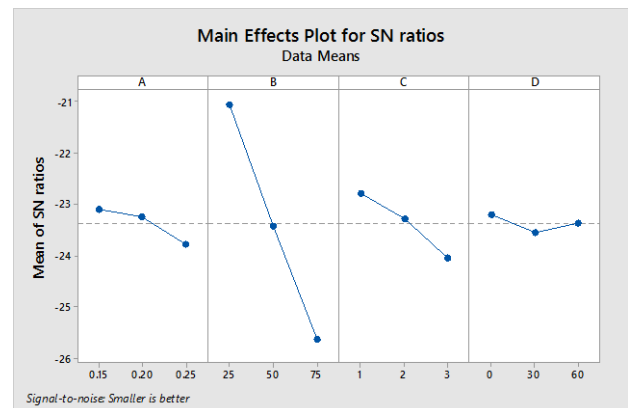


Figure 8 Main Effect Plot for Specimen Weight for PET-G

Table 6 Response Values for Specimen Weight for PET-G

Level	A	B	C	D
1	-23.08	-21.04	-22.78	-23.2
2	-23.25	-23.42	-23.29	-23.54
3	-23.77	-25.64	-24.04	-23.36
Delta	0.69	4.61	1.26	0.33
Rank	3	1	2	4

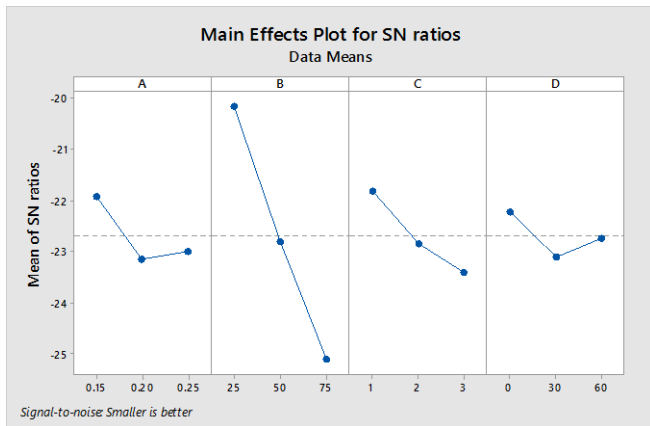


Figure 9 Main Effect Plot for Specimen Weight for PLA

Table 7 Response Values for Specimen Weight for PET-G

Level	A	B	C	D
1	-21.92	-20.16	-21.82	-22.23
2	-23.15	-22.8	-22.85	-23.1
3	-22.99	-25.11	-23.4	-22.74
Delta	1.23	4.95	1.59	0.87
Rank	3	1	2	4

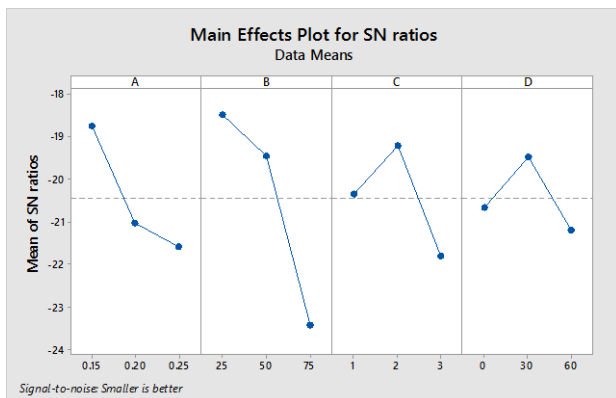


Figure 10 Main Effect Plot for Specimen Weight for HIPS

Table 8 Response Values for Specimen Weight for HIPS

Level	A	B	C	D
1	-18.76	-18.5	-20.35	-20.67
2	-21.03	-19.45	-19.22	-19.5
3	-21.58	-23.42	-21.8	-21.2
Delta	2.82	4.92	2.57	1.71
Rank	2	1	3	4

Figure 8,9,10 shows the main effect plot for specimen weight for the materials PET-G, PLA and HIPS. Tables 6, 7, 8 represents the response values for specimen weight for the materials PET-G, PLA and HIPS and their rankings. By considering smaller the better characteristic in calculating the signal to noise ratio for generating the response graphs The optimum process parameter combination for **PET-G** to have less specimen weight is found to be **A1B1C1D1** (0.15mm Layer

Thickness 25% Infill Density 1mm Shell Thickness 0 Degree Raster Angle). For **PLA A1B1C1D1** (0.15mm Layer Thickness 25% Infill Density 1mm Shell Thickness 0 Degree Raster Angle) and for **HIPS** material the process parameter combination is found to be **A1B1C2D2** (0.15mm Layer Thickness 25% Infill Density 2mm Shell Thickness 30 Degree Raster Angle) respectively. The response values are obtained for the experimental data by considering smaller the better characteristic and it can be understood that infill density is the most significant parameter which influences the specimen weight.

Table 9 ANOVA results for Specimen Weight – PETG

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution Percentage
Regression	4	99.125	24.78	129.76	0	
A	1	1.0417	1.0417	5.45	0.08	1.04%
B	1	92.041	92.041	481.96	0	92.14%
C	1	6	6	31.42	0.005	6.01%
D	1	0.0417	0.0417	0.22	0.665	0.04%
Error	4	0.7639	0.191			0.76%
Total	8	99.8889				100%

The experimental data is further statistically analyzed through ANOVA to obtain the contribution of various input parameters over the weight of specimen for all the three materials. The input parameter which has a P-value less than 0.05 is found to be the most significant parameter which has greatest influence over the output response as per ANOVA analysis. It can be observed that Infill density has 92.14%, 88.86% and 63.52% of significant contribution over specimen weight for the materials PET-G, PLA and HIPS. Raster angle is the parameter which has very less considerable contribution towards the output response for all the three materials considered. Tables 9,10 and 11 represents the ANOVA results obtained for PET-G, PLA and HIPS.

Table 10 ANOVA results for Specimen Weight – PLA

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution Percentage
Regression	4	96.375	24.0937	33.85	0.002	
A	1	2.0417	2.0417	2.87	0.166	2.06%
B	1	88.1667	88.1667	123.86	0	88.86%
C	1	6	6	8.43	0.044	6.05%
D	1	0.1667	0.1667	0.23	0.654	0.17%
Error	4	2.8472	0.7118			2.87%
Total	8	99.222				100%

**Table 11 ANOVA results for Specimen Weight – HIPS**

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution Percentage
Regression	4	75.357	18.8437	3.9	0.108	
A	1	10.6667	10.6667	2.21	0.212	11.26%
B	1	60.1667	60.1667	12.44	0.024	63.52%
C	1	4.1667	4.1667	0.86	0.406	4.40%
D	1	0.375	0.375	0.08	0.794	0.40%
Error	4	19.3472	4.8368			20.43%
Total	8	94.7222				100%

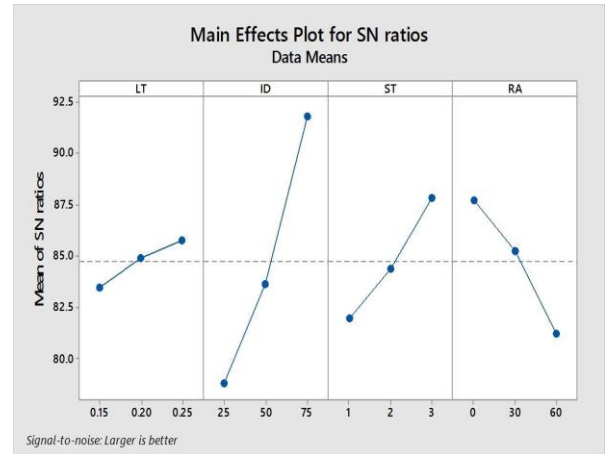
From the comparison of physical properties of all the three different materials considered in the study, PET-G is found to have more density than PLA followed by HIPS. The material with higher density is found to have more specimen weight than the material with low density.

**6.2 Effect of Input Parameters on Fatigue Strength**

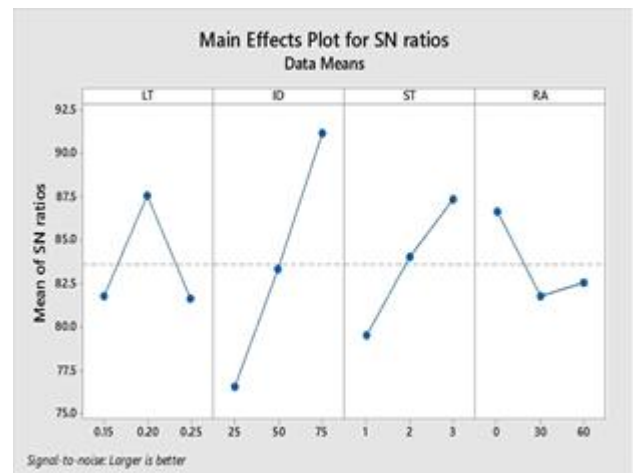
The main effect plots for the fatigue strength of the materials under study has been obtained by considering larger the better characteristic Signal to Noise ratio method. The optimum process parameter combination for PET-G to withstand high fatigue load is found to be A3B3C3D1 (0.25mm Layer Thickness 75% Infill Density 3mm Shell Thickness 0 Degree Raster Angle). For PLA A2B3C3D1 – 0.20mm Layer Thickness 75% Infill Density 3mm Shell Thickness 0 Degree Raster Angle) and for HIPS material the process parameter combination is found to be A2B3C3D3 (0.20mm Layer Thickness 75% Infill Density 3mm Shell Thickness 60 Degree Raster Angle) respectively.

**Table 12 Experimental Values of Fatigue Strength and Corresponding S/N Ratio**

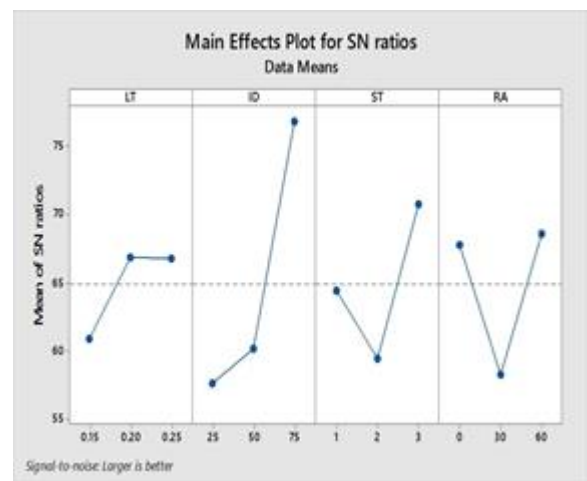
Test Run	Fatigue Strength			S/N Ratio		
	PETG	PLA	HIPS	PETG	PLA	HIPS
R1	7756	4729	635	77.79	73.5	56.06
R2	13390	9978	160	82.54	79.98	44.08
R3	32132	39130	13324	90.14	91.85	82.49
R4	5684	9680	786	75.09	79.72	57.91
R5	31250	49290	3563	89.9	93.86	71.04
R6	30590	28217	3868	89.71	89.01	71.75
R7	14910	6538	868	83.47	76.31	58.77
R8	8330	6330	1846	78.41	76.03	65.32
R9	59268	41716	6558	95.46	92.41	76.34



**Figure 11 Main Effects Plot for Fatigue Strength – PET-G**



**Figure 12 Main Effects Plot for Fatigue Strength – PLA**



**Figure 13 Main Effects Plot for Fatigue Strength – HIPS**



**Table 13 Response Values for Fatigue Strength – PET-G**

Level	A	B	C	D
1	83.5	78.79	81.97	87.72
2	84.9	83.62	84.36	85.24
3	85.8	91.77	87.84	81.21
Delta	2.29	12.98	5.86	6.5
Rank	4	1	3	2

**Table 14 Response Values for Fatigue Strength – PLA**

Level	A	B	C	D
1	81.78	76.51	79.51	86.59
2	87.53	83.29	84.03	81.77
3	81.58	91.09	87.34	82.53
Delta	5.95	14.58	7.83	4.82
Rank	3	1	2	4

**Table 15 Response Values for Fatigue Strength – HIPS**

Level	A	B	C	D
1	60.88	57.58	64.38	67.81
2	66.9	60.15	59.44	58.2
3	66.81	76.86	70.77	68.58
Delta	6.02	19.28	11.32	10.37
Rank	4	1	2	3

The Figures 11, 12 and 13 shows the main effect plots for fatigue strength for the materials PET-G, PLA and HIPS by considering larger the better characteristic Tables 13, 14 and 15 show their response values and their rankings. The response values are obtained for the experimental data by considering larger the better characteristic and it can be understood that infill density is the most significant parameter which influences the fatigue strength of the material. The experimental data is further statistically analyzed through ANOVA to obtain the contribution of various input parameters over the output response for all the three materials. It can be observed that Infill density has 60.18%, 50.86% and 53.90% of significant contribution over the fatigue strength of the materials PET-G, PLA and HIPS comparing to other input parameters. Raster angle is the parameter which has very less considerable contribution towards the output response for PLA and for the other two materials PET-G and HIPS layer thickness is found to be less significant.

**Table 16 ANOVA results for Fatigue Strength – PETG**

Source	D F	Adj SS	Adj MS	F-Value	P-Value	Contribution Percentage
Regression	4	2223290390	555822597	10.85	0.02	
A	1	142398817	142398817	2.78	0.171	5.86%
B	1	1461408267	1461408267	28.53	0.006	60.18%
C	1	166595243	166595243	3.25	0.146	6.86%
D	1	452888064	452888064	8.84	0.041	18.65%
Error	4	204861050	51215263			8.40%
Total	8	2428151440				100%

**Table 17 ANOVA results for Fatigue Strength – PLA**

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution Percentage
Regression	4	2085571102	521392776	4.55	0.086	
A	1	93002	93002	0	0.979	0.03%
B	1	1294071576	1294071576	11.29	0.028	50.86%
C	1	516747521	516747521	4.51	0.101	20.30%
D	1	274659004	274659004	2.4	0.197	10.79%
Error	4	458566571	114641643			18.02%
Total	8	2544137674				

**Table 18 ANOVA results for Fatigue Strength – HIPS**

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution Percentage
Regression	4	106867461	26716865	3.01	0.156	
A	1	3915568	3915568	0.44	0.543	2.75%
B	1	76762420	76762420	8.64	0.042	53.90%
C	1	21682806	21682806	2.44	0.193	15.22%
D	1	4506667	4506667	0.51	0.516	3.16%
Error	4	35525737	8881434			24.95%
Total	8	142393198				

**6.3 Range Analysis**

The range analysis of orthogonal experiments are conducted to identify the optimum combination of parameters and the order of priority of the input factors for both the output responses have been done for all the materials considered and the results obtained can be compared with the optimum parameter combination and ranking of input factors achieved through Taguchi’s S/N ratio method.. The procedure of range analysis is summarized below in a simplified manner for better understanding.

**Table 19 Range Analysis of Fatigue Strength – PET-G**

Levels	A	B	C	D
1	53278	28350	46676	98274
2	67524	52970	78342	58890
3	82508	121990	78292	40462
Mean	A	B	C	D
1	17759.3	9450	15558.67	32758
2	22508	17656.67	26114	19630
3	27502.7	40663.33	26097.33	13487.3
R	9743	31213	10555	19271
Optimum level	A3	B3	C2	D1
Optimum Assembly	A3B3C2D1			
Order of Priority	BDCA			

The mean values of factor levels for all the four different factors are calculated and to find the optimum level in a particular factor the lowest mean value is considered for the output response Specimen weight as it has to be low or minimum and for Fatigue strength the factor level with highest mean value is considered to be optimum as the fatigue strength of the materials should be higher in general. The range values in

descending order are considered to be the order of maximum significance or priority of the input parameters over the output responses.

**Table 20 Range Analysis of Fatigue Strength – PLA**

Levels	A	B	C	D
1	53837	20947	39276	95735
2	87187	65598	61374	44733
3	54584	109063	94958	55140
Mean	A	B	C	D
1	17945.7	6982.333	13092	31911.7
2	29062.3	21866	20458	14911
3	18194.7	36354.33	31652.67	18380
R	11116.7	29372	18560.67	17000.7
Optimum level	A2	B3	C3	D1
Optimum Assembly	A2B3C3D1			
Order of Priority	BCDA			

Irrespective of the material considered for study, Infill density is found to be the most significant factor which affects the fatigue strength of the material and Layer thickness have shown very less significance over the output response. For both PLA and HIPS, Next to Infill Density Shell thickness have shown more significant effect over fatigue strength of the material and in case of PET-G raster angle ranks second position to infill density as significant parameter. The table 19,20 and 21 shows the range analysis values of Fatigue strength for PET-G , PLA and HIPS respectively.

**Table 21 Range Analysis of Fatigue Strength – HIPS**

Levels	A	B	C	D
1	14119	2289	6349	10756
2	8217	5569	7504	4896
3	9272	23750	17755	15956
Mean	A	B	C	D
1	4706	763	2116	3585
2	2739	1856	2501	1632
3	3091	7917	5918	5319
R	1967	7154	3802	3687
Optimum level	A1	B3	C3	D3
Optimum Assembly	A1B3C3D3			
Order of Priority	BCDA			

The optimum combination of parameters for both PET-G and PLA to have low specimen weight is found to be A1B1C1D1 which is corresponding to 0.1mm Layer Thickness , 25% Infill Density , 1mm Shell Thickness with 0° Raster Angle as per range analysis. But in case of HIPS material the optimum parameter combination is found to be A1B1C2D2 which is corresponding to 0.1mm Layer Thickness , 25% Infill Density , 2mm Shell Thickness with 30° Raster Angle. The optimum parameter combination obtained from both Taguchi's Signal to Noise Ratio method and Range Analysis are in good agreement. Irrespective of the materials considered the order of priority remains the same as per Range Analysis. The sequence of influencing parameter for all the three materials considered in the present work is found to be BCAD which

corresponds to Infill Density, Shell Thickness, Layer Thickness and Raster Angle. Table 22, 23, 24 shows the results of range analysis of materials PET-G, PLA and HIPS towards specimen weight.

**Table 22 Range Analysis of Specimen Weight – PET-G**

Levels	A	B	C	D
1	44.5	34	42.5	45
2	44.5	44.5	45	45.5
3	47	57.5	48.5	45.5
Mean	A	B	C	D
1	14.83	11.33	14.17	15.00
2	14.83	14.83	15.00	15.17
3	15.67	19.17	16.17	15.17
R	0.83	7.83	2.00	0.17
Optimum level	A1	B1	C1	D1
Optimum Assembly	A1B1C1D1			
Order of Priority	BCAD			

**Table 23 Range Analysis of Specimen Weight – PLA**

Levels	A	B	C	D
1	39.5	31	32	41
2	44	41.5	42.5	43.5
3	43	54	45	42
Mean	A	B	C	D
1	13.17	10.33	10.67	13.67
2	14.67	13.83	14.17	14.50
3	14.33	18.00	15.00	14.00
R	1.50	7.67	4.33	0.83
Optimum level	A1	B1	C1	D1
Optimum Assembly	A1B1C1D1			
Order of Priority	BCAD			

**Table 24 Range Analysis Values of Specimen Weight – HIPS**

Levels	A	B	C	D
1	28.5	25.5	32.5	34
2	34.5	29.5	29.5	30
3	36.5	44.5	37.5	35.5
Mean	A	B	C	D
1	9.5	8.5	10.83	11.33
2	11.5	9.83	9.83	10
3	12.17	14.8	12.50	11.83
R	2.67	6.3	2.67	1.8
Optimum level	A1	B1	C2	D2
Optimum Assembly	A1B1C2D2			
Order of Priority	BCAD			

## 7. Confirmation Experiment

The confirmation experiment conducted for both the output responses specimen weight and fatigue strength for all the three materials under study has good agreement with the optimum combination obtained from taguchi's signal to noise ratio method and range analysis.

## 8. Conclusion

The conclusion for the above work may be drawn further and it can be divided in to two sections. The first section explains the concluding remarks obtained for the output response Specimen weight and the second section describes about the research findings on Fatigue strength of the materials through taguchi's signal to noise ratio method and range analysis.

### (a) Specimen Weight

- Specimen weight with smaller the better characteristic has been considered for the calculation of S/N ratio method.
- The Response table values and ANOVA analysis have shown that the input factor Infill Density is the most significant parameter which contributes more towards the output response specimen weight than the other variable taken for study for all the three materials and Raster Angle is found to have very less contribution towards specimen weight. The increase in infill density adds more material to the specimen and thereby increases the specimen weight.
- Infill density has **92.14%, 88.86% and 63.52%** of significant contribution over Specimen Weight for the materials **PET-G, PLA and HIPS** respectively.
- HIPS is found to have very less specimen weight compared to other materials and PET-G is found to have high specimen weight for the printing conditions as the density of HIPS is lesser than PLA and PET-G.
- The optimum parameter combination obtained from both taguchi's signal to noise ratio method and range analysis are in good agreement for all the three materials.
- The order of priority for all the three materials as per range analysis is found to be Infill Density, Shell Thickness, Layer Thickness and Raster Angle.
- To evaluate the effect of FDM parameters over specimen weight other input factors may be considered for expanding the experimental plan and techniques such as TOPSIS, Grey relational analysis may be considered.

### (b) Fatigue Strength

- Experimental values of Fatigue strength under rotating bending fatigue test with larger the better characteristic are considered for Signal to Noise ratio calculation.
- Infill density has **60.18%, 50.86% and 53.90%** of significant contribution over Fatigue Strength of the materials **PET-G, PLA and HIPS** respectively.
- PET-G is found to have more fatigue strength than PLA and HIPS. HIPS has the poor fatigue strength for the experimental conditions considered.
- Similar to specimen weight from both ANOVA and range analysis infill density is the most significant factor than other parameters considered and layer thickness has the least contribution towards fatigue strength of all the three materials.
- The order of priority for the three materials PLA and HIPS as per range analysis is found to be Infill Density, Shell Thickness, Raster Angle and Layer Thickness and for PET-G the order of priority varies and is given by Infill Density, Raster Angle, Shell Thickness and Layer Thickness.

- The fatigue strength of the materials considered may be further studied by varying the speed of rotation, other input FDM parameters and optimization techniques for better understanding of the material properties.

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