EFFECT OF FDM PROCESS PARAMETERS ON PRINTING TIME, PART WEIGHT AND DAMPING FACTOR FOR ABS MATERIAL

Abstract

The current study focus upon the effect of fused deposition modeling parameters over printing time, part weight and damping factor. The study considers three FDM input factor such as infill density, layer height and print speed varied in two levels. Taguchi's orthogonal array has been adopted for creating the experimental layout and output responses have been analyzed using appropriate signal to noise ratio method. The response table rankings and main effect plot indicates the significant parameter and optimal combination of input factors for controlling the output responses. Infill density is the most significant factor for both printing time and part weight of the sample prepared. Layer thickness is most influencing over damping factor of the sample. Printing speed is found to be the least significant factor over printing time and damping factor of the material. The change in layer thickness from 0.15mm to 0.20mm at 50% infill density has decreased printing time by 11.59%, but part weight and damping factor enhanced by 14.96% and 160% respectively. Similarly, at 100% infill density with 0.15mm layer thickness, printing time increased by 98.5% , part weight and damping factor increased by 84% and 59.63% respectively.

Keywords: Taguchi Orthogonal Array, ABS , Signal to Noise ratio , Damping factor

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AM- Additive Manufacturing
FDM – Fused Deposition Modeling
ABS – Acronitrile Butadiene Styrene
PLA – Polylactic Acid
TOPSIS – Technique Order Preference in Similarity to Ideal Solution
DoE – Design of Experiments

I. INTRODUCTION

Additive Manufacturing techniques possess numerous advantages over traditional manufacturing methods which involve difficulties such as high material waste, multi process dependent and labour intensive. AM processes that are commercially available can be classified as Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), Solid Ground Curing (SGC) and Three Dimensional Printing (3DP) etc [1].Fused deposition modeling (FDM) is a popular additive manufacturing process which utilizes diverse materials such as thermoplastics and its composites , ceramics and metals for developing prototypes , conceptual models and industrial grade parts. The process involves heating the material below the melting point and extruding the same through a heated nozzle to deposit layers one over the another [2].ABS and PLA are the traditional materials that has been used in FDM process for developing parts and the parts produced are found to have anisotropic mechanical properties , dimensional inaccuracies and poor surface finish. Research in the past decade have addressed about the optimization of input factors to enhance the performance of final parts produced through FDM. Chohan et.al [3] employed taguchi orthogonal array and genetic algorithm for optimizing the FDM process parameters over surface finish and dimensional accuracy for ABS material. The speed of printing is found to have higher influence over surface finish with 83.41% contribution. The optimal factor settings for reducing the surface roughness in ABS material have been studied by Amanuel et.al [4] through taguchi orthogonal array , ANOVA and response surface methodology The optimum factor combination for reduced surface roughness is found to be 01mm layer thickness , 0º orientation angle and 0º raster angle. Raman et.al [5] implemented both taguchi and TOPSIS techniques for studying the combined effect of orientation angle , finishing temperature and finishing time over the surface roughness of the printed part. The study involves the application of chemical finishing of FDM parts to understand the influence of acetone vapour based treatment over surface roughness. The authors have concluded that surface finish has linear relationship with prolonged exposure to acetone vapour. Signal to Noise plot and ANOVA has been considered for optimizing the parameters. Karin et.al [6] conducted optimization of three FDM parameters such as printing speed , nozzle temperature and bed temperature over surface roughness (R_a) through response surface methodology using ABS material. Statistical analysis carried out indicates that both bed temperature and printing speed have significant over surface roughness. Kovan et.al [7] explored the mechanical behavior of PLA material reinforced with 15% carbon fibre to understand the impact of layer thickness and printing orientation angle over tensile strength , modulus of elasticity. The authors have compared the values obtained for PLA/C composites with pure PLA filament. The properties of PLA/C composites are found to be lower than pure PLA parts. The presence of short carbon fibers as reinforcement separated easily from the matrix layers. The tensile performance of carbon fibre reinforced nylon 6 composite material has been investigated by [8].The parameters such as printing orientation and build plate temperature are found to have significant impact over the properties studied. Ranjeet kumar et.al [9] applied fuzzy logic method for improving the dimensional accuracy of ABSP400 parts printed through FDM technique. The authors have varied parameters such as layer thickness , part orientation , raster width , raster angle and air gap with three different levels. The contribution of part orientation is higher than other parameters considered over dimensional accuracy. Vinod and Shinde [10] carried out multi response optimization of FDM process parameters using Multi-Objective Optimization using Ratio Analysis (MOORA) method towards surface roughness and part building time. The rankings obtained from MOORA method have been compared with TOPSIS technique and they are in good agreement. Garret et.al [11] evaluated the impact of input factors over dimensional accuracy of PLA parts printed using Makerbot 3D desktop printer. Both layer thickness and infill density are found to have significant impact over the tensile properties of the material considered. Flaviana et.al [12] investigated the effect of FDM process parameters over the mechanical properties of carbon fibre reinforced nylon filament such as hardness , tensile properties and resilience. The authors have stated that both hardness and tensile strength are highly affected by building direction and infill percentage. Wang et.al [13] integrated taguchi and grey relational analysis methods for optimizing the FDM process parameters over the mechanical properties using ABS P400.The ranking of alternatives through grey relational analysis and TOPSIS methods are found to be similar. The impact resistance of FDM prepared nylon 12 parts have been analyzed through response surface methodology by salam et.al [14] .The authors have communicated that Z directed specimens have inverse relationship with impact strength while the specimens printed at 0 and 45 degrees are found to have linear relationship with impact strength. The impact of FDM process parameters over the dimensional variation in ABS material has been focused by Krishna et.al[15] .Both layer thickness and print speed are found to be influencing. Low layer thickness and higher printing speed has been suggested by the authors for reduced dimensional variation.

The current study involves three input factors namely infill density , layer thickness and printing speed to evaluate their effect over printing time , part weight and damping factor for ABS material. The damping factor of the printed part has been obtained from frequency response function resulted from impact hammer testing. The tabulated output responses have been analyzed using signal to noise ratio method to identify the optimal combination of input factors for minimizing or maximizing the output response. The response table indicates the ranking of individual factor for a particular output response. Figure 1 shows the schematic representation of research workflow adopted in the current study. Figure 2 portrays the technical illustration of fused deposition modeling process.

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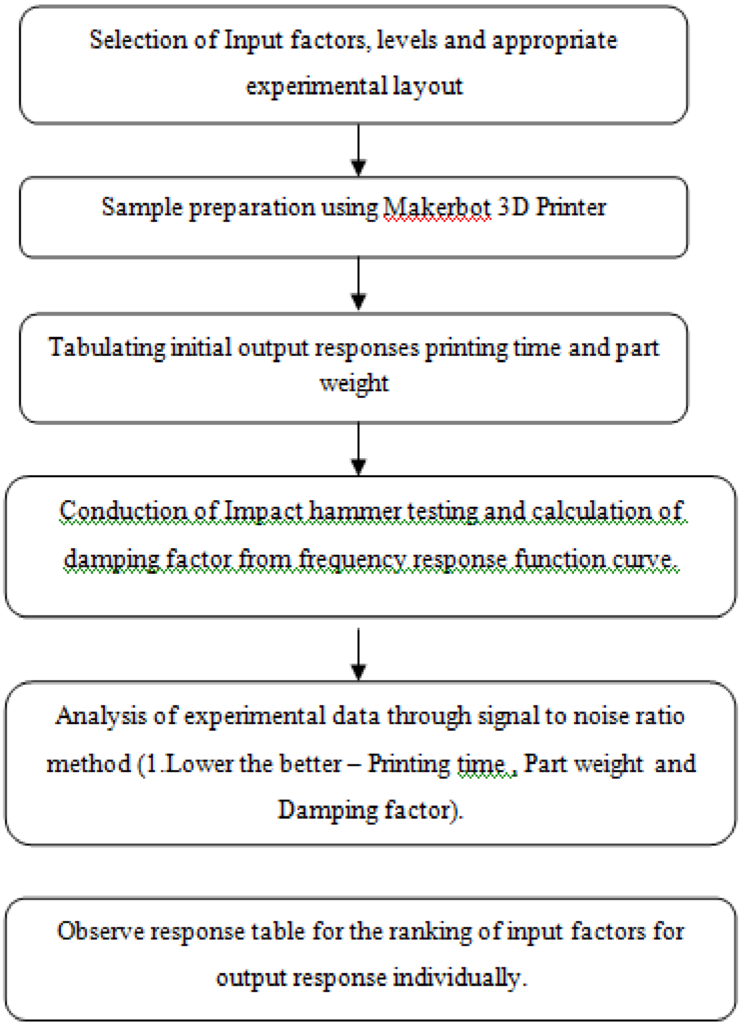

Figure 1: Schematic Representation of Research Workflow

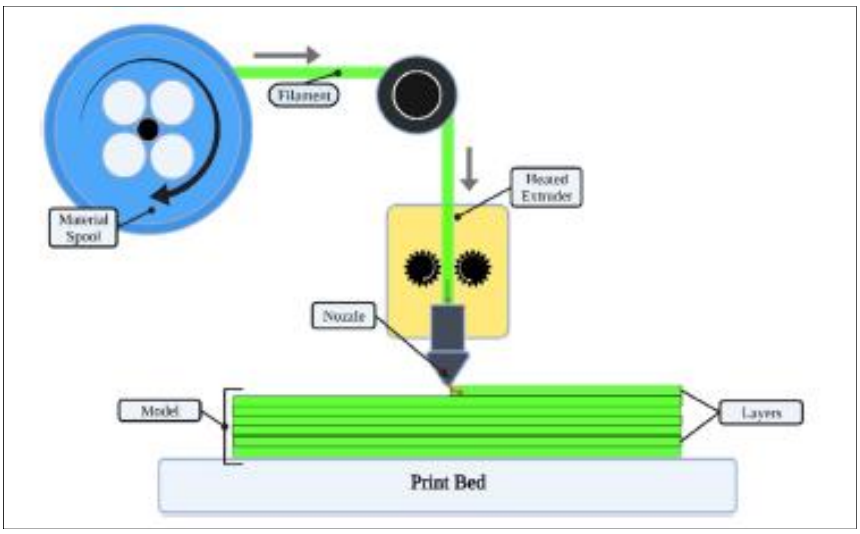

Figure 2: Illustration of Fused Deposition Modeling Process

II. MATERIAL AND METHODS

The most popular material for 3D printing is undoubtedly ABS (acrylonitrile butadiene styrene). It is particularly useful in sturdy plastic components that need to maintain their resilience in the face of temperature changes. Acrylonitrile, butadiene, and styrene are the three monomers that make up the thermoplastic polymer known as ABS. It is made by polymerizing acrylonitrile and styrene in the presence of butadiene. Acrylonitrile gives it rigidity, chemical resistance, and strength. Styrene provides a smooth and shiny texture; butadiene is the rubbery component that makes ABS tough.ABS is used in many industries today because of its flexibility, moldability, and strength. It finds application in making of Lego toys, home appliances, and piping systems. Compared to most inexpensive polymers, ABS is quite flexible, resists high temperatures, and can easily be machined. Table 1 shows the physical and mechanical properties of ABS filament material used in the current study.

Table 1: Physical and Mechanical Properties of ABS Filament

S.No	Property	S.I Unit	Value
1	Density	(g/mL)	1.04
2	Tensile Strength	MPa	2.96-43
3	Young's Modulus	GPa	1.79-3.2
4	Impact Strength	j/m	200-215
5	Elongation at break	%	10-50
6	Flexural Modulus	MPa	2400
7	Hardness Shore D	-	100

1. **Design of Experiments:** Experimental design is an important phase in research as it involves the selection of input factors, levels and appropriate experimental matrix for conduction of trials. The concept of experimental design is to identify the root cause behind the factors influencing the performance of a process or product. Doe reduces the time, resources and money involved in conduction of experimental trials. The current study considers three FDM parameters namely infill density , layer thickness and print speed varied in two levels (2^4).The experimental layout consists 4 experimental trials which comes under the category of fractional factorial design.

   The definitions of the input factors varied in the current study are provided below.

   - **Infill Density**: It denotes the amount of material filled inside a part. A higher infill density represents the presence of more material inside the part. An increase in infill density increases material consumption and also it enhances strength.

   - **Layer Thickness:** It is defined as the height or thickness of the individual layer deposited one over another while printing a model. A low value of layer thickness increases printing time and results in better surface finish in comparison with high layer thickness.

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- **Printing Speed:** The speed at which the nozzle deposits every individual. High printing speed reduces the printing time ,but the bonding between the deposited layer will be weak.

Table 2: Shows the FDM input factors and their values considered for experimental trials.

Table 2: FDM Input Factors and Levels

S.No	Input Factors	Symbol	S.I Unit	Level 1	Level 2
1	Infill Density	A	%	50	100
2	Layer Thickness	B	mm	0.15	0.20
3	Printing Speed	C	mm/s	45	55

Table 3 shows the combination of input factors for experimental trial as per Taguchi L4 Orthogonal array.

Table 3: Experimental Layout – Taguchi L4 Orthogonal Array

A	B	C
1	1	1
1	2	2
2	1	2
2	2	1

2. **Sample Preparation:** The sample for the current study is in the form of rectangular shaped prism with dimensions 150 x 20 x 6 mm (Length x width x thickness) respectively. Figure 3 shows the 3D model of rectangular prism shaped specimen. The input material ABS is in the form of filament with 1.75mm diameter and it has been extruded through a heated nozzle to deposit layers one over another. The current study adopts Makerbot 3D printer which works under the principle of fused deposition modeling. The 3D model of the sample has been created using CATIA software and saved in .stl format. The prepared .stl format file is inputted in to CURA slicing software for preparing the files for printing. The sliced part files consists G-code and M-code which provides instructions for the operation of FDM machine to print parts.

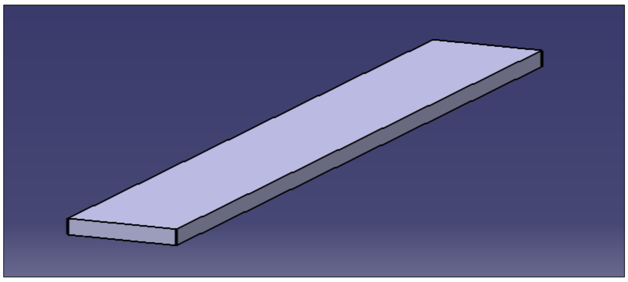

Figure 3: Rectangular Prism Shaped Specimen

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III. EXPERIMENTAL WORK

In the current study, three different outcomes have been assessed for understanding the influence of FDM process parameters. Printing time; part weight and damping factor of the sample have been taken as output parameters. The output response printing time for the sample can be easily calculated as the sliced file conveys the amount of time required for part printing and the same can be verified. The weight of every individual specimen has been measured using digital weighing machine which can measure low weighing parts with good accuracy.

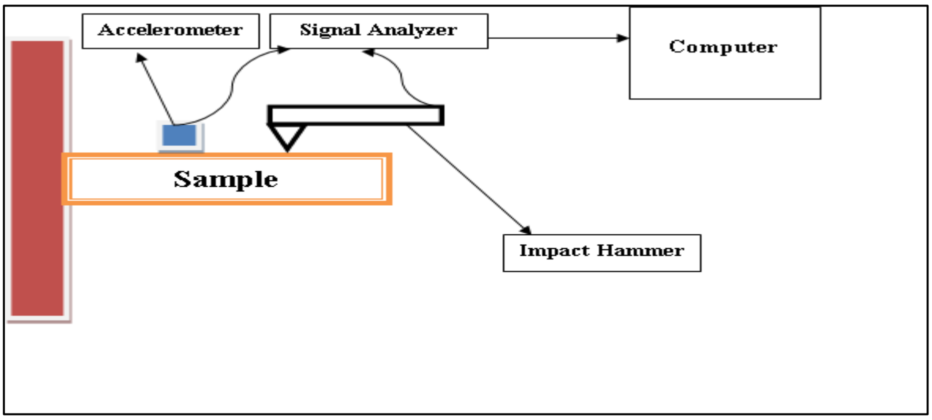

Figure 4: Schematic Arrangement of Impact Hammer Testing

The evaluation of damping factor of the sample has been done through modal analysis of the prepared sample. Modal analysis is the process of determining the inherent dynamic characteristics of a system in forms of natural frequencies, damping factors and mode shapes, and using them to formulate a mathematical model for its dynamic behavior. The current involves impact hammer testing for generating the frequency response curve which acts as the base for calculating the damping factor. The sample is held in the form of cantilever beam and accelerometers are placed at a random point on the sample for collection of signals. The impact hammer is made to hit over the sample at different spots to observe the response of the sample. The signal analyzer connected with the sample analyses the signal and transforms the information for further processing to the computer. The frequency response curve for corresponding sample can be viewed in the form of a graph with representation of frequency peak and amplitude of vibration. Table 4 shows the values of frequency and amplitude for different samples through modal analysis.

Table 4: Frequency and Amplitude values from Modal Analysis

Trial No	Frequency (Hz)	Amplitude (g/N)
1	283.91	27.92
2	292.78	46.12
3	250.00	37.45
4	410.17	35.67

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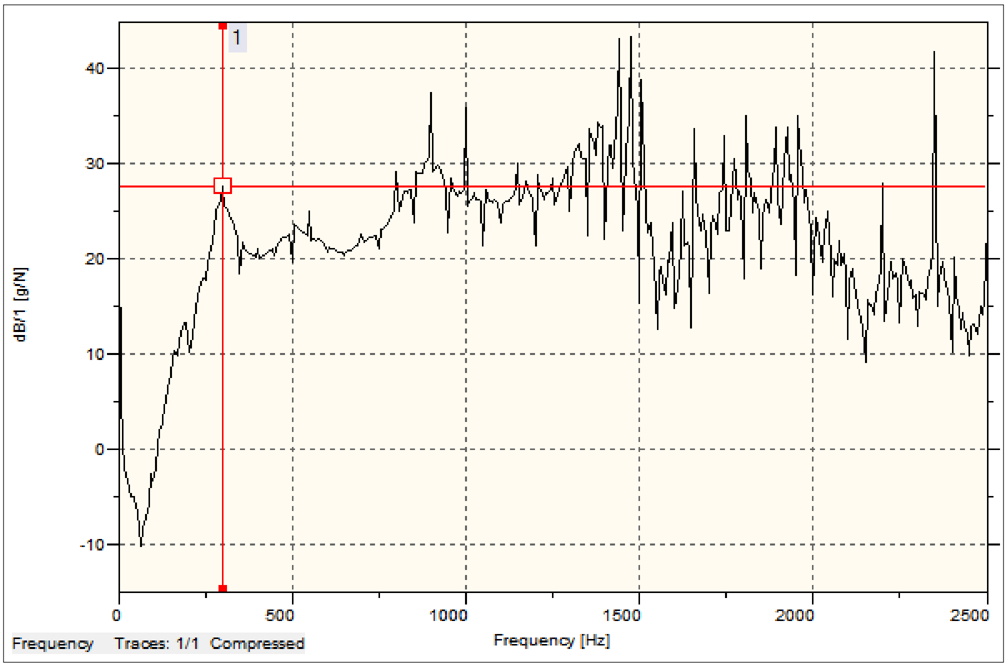

Figure 5: Frequency Response Function for ABS Sample 1

The frequency response function curve can be analyzed for evaluating the damping quantities of the system. The "quality factor" (also known as "damping factor") or "Q" is found by equation1.A classical method of determining the damping at a resonance in a Frequency Response Function (FRF) is to use the "3 dB method" (also called "half power method").Equation 2 shows the various quantities that can be obtained from damping factor.

$$Q = \frac{f_o}{f_2 - f_1} \quad (1)$$

- f0 = frequency of resonant peak in Hertz
- f2 = frequency value, in Hertz, 3 dB down from peak value, higher than f0
- f1 = frequency value, in Hertz, 3 dB down from peak value, lower than f0

$$\eta = \frac{1}{Q} = 2\zeta = \frac{\%Cr}{50} = tan\phi = \frac{\Delta w_{3dB}}{\omega_o} \quad (2)$$

$\eta = loss\ factor$
$Q = Damping\ factor\ or\ Quality\ factor$
$\zeta = Damping\ ratio$
$\%Cr = Percent\ of\ critical\ damping$
$\emptyset = Phase\ angle\ between\ cyclic\ stress\ and\ strain$

In a FRF, the damping is proportional to the width of the resonant peak about the peak's center frequency.By looking at three dB down from the peak level, one can determine the associated damping as shown in Figure 6.

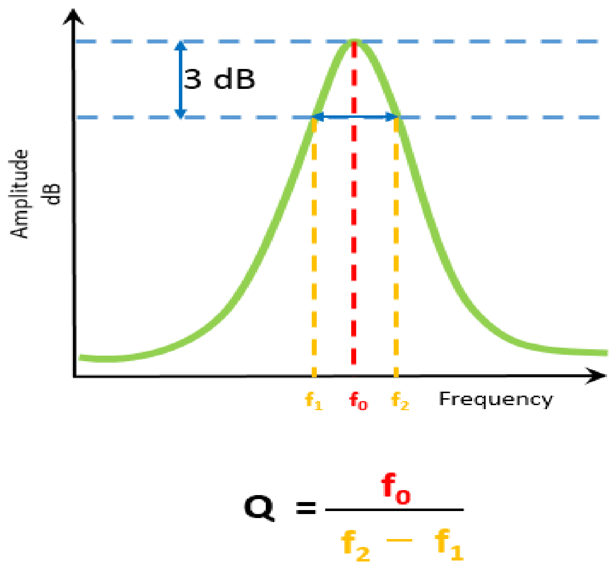

Figure 6: 3 dB Diagram for Calculating Damping Factor Q

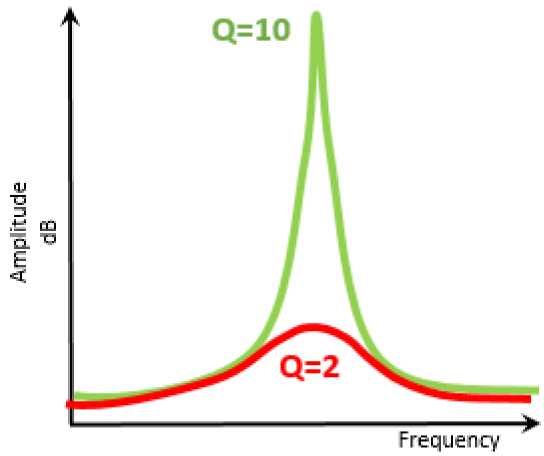

Figure 7: Comparison of Damping Factors with respect to peak width

As the peaks in a FRF get wider relative to the peak, the damping increases (i.e., "more" damping). This means that any vibration set in motion in the structure would decay *faster* due to the increased damping. Depending on the form being used to express damping, the value may be higher or lower. For example, the "quality factor" or "damping factor" will decrease with more damping, while "loss factor" and "percent critical damping" would increase with more damping. Figure 7 shows the comparison of different damping factor values.

IV. RESULTS AND DISCUSSION

The output response values obtained for individual experimental trail has been tabulated for further analysis. The factor infill density varied with 50% and 100% indicates amount of material deposited inside the part. Layer thickness at 0.15mm represents thin layers and 0.20mm results with thick layers. Printing speed at 45 mm/s is considered as low and 55 mm/s has been taken as higher printing speed in the current study. Table 5 shows the values of output responses at different experimental trials.

Table 5: Values of Output Responses for Experimental Trails

Trial No	A (%)	B (mm)	C (mm/s)	PT (mins)	PW (gms)	DF
1	1	1	1	69	10.93	22.37
2	1	2	2	61	12.53	58.54
3	2	1	2	137	20.168	35.71
4	2	2	1	118	19.85	102.54

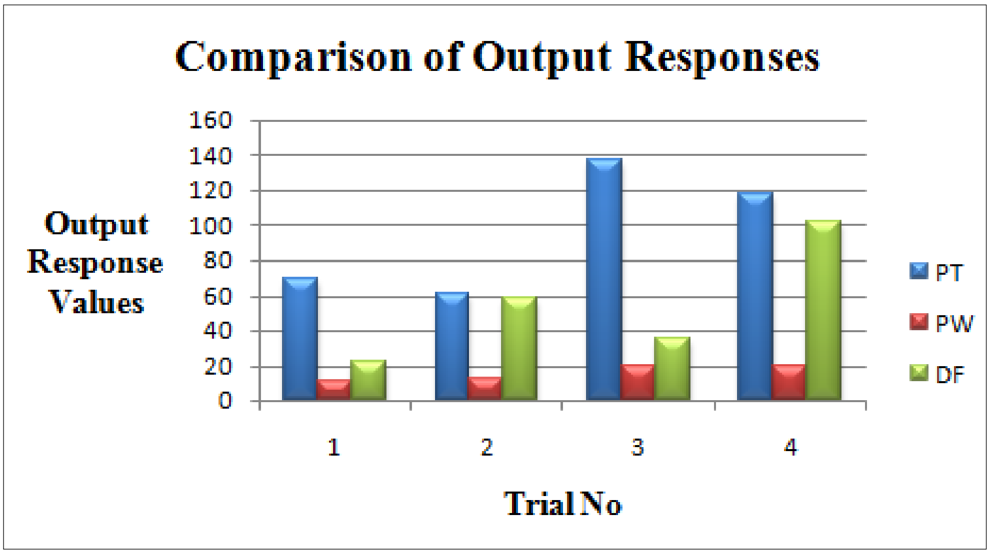

Figure 6: Comparisons of Output Responses

Figure 6 depicts the value of output responses in together in chart form for better understanding.

1. **Effect of Input Factors on Output Responses:** The experimental values obtained have been analyzed to understand the effect of FDM parameters. In case of printing time, the experimental trial 1 has resulted with 69 mins when 50% infill density with 0.15mm layer thickness is considered and printing speed of 45 mm/s. For the same 50% infill density , when there is an increase in layer thickness from 0.15mm to 0.20mm is followed the printing time has dropped to 61 mins. This shows a decrease of 11.59% of printing time when there is an increase of layer thickness by 0.05mm.The additional reason is due to the increase in printing speed by 10 mm/s with respect to experimental trial 1.For the same layer thickness of 0.15 mm with 100% infill density, the printing time increases by 98.5% as double the amount of material need to be filled in the part.

The part weight resulted from experimental trials has been analyzed and the lowest part weight is obtained when 50% infill density, 0.1mm layer thickness with printing speed of 45 mm/s has been considered. For the same input factor condition, when the layer thickness is changed from 0.15 mm to 0.20 mm the part weight increased by 14.96% , this is due to the fact that layer become thicker. The increase in infill density from 50% to 100% for 0.15mm layer thickness has increased the part weight around 84% in comparison with 50% filled parts.

In case of damping factor, the lowest value indicates more damping and high value represents less damping. But in case of damping, it has to be considered depending upon the requirement of a specific application. Considering high or low damping may be benfit or non benefit a particular situation. In the present study carried out, experimental trial l indicates lowest damping factor and it is a sign of high damping from the conducted experimental trials. Similar part weight, damping factor also followed the same trend.For the same infill density of 50% when there is an increase in layer thickness by 0.05mm , damping factor increased by 160%.But in case of same layer thickness of 0.15mm for 100% infill density the damping factor raised by 59.63% only. This shows that increase in layer thickness have shown major impact over damping factor than infill density.

2. **Signal to Noise Ratio:** The printing time for the sample is generally considered as smaller the better as higher printing time reduces the productivity and also increases the printing time. The measured printing time for the samples has been analyzed to identify the optimum factor settings for reducing printing time. The factors combination A1B2C1 (50% infill density , 0.20mm layer thickness and 45mm/s printing speed) is found to be the optimum combination for reduced printing time of the sample. This combination indicates the selection of low infill density with thick layer deposition at low printing speed. Figure 7 shows the main effect plot for printing time.

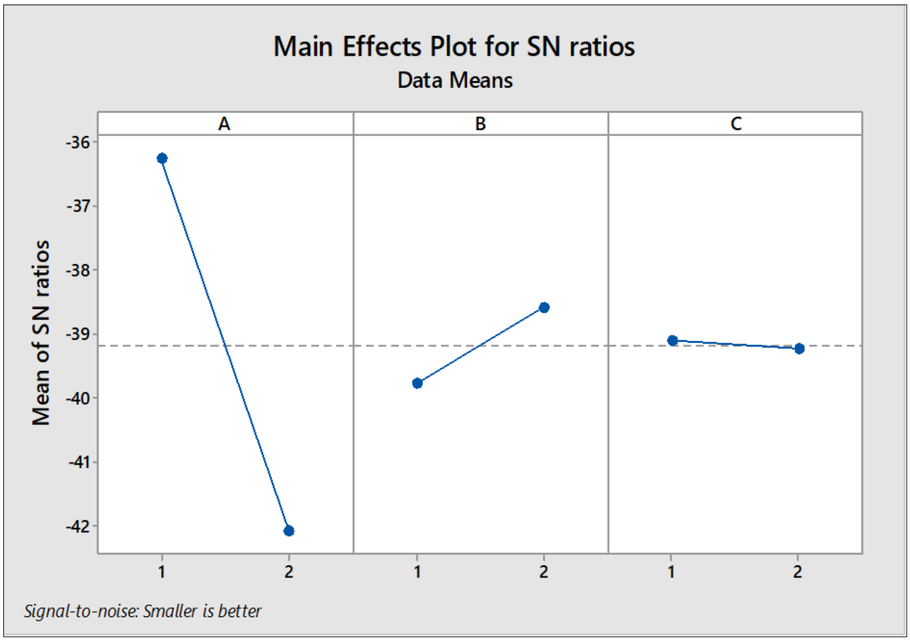

Figure 7: Main effect plot for printing time

Table 6: Response Table for Printing Time

Level	A	B	C
1	-36.24	-39.76	-39.11
2	-42.09	-38.57	-39.22
Delta	5.84	1.18	0.11
Rank	1	2	3

Table 6 shows the response table values for printing time. Infill density is found to be ranking top subsequently followed by layer thickness and printing speed. This indicates that when low amount of material is filled in apart with thick layers the time for part printing will be less.

Figure 8 shows the main effect plot for part weight. The combination A1B1C1 (50% infill density , 0.15mm layer thickness and 45mm/s printing speed) is found to better for reducing the sample weight when developing light weighted components. The response table rankings indicate infill density as the highly significant factor followed by printing speed and layer thickness. Table shows the response table rankings for part weight.

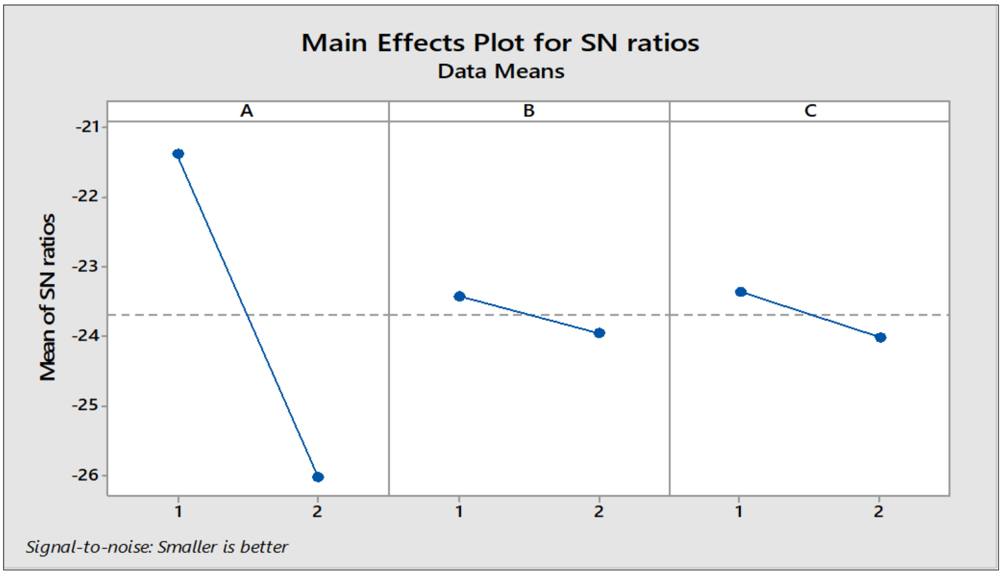

Figure 8: Main effect plot for Part Weight

Table 8: Response Table for Part Weight

Level	A	B	C
1	-21.37	-23.43	-23.36
2	-26.02	-23.96	-24.03
Delta	4.66	0.52	0.66
Rank	1	3	2

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The damping factor of the sample is found to be lower when the combination A1B1C2 ((50% infill density , 0.15mm layer thickness and 55mm/s printing speed) is considered. As per response table rankings, layer thickness ranks top, followed by infill density and print speed. Figure 9 shows the main effect plot for damping factor. Table 9 shows the response table rankings of the input factors.

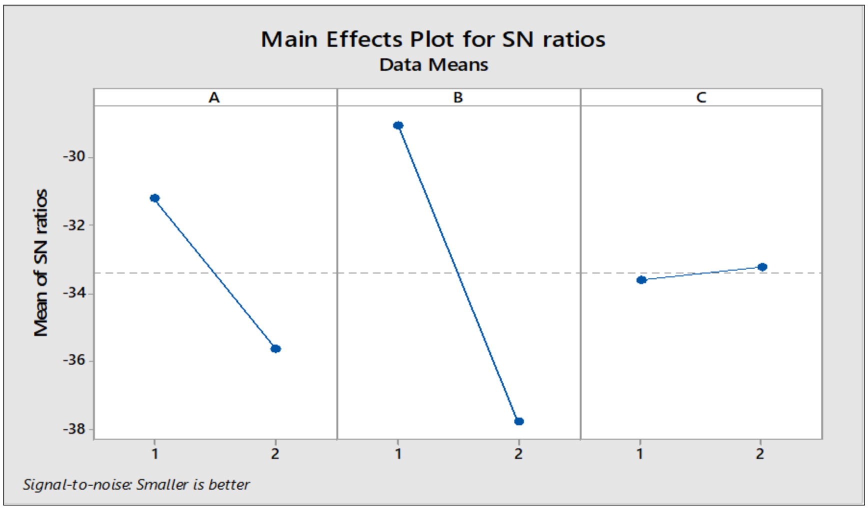

Figure 9: Main Effect Plot for Damping Factor

Table 8: Response Table for Damping Factor

Level	A	B	C
1	31.17	29.02	33.61
2	35.64	37.78	33.2
Delta	4.47	8.76	0.40
Rank	2	1	3

V. CONCLUSION

The current section highlights the major findings of the research carried out

- The sample for the experimental work has been prepared through fused deposition modeling and responses such as printing time , part weigh and damping factor have been evaluated to understand the effect of three input factors namely infill density , layer thickness and print speed.
- The experimental values indicate that when there is change in input factor, the output responses are affected in a considerable manner.
- For the same infill density of 50% with an increase in layer thickness by 0.05mm from the initial value has decreased the printing time by 11.59%.Buth for the same layer thickness of 0.15mm , when the infill density increased by 100% when comparing to initial value of 50% , printing time increased by 98.5%.
- In case of part weight , For the same input factor condition, when the layer thickness is changed from 0.15 mm to 0.20 mm the part weight increased by 14.96% , this is

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due to the fact that layer become thicker. The increase in infill density from 50% to 100% for 0.15mm layer thickness has increased the part weight around 84% in comparison with 50% filled parts.

- For the same infill density of 50% when there is an increase in layer thickness by 0.05mm , damping factor increased by 160%.But in case of same layer thickness of 0.15mm for 100% infill density the damping factor raised by 59.63% only.
- The output responses has been analyzed using signal to noise ratio method and optimal factor combinations has been identified for every individual output response and main effect plot indicates the combination. Printing time - A1B2C1 (50% infill density, 0.20mm layer thickness and 45mm/s printing speed). Part weight - A1B1C1 (50% infill density , 0.15mm layer thickness and 45mm/s printing speed), Damping factor - A1B1C2 ((50% infill density , 0.15mm layer thickness and 55mm/s printing speed).
- The response table value indicates that for both printing time and part weight infill density is the dominant factor. Layer thickness is the significant factor for controlling damping factor. Print speed has not attained top ranking for any output response.

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