Optimization Of Process Parameters In 3d Printing –Fused Deposition Modeling Using Taguchi Method

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ABSTRACT:
3D printing or Rapid Prototyping (RP) or Additive Manufacturing (AM) is an innovative manufacturing method that is mostly used for prototypes in various Industries such as Aerospace, Defense, Medical, Automotive, etc. One of the worthy and widely used 3D printing techniques is Fused Deposition Modeling (FDM), which involves adding melted material layer by layer. FDM has several benefits over other manufacturing methods. While setting the 3D printing options, we have to take several parameters into account, such as speed, layer thickness and infill density, etc. The present experimental work illustrates the performance of ABS built parts fabricated by AION 500 make FDM machine. The quality of parts produced by FDM process mainly depends on the selection of process parameters. The present research work consists of process parameters such as layer thickness, infill density and speed of deposition, etc. This study aims to find effects of process parameters on different performance parameters i.e., mechanical considerations (impact strength), build time, surface roughness in a systematic manner with less number of experimental runs. Taguchi design of experiment (DOE) approach has been used to save cost and time of experimentation. Statistical significance of process parameters is analyzed using analysis of variance (ANOVA). The significant parameters for optimum results and optimal parameter setting has been suggested using S/N ratio.

Keywords: - 3D Printing, FDM, Build & Support Materials, ABS Plastic, Impact Strength, Surface roughness, MINITAB-18, ANOVA and S/N Ratio.

1.INTRODUCTION:
Prototyping is one of the important steps to finalize the product design. Manual prototyping is out dated method. In the recent times, Rapid Prototyping is used. This process was introduced in 1980's. Rapid Prototyping is a group of techniques used to fabricate a small scale model of physical part, quickly by using the three-dimensional Computer Aided Design (CAD). It is the latest, advanced technology, which saves time, especially for most complicated products. Rapid Prototyping is also known as Additive Manufacturing. These processes make three-dimensional parts directly from CAD models by adding materials layer by layer.

Fundamentally, all the manufacturing techniques are of two types: i. Additive and ii. Subtractive manufacturing. Subtractive type is a material removal technique from solid piece until the desired shape and size is obtained as per the drawing of the Component. Additive type RP is opposite to subtractive type. In this Rapid Prototyping, the material is added layer by layer up to the desired shape and size of the Component. Additive fabrication has the capability to create any shape and geometry. RP technology requires less time for classical prototyping in the sense that the creating – testing – redesigning – rebuilding and repeating the process. RP or 3D Printing process makes the model by accumulating layers in required shape on an x-y plane. The z-axis is generated by stacking one layer over the other, thereby the product will be
fabricated. RP processes can be divided into different groups according to their layer formation of materials. To make the physical model, different processes, such as StereoLithography, Fused Deposition Modeling, Selective Laser Sintering, Laminated Object Manufacturing, and 3D Printing etc., are used. The various Computer Aided Design packages use a number of different algorithms to represent solid objects. To establish consistency, the .STL file format is being used as the standard of the rapid prototyping industry. Therefore, it is required to convert the CAD file into .STL file format. FDM consists of three steps: i. Pre-Processing, ii. Production, and iii. Post Processing. In the pre-processing, a CAD model is constructed, and later, it is converted into .STL file format for FDM process. The layers are built until completion of the model. In post processing procedure supports are removed by washing or stripping away. The surface of the model is then finished and cleaned using different techniques. FDM Technology produces parts layer-by-layer by heating thermoplastic material to a semi-liquid state and extruding it according to computer-controlled paths.

FDM uses two materials: i. Build or modeling material and ii. Support material. Modeling material develops the finished piece, and Support material acts as scaffolding. Material filaments are fed from the 3D printer’s material bays to the printer head, which moves in X and Y coordinates, depositing material to complete each layer. The base moves down along the Z axis and the next layer starts. For building complex shaped parts, FDM uses support material apart from the build material which supports the overhanging structures during the process. This helps to maintain structural integrity of component until it is strengthened before the support material is removed by breaking or by dissolving using appropriate liquid solvents.

2. LITERATURE REVIEW:

CanyMendonsa, et, al.[1]: The objective of this paper is to study the influence of process parameters like Print speed (A), Layer thickness(B), Infill density(C) on the build time and optimization of these parameters to get Fused Deposition Modeling part in lower lead time using Taguchi and ANOVA approaches. The results show that the build time depend on infill density and the layer thickness. Positively decreasing the layer thickness and negatively reducing the infill density can reduce the build time for a given print. In addition, it is concluded that Layer thickness is the most significant factor for Build time in FDM components.

Xinhua Liu, et, al.[2]: In this paper, tensile strength, impact strength, and flexural strength are considered as three evaluation indexes to characterize the mechanical properties of a FDM part. The orthogonal test of five factors and three levels was designed. The Taguchi method is used to optimize and study the influence of various process parameters on the three performance indexes.

J. Santhakumar, et, al. [3]: In this paper, the improvement of Impact Strength is achieved by Optimizing the FDM Process Parameters using Polycarbonate material. This study includes four important process parameters like layer thickness, build orientation, raster angle and raster width whose influence on Impact Strength is studied. Using Taguchi Design of Experiments methodology experiments were conducted out. This work finds out the optimum process parameters required to obtain maximum impact strength on Polycarbonate Material. Analysis of Variance test (ANOVA)
was carried to find the most effecting process parameters on Impact strength. Also, it is concluded that Layer thickness is the most vital factor for Impact strength for a Polycarbonate Material.

M. Tharunkumar, et al. [4]: In this paper, the effect of FDM parameters on Impact Strength is experimentally investigated. Experiments were conducted according to DOE with three different process parameters such as direction of rotation, build orientation angle and model interior. The process parameters were optimized by using Taguchi method, S/N ratio is evaluated and the effect of the process parameters on Impact strength was estimated by the analysis of variance. In addition, it is concluded that Angle of Rotation is the most vital factor for Impact Strength of ABS Plus FDM parts.

R. Anitha, et al. [5]: In this paper, it is studied the effect of various process parameters, i.e. layer thickness, road width and speed of deposition of fused deposition modeling parts. The FDM parts which are fabricated depend upon the process parameters. Taguchi approach was used for design of experiments. L18 orthogonal array was selected for experiments. In addition, it is concluded that the layer thickness is the most crucial factor for Minimum Surface Roughness of FDM parts.

Raju Bangalore Singe Gowda, et al. [6]: In this paper, the influence of the physical build parameters over the part quality are studied. An L9 orthogonal array was designed with the minimum number of experimental runs with desired parameter settings and by analysis tools such as ANOVA (analysis of variance). M. Alhubail, et al. [7]: This paper presents the results of the experimental work on the effect of the Fused Deposition Modelling (FDM) process, variable parameters such as layer thickness, air gap, raster width, contour width and raster orientation on the quality characteristics such as surface roughness (SR) and tensile strength (TS). Taguchi design (L32) was used to obtain the experimentation runs. The results showed that higher tensile strength could be obtained by changing layer thickness and raster width at a low level and the air gap at -0.01 mm.

P. Chennakesava and Y. Shivraj Narayan [8]: In this review paper, an attempt has been made to know the insights of one such additive manufacturing process i.e., Fused Deposition Modeling (FDM).

Ashay Kohad, et al. [10]: This study includes identification of various process parameters involved in FDM, which affects quality of Parts fabricated. This study aims to find effects of process parameters on different performance parameters based on previous research done. This study also aims to compare different techniques for optimization of process parameters in Fused Deposition Modeling.

3. MATERIALS AND METHODS:

For extrusion and deposition purposes, most existing FDM machines use thermoplastic materials in a filament type. Acrylonitrile Butadiene styrene (ABS) and Polylactide (PLA) thermoplastics are predominantly used in the process.

| S.no | Name of material | Normal boiling point | Temperature used in FDM |
|------|------------------|----------------------|-------------------------|
| 1    | ABS              | 105°C                | 230°C                   |
| 2    | PLA              | 65°C                 | 180°C                   |

Table 1: Properties of materials

3.1 Process Parameters:
1. Layer thickness: - The thickness of the layer deposited by the nozzle depends on the nozzle type used.
2. Speed of deposition: - It is the rate at which the nozzle deposits the raster.
3. Fill Density: - This percentage number determines the amount of plastic infill there will be in an object. Usually a setting of around 0.30 is used.

3.2 Performance Parameters:
Performance parameters are those for which the optimization is going to perform.

1. **Impact strength.**
2. **Built Time:** Fabrication of part using FDM is quite time-consuming process so there must be need to minimize the total time required to complete part fabricated using FDM.
3. **Surface Roughness:** To get functioning part fabricated from FDM, the component must possess good surface roughness as per the application where that part is going to perform.

Advanced Fusion Plastic Modeling (AFPM) technology was the India’s first industrial grade professional 3D printer. The AION 500 is a high-performance 3D printer at an affordable price that provides a professional-level build volume. This AION 500 offers a large build size, ultra fast print speeds, and more precision. It is designed for versatility.

![Figure 2: AION 500 Machine](image)

The standard specimen for **ASTM D256** is 64 x 12.7 x 4.0 mm. The depth under the notch of the specimen is 10.2 mm.

The parameters which can be adjusted in KISSlicer software for optimizing the performance parameters.

- **Layer Thickness:** - This is the vertical resolution setting in millimeters, usually set to 0.2, but can be set as less as 0.05, as per the requirement. Layer thickness directly affects printing time, as thinner layers will cause more layers, which will take more time or vice versa with thicker layers.
- **Infill density:** - It is necessary to set the density of printed material within the boundary of the loops. 100% will print an entirely solid piece but it is mostly required. Having a sparser infill will decrease printing time, reduce warping due to heating, conserves material, lightens the object, and may actually increase rigidity. This setting needs to be adjusted according to the size of the part.
- **Infill Style:** - It is required to set the lattice shape of the sparse infill structure like straight, round, or hexagonal.
- **Speed of deposition:** - It is the rate at which the nozzle deposits the material.

![Figure 3: KISSlicer Software settings bar](image)

### 3.3 Design Of Experiments:
Taguchi method is used to reduce the variation of processes through robust design of experiments. The objective of the method is to produce high quality product at minimum cost to the manufacturer. Genichi Taguchi developed the Taguchi method. For the design of experiments, a method was built to investigate how various parameters influence the mean and variance of a process output attribute that
determines how well the process operates. The experimental design is proposed by Taguchi method which involves orthogonal arrays to organize the process parameters affecting the process and the levels at which they should be varied. The Taguchi method measures pairs of combinations instead of trying to test all possible combinations, such as factorial design. This facilitates the collection of the necessary data to determine which factors most affect the product quality with optimum or less number of experiments. This saves time and resources. The Taguchi method is widely used when there are an intermediate number of variables (3 to 50), few interactions between variables, and when only a few variables contribute significantly.

In this experimental work, an attempt has been made to demonstrate the application of Taguchi’s Method to improve the impact strength and surface roughness characteristics of an ASTM D256 test specimens that were produced on FDM (Fused deposition modeling) by optimizing the process parameters (control factors) like speed, layer thickness and infill density.

When the process parameters are more, a large number of experiments have to be conducted. In order to solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. Three process parameters (controlling factors) are i. Speed, ii. Layer thickness and iii. Infill density for experiments. Each parameter has three levels, denoted by 1, 2 and 3 respectively. If three parameters and three levels are used for each parameter, according to the Taguchi method, the L9 Orthogonal array should be used for experimentation. Orthogonal arrays involve special standard experimental design that requires only a small number of experimental trials to find the main factors effects on output.

Based on this orthogonal array (OA) is to be selected which has at least nine rows i.e., 9 experimental runs.

In this work, L9 is sufficient. It would require 27 experiments to optimize the parameters. L9 orthogonal array suggests nine experiments which are necessary to optimize the parameters. The experiments are selected as per the level combinations depending on the orthogonal array. It is important that all experiments be conducted. The performance parameter (output) are noted for each experimental run for analysis.

Process parameters
1. Speed of deposition
2. Layer thickness
3. Infill density

| Parameters                  | Level 1 | Level 2 | Level 3 |
|-----------------------------|---------|---------|---------|
| Speed, mm/s                 | 40      | 55      | 70      |
| Layer thickness, mm         | 0.4     | 0.3     | 0.2     |
| Infill density, %           | 50      | 33.33   | 25      |

Table 2: Process parameters with their levels

The fabrication of parts is carried out accordingly by changing the parameters suggested by Taguchi method.
1. EXPERIMENTAL PROCEDURE: Impact Test specimen has been modeled according to ASTM D256.

|   | 4 | 2 | 1 | 2 |
|---|---|---|---|---|
| 5 | 2 | 2 | 3 |
| 6 | 2 | 3 | 1 |
| 7 | 3 | 1 | 3 |
| 8 | 3 | 2 | 1 |
| 9 | 3 | 3 | 2 |

Table3: Taguchi Orthogonal Array Design - L9(3*3)

For manufacturing the Specimens in FDM process, we need to convert the CATIA file into Stereolithography file format (STL). This file is supported by many other software packages. It is mostly used for 3D printing, rapid prototyping and computer-aided manufacturing. After drawing the Izod Impact Test Specimen (ASTM D256) in CATIA, we save the design in STL format by changing the file extension of Test specimen from .cat to .stl (Stereolithography) file format.

Impact Strength Parts Fabricated by FDM Process
5. TESTING:

5.1 Impact Test:
Izod Impact Testing (Notched Izod) ASTM D256 is a common test to understand notch sensitivity in plastics.
Notched Izod Impact is a single point test that measures the material resistance to impact from a swinging pendulum. Izod impact is defined as the kinetic energy needed to initiate fracture and continues the fracture until the specimen is broken. Izod specimens are notched to prevent deformation of the specimen upon impact. This test can be used as a rapid and easy quality control check to determine if a material meets specific impact properties or to compare materials for general toughness.
ASTM impact energy is expressed in J/m. Impact strength is calculated by dividing impact energy in J by the thickness of the specimen. The test result is typically the average of three specimens. The higher the resulting numbers the tougher the material.

Izod impact testing is an ASTM standard method of determining the impact resistance of materials. A pivoting arm is raised to a specific height and then released. The arm swings down hitting the sample, breaking the specimen. The energy absorbed by the sample is calculated from the height the arm
swings to after hitting the sample. A notched sample is generally used to determine impact energy and notch sensitivity.

5.2 Surface Roughness:

![Surface Roughness test for ASTM D256 samples](image)

The surface roughness of ASTM D256 samples is tested by using Mitutoyo, Japan made surface roughness tester. The values of $R_a$ ($\mu$m) in X & Y directions are noted down. $R_a$ ($\mu$m) is the average roughness of the sample.

5.3 Build Time:
After opening the STL file in KISSlicer software, we adjust the process parameters i.e., Layer thickness, Infill density and Speed. After adjusting the process parameters we need to slice the file and note down the time required for printing of Specimens and Volume of material required for printing of specimens.

6. EXPERIMENTAL RESULTS:

6.1 Experimental Impact Strength of ABS Parts:

| Run No | IS 1      | IS 2      | IS 3      | Mean value |
|--------|-----------|-----------|-----------|------------|
| 1      | 142.857   | 142.857   | 176.47    | 154.063    |
| 2      | 135.135   | 210.526   | 131.579   | 159.080    |
| 3      | 147.059   | 176.47    | 147.059   | 156.863    |
| 4      | 236.842   | 153.846   | 153.846   | 181.511    |
| 5      | 138.88    | 138.88    | 138.88    | 138.88     |
| 6      | 142.857   | 147.059   | 117.65    | 135.856    |
| 7      | 147.059   | 147.059   | 147.059   | 147.059    |
| 8      | 131.35    | 162.162   | 108.108   | 131.135    |
| 9      | 171.429   | 171.429   | 171.429   | 171.429    |

Table 4: Impact strength values

6.2 Surface Roughness: The surface roughness of ASTM D256 samples are given below:

| Run order | $R_a$ in X direction | $R_a$ in Y direction | $R_a$ Mean |
|-----------|----------------------|----------------------|------------|
| 1         | 6.57                 | 5.91                 | 6.24       |
| 2         | 3.47                 | 3.995                | 3.735      |
| 3         | 14.335               | 10.468               | 12.402     |
| 4         | 11.383               | 12.303               | 11.843     |
| 5         | 7.6905               | 9.1405               | 8.416      |
6.958 4.6665 5.812
12.510 13.041 12.776
5.0415 5.5325 5.287
4.2073 3.8113 4.009

Table 5: Surface Roughness values for ASTM D-256 samples

6.3 Build Time: The time required for printing of Specimens:

| Run Order | Speed | Layer Thickness | Infill Density | Build Time (min.) |
|-----------|-------|-----------------|----------------|-------------------|
| 1         | 40    | 0.4             | 50             | 9.830             |
| 2         | 40    | 0.3             | 33.33          | 11.227            |
| 3         | 40    | 0.2             | 25             | 16.167            |
| 4         | 55    | 0.4             | 33.33          | 10.027            |
| 5         | 55    | 0.3             | 25             | 12.277            |
| 6         | 55    | 0.2             | 50             | 19.460            |
| 7         | 70    | 0.4             | 25             | 11.253            |
| 8         | 70    | 0.3             | 50             | 14.893            |
| 9         | 70    | 0.2             | 33.33          | 20.933            |

Table 6: Build Time

7. STATISTICAL ANALYSIS:

A statistical model is developed by correlation of input parameters such as Speed of deposition, Layer thickness and Infill density based on analysis of data.

7.1 Impact Strength:

Taguchi optimization plan utilizes data obtained from the experiment and analysis with the help of S/N ratio gives the optimum possibilities for the number of trails selected according to the plan.

Taguchi Analysis:

Impact strength versus Speed, Thickness, Density

| Level | Speed of deposition | Layer Thickness | Infill Density |
|-------|---------------------|-----------------|---------------|
| 1     | 156.7               | 160.9           | 140.4         |
| 2     | 152.1               | 143.0           | 170.7         |
| 3     | 149.9               | 154.7           | 147.6         |
| Delta | 6.8                 | 17.8            | 30.3          |

Table 7: Response Table for Means
**Signal to Noise Ratio Calculations**

The signal to noise ratio is obtained from Minitab software, which presents the percentage contribution of each factor taken. The response output of statistical analysis is maximum impact strength for the combination of process parameters from the design of experiments. Hence, better formula is chosen for calculation.

**S/N Ratio formula for larger the better**

\[
S/N = -10 \times \log(\Sigma(1/Y^2)/n)
\]

For these calculations, we have three Impact strength values i.e., Y1, Y2 and Y3. Then “n” value is “3”.

**S/N Ratio values:**

| Run. No | Impact strength | S/N ratio |
|---------|-----------------|-----------|
| 1       | 154.063         | 43.7540   |
| 2       | 159.080         | 44.0323   |
| 3       | 156.863         | 43.9104   |
| 4       | 181.511         | 45.1781   |
| 5       | 138.890         | 42.8534   |
| 6       | 135.856         | 42.6166   |
| 7       | 147.060         | 43.3499   |
| 8       | 131.135         | 42.3544   |
| 9       | 171.430         | 44.6817   |

**Table 8: S/N Ratio values**

| Level | Speed of deposition | Layer Thickness | Infill Density |
|-------|---------------------|-----------------|----------------|
| 1     | 43.90               | 44.09           | 42.92          |
| 2     | 43.56               | 43.08           | 44.63          |
| 3     | 43.46               | 43.75           | 43.37          |
| Delta | 0.44                | 1.01            | 1.71           |
| Rank  | 3                   | 2               | 1              |

**Table 9: Response Table for Signal to Noise Ratios**

From the analysis of experiments, done highest S/N ratio (45.1781) is obtained for experiment number 4 having the 181.511 j/m impact strength.
From the S/N ratio graphs, the best combination for Speed of deposition is 40 mm/s, Layer thickness is 0.4 mm and Infill Density is 33.33 %.

7.2 Surface Roughness:

Taguchi Analysis:
Surface Roughness versus Speed, Thickness and Density.

| Level | Speed of deposition | Layer thickness | Infill Density |
|-------|---------------------|-----------------|---------------|
| 1     | 7.459               | 10.286          | 5.780         |
| 2     | 8.690               | 5.813           | 6.529         |
| 3     | 7.357               | 7.408           | 11.198        |
| Delta | 1.333               | 4.474           | 5.418         |
| Rank  | 3                   | 2               | 1             |

Table 10: Response Table for Means

![Figure 13: Main Effect plots for Means](image)

S/N Ratio Values:

| Run order | R_a Mean | S/N Ratio |
|-----------|----------|-----------|
| 1         | 6.24     | -15.9037  |
| 2         | 3.735    | -11.4458  |
| 3         | 12.402   | -21.8698  |
| 4         | 11.843   | -21.4692  |
| 5         | 8.416    | -18.5021  |
| 6         | 5.812    | -15.2865  |
| 7         | 12.776   | -22.1279  |
| 8         | 5.287    | -14.4642  |
| 9         | 4.009    | -12.0607  |

Table 11: S/N Ratio for SR

| Level | Speed of Deposition | Layer thickness | Infill Density |
|-------|---------------------|-----------------|---------------|
| 1     | -16.41              | -19.83          | -15.22        |
| 2     | -18.42              | -14.80          | -14.99        |
| 3     | -16.22              | -16.41          | -20.83        |
| Delta | 2.20                | 5.03            | 5.84          |

Table 12: Response Table for S/N Ratios
Figure 14: Main effects plot for Signal to Noise Ratios

From the analysis of experiments conducted, highest S/N ratio (-11.4458) is resulted for experimentation number 2 having the 3.735 µm surface roughness.

From the S/N ratio graphs, the best combination of Speed of deposition of 70 mm/s, Layer thickness of 0.3 mm and Infill Density of 33.33% for Minimum Surface Roughness.

7.3 Build Time:

Taguchi Analysis

Build Time versus Speed, Layer thickness & Infill Density

| Level | Speed of deposition | Layer thickness | Infill Density |
|-------|---------------------|-----------------|---------------|
| 1     | 12.41               | 10.37           | 14.73         |
| 2     | 13.92               | 12.80           | 14.06         |
| 3     | 15.69               | 18.85           | 13.23         |
| Delta | 3.28                | 8.48            | 1.50          |
| Rank  | 2                   | 1               | 3             |

Table 13: Response Table for Means

Figure 15: Main effects plot for Means

S/N Ratios for Build time

| Run Order | Build Time (min.) | S/N Ratio  |
|-----------|-------------------|------------|
| 1         | 9.830             | -19.8511   |
| 2         | 11.227            | -21.0053   |
| 3         | 16.167            | -24.1726   |
| 4         | 10.027            | -20.0234   |
| 5         | 12.277            | -21.7818   |
| 6         | 19.460            | -25.7829   |
From the analysis of experiments done, highest S/N ratio (19.8511) is obtained for experimentation number 1 having the 9.830 min. Build time.

From the S/N ratio graphs, the best combination of Speed of deposition of 40 mm/s, Layer thickness of 0.4 mm and Infill Density of 25% for Minimum Build Time.

8. CONCLUSIONS:
1. From the analysis of experiments, done highest S/N ratio (45.1781) is obtained for experiment number 4 having the 181.511 J/m Impact strength.
2. From the S/N ratio graphs, the best combination of Speed of deposition is 40 mm/s, Layer thickness is 0.4 mm and Infill Density is 33.33 % for Highest Impact strength.
3. From the analysis of experiments done, highest S/N ratio (-11.4458) is obtained for experiment number 2 having the 3.735 µm surface roughness.
4. From the S/N ratio graphs, the best combination of Speed of deposition of 70 mm/s, Layer thickness of 0.3 mm and Infill Density of 33.33% for Minimum Surface Roughness.
5. From the analysis of experiments done, highest S/N ratio (-19.8511) is resulted. For experiment number 1 having the 9.830 min. Build time.
6. From the S/N ratio graphs, the best combination of Speed of deposition of 40 mm/s, Layer thickness of 0.4 mm and Infill Density of 25% for Minimum Build Time.

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