Experimental Investigation on the Effect of Fused Deposition Modelling Parameters for HIPS Material by Experimental Design and MRO Techniques

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Abstract. Fused Deposition Modelling (FDM) is one of the popular AM technique which utilizes thin thermoplastic filaments to create prototypes and end use products. The parts processed through FDM method have poor mechanical properties and surface quality characteristics in comparison to conventional manufactured products. Extensive research is underway in various parts of the world to bring an enhancement in mechanical properties and other related characteristics of the parts produced through FDM for making the process highly suitable to produce parts for diverse applications. The present work considers slice height, infill density, shell thickness and raster angle varied in three levels (3⁴) to study their effects over output responses such as specimen weight, flexural strain and flexural strength. Taguchi’s L9 orthogonal array is considered for preparing the experimental plan. Flexural testing is adopted for the evaluation of flexural strength. Grey Relational Analysis and Technique of Order Preference Similarity to the Ideal Solution methods have been adopted for multi response optimization of FDM parameters and the optimized parameter setting recommended have been validated through confirmation trials. The confirmation trail conducted has revealed that the setting recommended by TOPSIS A1B3C3D1 has shown higher flexural strength and slice height is found to be most significant factor. GRA method has recommended the combination A3B3C3D1 which shows lesser flexural strain and infill density is found to be significant from all the parameters considered.

Keywords – Grey Relational Analysis, TOPSIS, High Impact Polystyrene

Abbreviations

AM – Additive Manufacturing
ASTM – American Society for Testing and Materials
FDM – Fused Deposition Modelling
GRA – Grey Relational Analysis
TOPSIS - Technique of Order Preference Similarity to the Ideal Solution
ABS – Acrylonitrile Butadiene Styrene
1. Introduction

Three dimensional printing is an umbrella term used to represent multitude of techniques which converts a 3D modelled data in to a realistic product by adding material in thin layers. AM technique has become the most sought method for producing prototypes and end user products owing to its benefits associated. Fused Deposition Modelling (FDM) is one of the AM technique which primarily uses thermoplastic filaments as raw materials for making products by extruding the filament. The extruded filament is arranged over a heated bed in layer by layer fashion to achieve the final product. The process has attractive advantages such as non-requirement of specialized tools, highly skilled labor and low material wastage compared to traditional practice of manufacturing. Parts manufactured using FDM has certain uncertainties in comparison to the conventionally manufactured parts such as low mechanical properties, poor surface finish, high production time and many more. Many authors have considered such uncertainties as potential research problem to identify positive solution which makes the method more viable. Samir Kumar panda et.al [1] conducted optimization of FDM input factors for ABS P400 material by varying slice height, raster width, raster angle, orientation and air gap through bacterial foraging optimization technique. The authors have concluded that all the parameters has to be maintained at higher level for the improvement of mechanical properties except slice height need to be maintained at lower level. OgnjanLužanin et.al [2] studied effect of slice height, deposition angle and infill density on maximum flexural force for PLA material. The authors concluded that slice height is found to be statically significant than other two parameters considered. Sandeep et.al [3] investigated the effect of part built orientation over the mechanical properties and total cost of the FDM parts printed using ABS as main material. The authors have reported that built orientation has significant effect over the tensile flexural and total cost of the parts produced. K.G. et.al [4] analysed flexural properties for 3D printed PLA specimens at different test conditions by varying the slice height, printing speed and orientation angle. The authors have conducted flexural testing as per ASTM D790 standard and observed maximum flexural strength with the parts fabricated in horizontal direction than vertical direction and the increase in speed of printing decreases the flexural strength of parts produced. K.G. Jaya Christiyan et.al [5] studied the effect of FDM input factors over the mechanical properties of ABS + hydrous magnesium silicate. The achievement of maximum mechanical properties of the composite part manufactured is observed at low slice height and printing speed. Omar Ahmed Mohammed et.al [6] conducted experiments to investigate the tribological behaviour and wear mechanism of PC-ABS material by varying the FDM parameters such as slice height, raster angle, air gap, raster width, no of contours and build orientation. The authors have adopted definitive screening design to prepare the experimental layout for conducting experiments. The results obtained are further statistically treated for understanding the effects of input parameters over the wear rate. Krishna P. Motaparti et.al [7] experimentally investigates the effects of FDM parameters on the flexural properties of ULTEM 9085 by varying the build factors such as build direction, raster angle and air gap for the evaluation of flexural yield strength, flexural modulus, flexural modulus / mass ratio, flexural strength / mass ratio. The experimental results indicate that parts processed in the vertical direction have exhibited higher flexural strength than the parts processed in horizontal direction. Negative air has also shown improvement in flexural strength but is not statistically significant. MadhukarSomireddy et.al [8] studied the flexural behaviour of FDM made parts through different methods by considering the materials PLA and ABS. The authors have considered the 3D printed part in analogous to a composite laminate structure and applied the classical laminated theory for the calculation of flexural stiffness. Three point bending tests has been conducted and observed that parts with thin layers have maximum load bearing capacity and higher energy absorption than thick layer laminates. Z. Abdullah et.al [9] studied the effect of slice height and raster angle over the tensile and flexural strength of FDM made PLA and ABS parts. The tests has been carried out as per ASTM standards and the authors have observed that both slice height and raster angle has affected the tensile and flexural strength of the specimen. The authors have commented that

MRO – Multi Response Optimization
SNR - Signal to Noise Ratio
the results are uncommon as the PLA parts are found to have higher strength than ABS parts processed. PavelStoklasek et.al [10] analyzed the flexural behavior of 3D printed ABS – M30 parts for bending and charpy impact tests. The authors have observed the lowest flexural strength for the orientation XZ-V and slice height is found to be significant from the selected parameters. Y. Rosenthal1 et.al [11] studied about the crack propagation of AM-FDM printed ABS material by varying the input factors and evaluated the strength under flexural testing. Magdalena Pastor-Artigues et.al [12] considered PLA material for studying the elastic asymmetry between the experimental data set and numerical simulations. Abinesh Kurapatti Ravi et.al [13] involved in increasing the inter layer bond strength through localized heating and achieved an improvement of 50% for ABS filament. The present work considers four different FDM input factors such as slice height, infill density, shell thickness and raster angle varied in three levels to evaluate the specimen weight, flexural strain and flexural strength of the part produced.

2. Material and Methods

2.1. HIPS

The present work considers High Impact Polystyrene (HIPS) as the material for testing the output responses such as specimen weight, flexural strain and flexural strength. Polystyrene is one of the oldest thermoplastic worldwide which is generally created by polymerization of monomeric styrene. It has a transparent, crystal clear element with glossy surface and also has similar properties like ABS but it is much lighter. It has a very good resistance to alkalis, mineral oil and acids. It has many attractive advantages such as superior resistance to impact, easiness in machining, good dimensionally stable, low cost and FDA complaint. It finds applications in low strength structural applications such as housings and covers. It can be easily fabricated, painted and glued. Table 1 represents the various properties of HIPS material.

| S.No | Property / Characteristic | S.I Unit | Value |
|------|--------------------------|----------|-------|
| 1    | Tensile Module           | MPa      | 1550  |
| 2    | Tensile Strength         | MPa      | 22    |
| 3    | Elongation at Break      | %        | 50    |
| 4    | Standard Tolerance       | mm       | 0.05  |
| 5    | Impact Strength          | KJ/m²    | 15    |
| 6    | Flexural Modulus         | MPa      | 2126  |
| 7    | Density                  | kg/m³    | 1004  |
| 8    | Melting Temperature      | °C       | 180 -260 |

HIPS filament has to be printed in a heated bed with an enclosure and the extruder temperature need to be maintained around 230 – 245 °C throughout the process to attain parts with desired properties. The vapours that are getting created during the printing of HIPS material is one of the greatest disadvantage associated.

2.2. Experimental Design

Experimental Design is a systematic approach to study the effect of input factors over the output responses considered in a process or product manufacturing. Methods such as Taguchi’s orthogonal array, Response surface methodology, and Definitive screening design are few well known examples for DOE which is being practiced by various researchers in diverse fields to attain a solution for the
The major advantage of DOE method is the requirement of fewer experiments to achieve the desired accurate results at a lesser cost and time. The experimental results obtained may be further analyzed through statistical methods such as Analysis of Variance, Regression analysis, Desirability function and many more to understand the effect of input factors over the output factors and also the individual contribution of input factors may be obtained. The present work considers four different FDM parameters namely slice height, infill density, shell thickness and raster angle varying in three levels ($3^4$) to study their effects over the output responses such as specimen weight, flexural strain and flexural strength. For the number of input parameters and their levels considered in the present work either nine or twenty seven experimental trials may be taken for doing the experimentation. The present work considers the Taguchi’s orthogonal array with nine different experimental trials to prepare the experimental design layout through MINITAB 17.0 software. Table 2 and Table 3 represent the input factors considered for the preparation of specimen and the output responses considered along with their objectives.

Table 2. FDM Varying Input Parameters

| Input Factors       | Symbol | Unit | Low Value (-1) | Medium Value (0) | High Value (1) |
|---------------------|--------|------|----------------|------------------|---------------|
| Slice height        | A      | mm   | 0.17           | 0.25             | 0.33          |
| Infill Density      | B      | %    | 25             | 50               | 75            |
| Shell Thickness     | C      | mm   | 1              | 1.5              | 2             |
| Raster Angle        | D      | Deg  | 0              | 30               | 60            |

Table 3. Output Responses and Objectives

| Output Parameters   | Symbol | Unit  | Objective     |
|---------------------|--------|-------|---------------|
| Specimen Weight     | R1     | gms   | Minimize      |
| Flexural Strain     | R2     | Nil   | Minimize      |
| Flexural Strength   | R3     | MPa   | Maximize      |

Table 4. L$_9$ Experimental Design Layout with Coded and Uncoded Values

| Trial No | Input Parameters - Coded Values | Input Parameters - Uncoded Values |
|----------|---------------------------------|----------------------------------|
| A        | B      | C      | D      | A      | B      | C      | D      |
| 1        | -1     | -1     | -1     | 0.17   | 25     | 1      | 0      |
| 2        | -1     | 0      | 0      | 0      | 0.17   | 50     | 1.5    | 30     |
| 3        | -1     | 1      | 1      | 1      | 0.17   | 75     | 2      | 60     |
| 4        | 0      | -1     | 0      | 1      | 0.25   | 25     | 1.5    | 60     |
| 5        | 0      | 0      | 1      | -1     | 0.25   | 50     | 2      | 0      |
| 6        | 0      | 1      | -1     | 0      | 0.25   | 75     | 1      | 30     |
| 7        | 1      | -1     | 1      | 0      | 0.33   | 25     | 2      | 30     |
| 8        | 1      | 0      | -1     | 1      | 0.33   | 50     | 1      | 60     |
| 9        | 1      | 1      | 0      | -1     | 0.33   | 75     | 1.5    | 0      |
The other parameters associated in the process are kept constant throughout the manufacturing of the specimens to study the significance of input factors varied. Table 5 represents the various constant FDM parameters considered in the present study.

### Table 5. Constant FDM Printing Parameters

| S.No | Parameter / Characteristic  | S.I Unit | Value |
|------|----------------------------|----------|-------|
| 1    | Nozzle Diameter            | Mm       | 0.4   |
| 2    | Extruder Temperature       | °C       | 240   |
| 3    | Bed Temperature            | °C       | 100   |
| 4    | Filament Diameter          | mm       | 1.75  |
| 5    | Printing Speed             | mm/s     | 150   |
| 6    | Filament Colour            | -        | White |
| 7    | Infill Pattern             | -        | Honeycomb |

### 3. Experimental Work

#### 3.1. Preparation of Specimen

The specimen for the flexural testing of HIPS made specimens have been prepared using RAISE3D FDM printing machine using a filament diameter of 1.75mm. The dimensions of the specimen have been fixed as 200 x 20 x 10 mm in order to ensure the compatibility with the experimental setup available at SITARC Coimbatore. Figure 1 shows the 2D view of the flexural testing specimen printed for measuring the output responses. The Figure 2 (a), (b) and (c) shows the variation in infill density that has been considered in the present study.

![Figure 1](image1.png)

**Figure 1.** 2D Views of the Flexural Testing Specimen

![Figure 2 (a)](image2.png)

**Figure 2 (a).** Flexural Testing Specimen with 25 %Infill Density
3.2. Experimental Procedure

The specimens prepared using FDM technique is subjected to flexural testing to evaluate the bending strength and strain of different specimens prepared by varying the input parameters as per the experimental design matrix. The specimen is loaded in the experimental setup similar to an overhanging beam and the load is applied at specimen centre. The supports are in the form of cylindrical rollers which are placed below the specimen and the specimens have been loaded until it breaks into two pieces. The maximum load the specimen has withstood and the displacement due to the applied load has been recorded through the data acquisition system present in the experimental setup. The recorded values of force and displacement are used for calculating the flexural strain and flexural strength of the material. Table 6 shows the experimental values obtained for maximum force applied to the specimen before getting fractured in to two pieces and its corresponding displacement. Figure 3 (a), (b) and (c) shows the specimen under different stages of the three point bending test such as loading, flexion and breakage. Figure 4 shows the fractured specimens after three point bending test.

![Figure 2 (b). Flexural Testing Specimen with 50 % Infill Density](image)

![Figure 2 (c). Flexural Testing Specimen with 75 % Infill Density](image)

**Table 6.** Experimental Values of Three Point Bending Test

| Trial No | Input Parameters – Uncoded Values | Output Experimental Values |
|----------|-----------------------------------|-----------------------------|
|          | A       | B       | C       | D | Flexural Force | Displacement (mm) |

(a) Specimen under Loading  (b) Specimen under Flexion (c) Specimen under Breakage
Figure 4. Fractured Specimens after Three Point Bending Test

4. Results and Discussion

The values of maximum force applied to the specimen before breakage and the corresponding displacement have been utilized for calculating the flexural strain and flexural strength of the specimen. The weight of the printed specimen is checked using the weighing machine. The standard relations for calculating the flexural strength and strain are represented in equations 1 and 2.

**Equation for Flexural Strength** \((F_s)\)

\[
F_s = \frac{3PL}{2bd^2}
\]

\(P\) – Peak load in N
L – Specimen length in m
b – Specimen width in m
d – Specimen thickness in m

**Equation for Flexural Strain ($\varepsilon$)**

$$\varepsilon = \frac{6Dd}{L^2} \quad (2)$$

D – Specimen displacement in m
d – Specimen thickness in m
L – Specimen length in m

**Table 7. Experimental Values of Output Parameters**

| Trial No | Input Parameters – Uncoded Values | Output Parameters - Experimental Values |
|----------|-----------------------------------|----------------------------------------|
|          | A  | B  | C  | D  | R1 | R2 | R3  |
| 1        | 0.17 | 25 | 1  | 0  | 29 | 0.0095 | 46.80 |
| 2        | 0.17 | 50 | 1.5| 30 | 41 | 0.0036 | 44.55 |
| 3        | 0.17 | 75 | 2  | 60 | 52 | 0.0073 | 80.10 |
| 4        | 0.25 | 25 | 1.5| 60 | 34 | 0.0047 | 17.55 |
| 5        | 0.25 | 50 | 2  | 0  | 45 | 0.0093 | 17.55 |
| 6        | 0.25 | 75 | 1  | 30 | 53 | 0.0182 | 22.05 |
| 7        | 0.33 | 25 | 2  | 30 | 39 | 0.0115 | 13.05 |
| 8        | 0.33 | 50 | 1  | 60 | 45 | 0.0068 | 14.85 |
| 9        | 0.33 | 75 | 1.5| 0  | 54 | 0.0243 | 36.45 |

Table 7 represents the calculated values of bending strength and strain. From the calculated values of bending strength and strain, the highest flexural strength is observed with experiment trail 3 (A1B3C3D3) which has low value of slice height and higher values in case of infill density, shell thickness and raster angle. The lowest flexural strength is observed with 7th experimental trail (A3B1C3D2) which has higher values of slice height and shell thickness, low value in case of infill density and mid value in case of raster angle. In case of higher specimen weight and flexural strain 9th experimental trail (A3B3C2D1) which has higher values of slice height and infill density, low value in case of shell thickness and low value in case of raster angle is observed. For lowest specimen weight the 1st experimental trail (A1B1C1D1) where all the input parameters with low values have been observed. The low value of flexural strain is observed with 2nd experimental trail (A1B2C2D2) which has low value in case of slice height and mid values in all other input factors. The experimental values indicate the weight of the specimen increases with an increase in the value of infill density. For higher flexural strength low value of slice height in combination with an increased infill density is required. For a low flexural strain low slice height and mid value of all other parameters is recommended.

**4.1. Entropy Method**
The experimental values of specimen weight, flexural strain and flexural strength are further considered for understanding the combination of parameters which can satisfy all the objectives of the output responses together. The weightage of the individual output response need to be determined inorder to understand its importance while considering all the objectives of the output responses together. The weightage may be given equal for all the output responses also, but the weight need to be determined through as standard method. Methods such as entropy, analytical hierarchy process and analytical network process are generally considered for weight determination of output responses. The present method adopts entropy method for calculating the individual weight of output responses. The method consists of three different steps namely normalization of project outcomes($P_{ij}$), entropy measure computation and weightage of individual output parameters.

Step I: Normalizing the arrays of decision matrix to obtain $P_{ij}$ and it is tabulated in table 8

$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \quad (3)$

**Table 8. Normalized Values of Project Outcomes**

| Trial No | R1     | R2     | R3     |
|----------|--------|--------|--------|
| 1        | 0.074  | 0.0999 | 0.1598 |
| 2        | 0.1046 | 0.0373 | 0.1521 |
| 3        | 0.1327 | 0.077  | 0.2734 |
| 4        | 0.0867 | 0.0495 | 0.0599 |
| 5        | 0.1148 | 0.0975 | 0.0599 |
| 6        | 0.1352 | 0.1907 | 0.0753 |
| 7        | 0.0995 | 0.1212 | 0.0445 |
| 8        | 0.1148 | 0.0712 | 0.0507 |
| 9        | 0.1378 | 0.2553 | 0.1244 |

Step II: Entropy measure computation for project outcomes ($E_j$) by equation 4 and values are tabulated in Table 9.

$E_j = -K \sum_{i=1}^{n} P_{ij} \ln P_{ij} \quad (4)$

**Table 9. Entropy Measure of Project Outcomes**

| Trial No | R1     | R2     | R3     |
|----------|--------|--------|--------|
| 1        | -0.1926| -0.2301| -0.293 |
| 2        | -0.2361| -0.1228| -0.2864|
| 3        | -0.268 | -0.1975| -0.3546|
| 4        | -0.2121| -0.1487| -0.1686|
| 5        | -0.2485| -0.227 | -0.1686|
| 6        | -0.2705| -0.316 | -0.1947|
\[ K = \frac{1}{\ln(m)} \], \ m - \text{No of Experimental Trials }, \ m = 9

K = 0.45512

**Table 10.** Summed Values of Project Outcome Entropies

| S.No | R1    | R2    | R3    |
|------|-------|-------|-------|
| 1    | 0.9917| 0.9260| 0.9171|

Table 10 represents the summed valued of project outcomes for the output responses considered.

Step III: Defining the objective weight \((w_j)\)

\[
w_j = \frac{1 - E_j}{\sum_{j=1}^{n}(1 - E_j)} \tag{5}
\]

The value of \(1 - E_{ij}\) is given in Table No 11

**Table 11.** Value of \(1 - E_{ij}\)

| S.No | R1    | R2    | R3    |
|------|-------|-------|-------|
| 1    | 0.0083| 0.0740| 0.0829|

The sum of \(1 - E_{ij}\) is found to be 0.1652 and it can be found by adding all the values of \(1 - E_{ij}\)

The value of \(W_{ij}\) obtained for the individual output parameters are given in table no 12

**Table 12.** Weights of Output Parameters

| S.No | R1    | R2    | R3    |
|------|-------|-------|-------|
| 1    | 0.05  | 0.45  | 0.50  |

Out of 100 % the maximum weightage of 50% goes for Flexural strength, 45 % for flexural strain and only 5% for weight of the specimen.
4.2. Grey Relational Analysis

Multi objective optimization is generally considered in many real life problems as many conflicting objectives exists with the same problem. Methods such as Grey Relational analysis, TOPSIS, MOORA, Assignment of weights method and DEAR approach have been adopted in many research problems to identify the best combination of parameters which satisfies the conflicting objectives of the problem. The present study adopts GRA and TOPSIS methods for identifying the best combination of input factors. Grey relational analysis is a simple method which consists of few steps of finding the best combination of parameters. The experimental values of output responses has to be converted in to a suitable SNR value as per the objective. For the present work both specimen weight and flexural strain is considered as smaller the better characteristic and higher the better is considered for flexural strength. Equation 6 and 7 represents the relation for calculating SNR for higher the better and lower the better cases.

For higher the better case
\[ S/N = -10\log\left(\frac{\sum(1/Y_i^2)}{n}\right) \]  
(6)

For lower the better case
\[ S/N = -10\log\left(\frac{\sum(Y_i^2)}{n}\right) \]  
(7)

Where \( n \) = number of replications

\( Y \) = Experimental values of output response

| Trial No | Input Parameters – Uncoded Values | Output Parameters - Signal to Noise Ratio |
|----------|----------------------------------|------------------------------------------|
|          | A  | B  | C  | D  | SNR1 | SNR2 | SNR3 |
|  1       | 0.17| 25 | 1  | 0  | -29.25| 40.44| 33.40|
|  2       | 0.17| 50 | 1.5| 30 | -32.26| 48.98| 32.98|
|  3       | 0.17| 75 | 2  | 60 | -34.32| 42.69| 38.07|
|  4       | 0.25| 25 | 1.5| 60 | -30.63| 46.54| 24.89|
|  5       | 0.25| 50 | 2  | 0  | -33.06| 40.64| 24.89|
|  6       | 0.25| 75 | 1  | 30 | -34.49| 34.82| 26.87|
|  7       | 0.33| 25 | 2  | 30 | -31.82| 38.76| 22.31|
|  8       | 0.33| 50 | 1  | 60 | -33.06| 43.38| 23.43|
|  9       | 0.33| 75 | 1.5| 0  | -34.65| 32.29| 31.23|

The first step in GRA is to normalize the SNR values of output responses based upon the type of characteristic associated with the output response. Equation 8 and 9 represents the relationships for normalization of output responses.

For the output responses with Larger the Better Case of Normalization
\[ Z_{ij} = \frac{Y_{ij} - \min Y_{ij}}{\max Y_{ij} - \min Y_{ij}} \]  
(8)

For the output responses with Smaller the Better Case of Normalization
\[ Z_{ij} = \frac{\max Y_{ij} - Y_{ij}}{\max Y_{ij} - \min Y_{ij}} \]  
(9)
Table 14 represents the normalized values of SNR for different output responses.

Table 14. Normalized SNR values for Output Responses

| Trial No | R1    | R2    | R3    |
|----------|-------|-------|-------|
| 1        | 0.000 | 0.5118| 0.7039|
| 2        | 0.557 | 0.0000| 0.6767|
| 3        | 0.939 | 0.3767| 1.0000|
| 4        | 0.256 | 0.1463| 0.1633|
| 5        | 0.707 | 0.4993| 0.1633|
| 6        | 0.970 | 0.8479| 0.2891|
| 7        | 0.477 | 0.6122| 0.0000|
| 8        | 0.707 | 0.3358| 0.0712|
| 9        | 1.000 | 1.0000| 0.5661|

Table 15. Weighted Normalized Values of Output Responses

| Trial No | R1    | R2    | R3    |
|----------|-------|-------|-------|
| 1        | 0.0000| 0.2303| 0.3519|
| 2        | 0.0278| 0.0000| 0.3383|
| 3        | 0.0470| 0.1695| 0.5000|
| 4        | 0.0128| 0.0658| 0.0816|
| 5        | 0.0353| 0.2247| 0.0816|
| 6        | 0.0485| 0.3816| 0.1445|
| 7        | 0.0238| 0.2755| 0.0000|
| 8        | 0.0353| 0.1511| 0.0356|
| 9        | 0.0500| 0.4500| 0.2831|

Table 15 shows the weighted normalized values obtained by multiplying the individual weights obtained through entropy method for output responses.

The method continues by calculating the deviation sequence represented by equation 10 and the values of deviation sequence are tabulated in table 16.

For Calculation of Deviation Sequence

\[ \Delta_{01} = X_{0k} - X_{ik} \]  \hspace{1cm} (10)

Table 16. Deviation Sequence for Output Responses
For Calculating the Grey Relational Coefficient ($G_{Cij}$) the equation 11 is considered and the values are tabulated in table no 17.

\[
G_{Cij} = \frac{\Delta_{min} + \lambda \Delta_{max}}{\Delta_{0ij} + \lambda \Delta_{max}}
\]  

(11)

$\lambda$ value can be taken between 0 to 1. In the current study $\lambda$ value is taken as 1

| Trial No | R1     | R2     | R3     |
|----------|--------|--------|--------|
| 1        | 0.0500 | 0.2197 | 0.1481 |
| 2        | 0.0221 | 0.4500 | 0.1617 |
| 3        | 0.0030 | 0.2805 | 0.0000 |
| 4        | 0.0372 | 0.3842 | 0.4184 |
| 5        | 0.0147 | 0.2253 | 0.4184 |
| 6        | 0.0015 | 0.0684 | 0.3555 |
| 7        | 0.0262 | 0.1745 | 0.5000 |
| 8        | 0.0147 | 0.2989 | 0.4644 |
| 9        | 0.0000 | 0.0000 | 0.2170 |

The individual values of grey relational coefficient of output responses are considered to attain the the multi response performance index of the output responses considered in the present study. Equation 12 represents the grey relational grade and Table 18 represents the grey relational grade $G_i$ of individual experimental trial and the corresponding ranking obtained.

\[
G_i = \frac{1}{m} \sum G_{Cij}
\]  

(12)

$m$ – No of output responses. In the present study the value of $m = 3$. 

Table 17. Grey Relational Coefficient
Table 18. Grey Relational Grade and Ranking

| Trial No | GRG   | Rank |
|----------|-------|------|
| 1        | 0.6413| 6    |
| 2        | 0.6431| 5    |
| 3        | 0.8444| 2    |
| 4        | 0.5469| 9    |
| 5        | 0.6547| 4    |
| 6        | 0.7997| 3    |
| 7        | 0.6194| 8    |
| 8        | 0.6246| 7    |
| 9        | 0.8901| 1    |

The 9th experimental trail receives the topmost ranking as per the MRPI value and it has the combination of (A3B3C2D1) higher values in case of slice height and infill density, mid values in case of shell thickness and low value in case of raster angle.

Table 19. Level Totals for Input Parameters – GRA

| Input Factors | Low Level | Middle Level | High Level | Difference | Rank |
|---------------|-----------|--------------|------------|------------|------|
| A             | 2.1280    | 2.0010       | 2.1340     | 0.13       | 3    |
| B             | 1.8000    | 1.9200       | 2.5300     | 0.73       | 1    |
| C             | 2.0600    | 2.0800       | 2.1200     | 0.06       | 4    |
| D             | 2.1900    | 2.0600       | 2.0100     | 0.18       | 2    |

Table 19 shows the level totals of input parameters considered in the present study. From Grey Relational Analysis infill density is the most significant parameter with topmost ranking from the selected input variables. Raster angle and slice height receives the second and third position in the ranking. Shell thickness has the least significance over the output characteristics considered. The optimized parameter setting for achieving high flexural strength, low flexural strain and low specimen weight is found to be A3B3C3D1 i.e Higher values in case of slice height, infill density, shell thickness and low value in case of raster angle is recommended for achieving the desired objectives with HIPS material.

4.3. TOPSIS

Technique Order Preference Similar to Ideal Solution is a multi-response optimization technique which generally identifies the best alternative which has lower distance from the positive ideal solution and higher distance from the negative ideal solution. The solution obtained has been used for calculating the Euclidean distance which is the essence for the calculation of closeness coefficient values. Higher the closeness coefficient value represents better the solution which is the underlying concept of TOPSIS methodology. The following are the different steps involved in TOPSIS methodology for identifying the best alternative.

Step I: Calculation of normalized values from the experimental output values using equation 13
\[ r_{ij} = \frac{a_{ij}}{\sum_{i=0}^{m_i} a_{ij}^2} \quad (13) \]

\( r_{ij} \) is the normalized output value.

Table 20. Normalized Output Values

| Trial No | R1    | R2    | R3    |
|---------|-------|-------|-------|
| 1       | 0.2181| 0.2378| 0.4041|
| 2       | 0.3084| 0.0889| 0.3847|
| 3       | 0.3911| 0.1834| 0.6917|
| 4       | 0.2557| 0.1178| 0.1515|
| 5       | 0.3384| 0.2321| 0.1515|
| 6       | 0.3986| 0.4538| 0.1904|
| 7       | 0.2933| 0.2884| 0.1127|
| 8       | 0.3384| 0.1695| 0.1282|
| 9       | 0.4061| 0.6075| 0.3147|

Step II: Calculation of weighted normalized matrix \( V_{ij} \) using calculated weights \( W_i \) by entropy method and \( r_{ij} \) using equation 14.

\[ V_{ij} = W_i \times r_{ij} \quad (14) \]

The values of output responses obtained in the experimental work has been converted in to normalized values as per equation 13 and tabulated in table 20. By using equation 14 and the output parameter weights are computed using entropy technique, weighted normalized output values are obtained and tabulated in table 21.

Table 21. Weighted Normalized Output Values

| Trial No | R1    | R2    | R3    |
|---------|-------|-------|-------|
| 1       | 0.0109| 0.1070| 0.2021|
| 2       | 0.0154| 0.0400| 0.1923|
| 3       | 0.0196| 0.0825| 0.3458|
| 4       | 0.0128| 0.0530| 0.0758|
| 5       | 0.0169| 0.1045| 0.0758|
| 6       | 0.0199| 0.2042| 0.0952|
| 7       | 0.0147| 0.1298| 0.0563|
| 8       | 0.0169| 0.0763| 0.0641|
| 9       | 0.0203| 0.2734| 0.1574|

Step III: Determination of ideal solution for both positive and negative ideal solution cases
\[ V^+ = (V_1^+, V_2^+ \ldots V_n^+) \quad (15) \]
\[ V^- = (V_1^-, V_2^- \ldots V_n^-) \quad (16) \]

**Table 22. Ideal Best and Worst Values**

| Solution Models | R1   | R2   | R3   |
|-----------------|------|------|------|
| Ideal Best      | 0.0109 | 0.0400 | 0.3458 |
| Ideal Worst     | 0.0203 | 0.2734 | 0.0563 |

Where \( V^+ \) - Positive Ideal Solution, \( V^- \) - Negative Ideal Solution

Table 22 represents the ideal best and worst values obtained for the different output responses. In case of both specimen weight and flexural strain the lowest value is considered as the ideal best solution and the higher value is considered as the ideal worst solution for the material considered. For the flexural strength of the specimen the higher value of the output response is considered as the ideally best and the lower value is the ideally worst.

Step IV: Calculation of euclidean distance of each alternative and the values are tabulated in Table 23.

\[ S_{i}^+ = \sqrt{\sum_{j=0}^{M} (V_{ij} - V_{j}^+)^2} \quad (17) \]
\[ S_{i}^- = \sqrt{\sum_{j=0}^{M} (V_{ij} - V_{j}^-)^2} \quad (18) \]

Where \( i = 1, 2, \ldots, n \)

**Table 23. Euclidean Distance Values**

| Trial No | Euclidean Distances |
|----------|---------------------|
|          | Si+   | Si-   |
| 1        | 0.1586 | 0.2214 |
| 2        | 0.1536 | 0.1971 |
| 3        | 0.0434 | 0.3561 |
| 4        | 0.2704 | 0.0933 |
| 5        | 0.2777 | 0.1301 |
| 6        | 0.2998 | 0.2262 |
| 7        | 0.3031 | 0.1422 |
| 8        | 0.2841 | 0.1011 |
| 9        | 0.3001 | 0.3161 |

Step V: By equation 19 closeness coefficient values are computed and tabulated in Table 24.
\[ CC_i = \frac{\text{Si}^-}{\text{Si}^+ + \text{Si}^-} \]  

(19)

**Table 24. Closeness Coefficient Value of Output Responses**

| S.No | Cci    | Rank |
|------|--------|------|
|  1   | 0.5826 |  2   |
|  2   | 0.5620 |  3   |
|  3   | 0.8914 |  1   |
|  4   | 0.2566 |  9   |
|  5   | 0.3191 |  7   |
|  6   | 0.4300 |  5   |
|  7   | 0.3194 |  6   |
|  8   | 0.2624 |  8   |
|  9   | 0.5130 |  4   |

**Table 25. Level Totals for Input Parameters – TOPSIS**

| Input Factors | Low Level | Middle Level | High Level | Difference | Rank |
|---------------|-----------|--------------|------------|------------|------|
| A             | 2.03      | 1.00         | 1.01       | 1.03       |  1   |
| B             | 1.16      | 1.14         | 1.83       | 0.69       |  2   |
| C             | 1.27      | 1.33         | 1.53       | 0.26       |  3   |
| D             | 1.42      | 1.31         | 1.41       | 0.11       |  4   |

Table 25 shows the level totals of input parameters as per TOPSIS methodology. Slice height is the most influencing parameter with topmost ranking from the selected input variables. Infill Density and Shell thickness receives the second and third position in the ranking. Raster angle has the least significance over the output characteristics considered as per TOPSIS method. The optimized parameter setting for achieving high flexural strength, low flexural strain and low specimen weight is found to be A1B3C3D1 i.e Lower values in case of both slice height and raster angle. Higher values are recommended for both infill density and shell thickness.

4.4. **Confirmation Test**

The optimized parameter setting obtained by both Grey relational analysis and TOPSIS method is validated by conducting confirmation trials as per the setting arrived with those techniques. The experimental values from confirmation trials have been compared to understand the effectiveness of the results achieved. Figure 5 and 6 represents the specimen prepared as per TOPSIS and GRA recommended parameter settings.
The results of confirmation trials have been tabulated for the parameters such as printing time, specimen weight, flexural strain and flexural strength and the values are tabulated in Table 26.

| S.No | Method | Time (mins) | Weight (gms) | Force (N) | Displacement (mm) | Flexural Strain | Flexural Strength (MPa) |
|------|--------|-------------|--------------|-----------|------------------|----------------|------------------------|
| 1    | TOPSIS | 279         | 34           | 652       | 11.25            | 0.01688        | 97.8                   |
| 2    | GRA    | 151         | 34           | 492       | 10.1             | 0.01515        | 73.8                   |

From the experimental results attained through confirmation trials, the highest flexural strength is reported for the specimen prepared as per TOPSIS methodology. It has recommended a very thin slice height which results with higher number of layers with the printed part. The flexural strain of the part is slightly higher than the value obtained with GRA method. The weight of the specimen from both the methods are found to be similar 34 grams as the infill density is common. The specimen prepared as per GRA has low flexural strength as higher value of slice height has been recommended in comparison with TOPSIS methodology. The printing time for both the specimen varies as the number of layers are different from both the methods.

5. Conclusion

The following points may be considered as the conclusion of the present work conducted using HIPS material for optimizing FDM parameters for multiple responses:

- The parameters such as slice height, infill density, shell thickness and raster angle are varied in three levels and output responses such as specimen weight, flexural strain and flexural strength are considered in the present study.
- The weights for the individual responses have been determined using entropy method and flexural strength has got the maximum of 50% weightage followed by flexural strain with 45% weightage and very lowest weightage of 5% is obtained for specimen weight.
- Two different multi response optimization techniques such as GRA and TOPSIS have been adopted in the present study. In case of GRA method, the 9th experimental trail which has the combination of A3B3C2D1 holds the top ranking for MRPI value and in case of TOPSIS method 3rd experimental trail having the combination A1B3C3D3 takes first rank due to the highest ranking of closeness coefficient.
As per GRA method the MRPI level totals of individual parameter recommends the combination A3B3C3D1 for attaining the multiple objectives of the present study and infill density is the most significant factor affecting the output response followed by slice height and shell thickness of the specimen prepared.

Through TOPSIS method, the level totals of closeness coefficient values recommends the parameter combination A1B3C3D1 and Slice height is found to be more significant factor affecting the output responses followed by infill density, shell thickness and raster angle.

The optimized parameter setting obtained through both TOPSIS and GRA methods are similar in case of the levels for factors such as infill density, shell thickness and raster angle. The level of slice height recommended by both the methods vary from each other. TOPSIS recommends with low value of slice height and GRA recommends higher value of slice height.

Results of confirmation trail conducted for the parameter combination obtained through GRA and TOPSIS method have been compared and It is observed that the specimen weight is similar from both the parameter settings with 34 grams as the infill density recommended by both the method is 75%.

The flexural strength is higher in case of the specimen prepared through TOPSIS method as low slice height value is considered. The printing time and flexural strain is also higher.

The flexural strength, flexural strain and printing time is lower in case of the parameter combination recommended by GRA method due to the recommendation of higher slice height value..

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