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Comparative Analysis Based on MCDM Optimization of Printing Parameters Affecting Compressive and Tensile Strength of Fused Deposition Modelling Processed Parts

Abhishek Barua[1], Siddharth Jeet[2], Dilip Kumar Bagal[3], Pulkit Kumar Agrawal[4], Ajit Kumar Pattanaik[5]

[1,2]*Department of Mechanical Engineering,*
Centre for Advanced Post Graduate Studies, BPUT, Rourkela, Odisha, 769004, India
[3,4,5]*Department of Mechanical Engineering,*
Government College of Engineering, Kalahandi, Bhawanipatna, Odisha, 766002, India

Abstract— Fused deposition modelling (FDM) is a fast budding rapid prototyping (RP) technology due to its ability to manufacture functional parts with complex geometrical shapes in reasonable build time without any tooling requirement and human interface. It has a complex part building contrivance making it challenging to obtain reasonably noble functional relationship among responses and process parameters. The properties of FDM built parts i.e. dimensional accuracy, surface roughness, mechanical strength etc. and above all functionality of built parts exhibit high dependence on many process variables and their settings. Present study determines the relationship between five important process parameters such as layer thickness, orientation, raster angle, raster width and air gap have been considered to study their effects on compressive strength and tensile strength of the built part. Twenty-seven experiments have been conducted using Taguchi's design and two different optimizations has been used i.e. MOORA technique and Utility concept. Finally, the confirmation test was carried out to validate the obtained results and the models are validated using analysis of variance (ANOVA).

Keywords— Rapid Prototyping, Fused Deposition Modelling, Mechanical strength, MOORA, Utility Concept

I. INTRODUCTION

Decline of product improvement cycle time is a chief concern in industries to remain competitive in the marketplace and hence, focus has shifted from traditional product development methodology to rapid fabrication techniques like rapid prototyping (RP). Fused deposition modelling (FDM) is a rapid prototyping (RP) technology that fabricates parts by piling and bonding layers in one direction. This method uses heated thermoplastic filaments which are extruded from the tip of nozzle in a prearranged manner on before deposited layer to build the parts layer by layer [1-4]. For wide-ranging manufacturing applications, the FDM processed parts sometimes become unsuitable because surface finish is unsurprisingly extremely rough, especially on the inclined surfaces of the parts. As a result, considerable efforts have been dedicated by numerous researchers to improve the surface finish of the parts. In broad continuum of RP, investigators have proposed many experimental models through experimental data analysis. A critical analysis of literature reveals that most of the surface roughness models consider layer thickness and build orientation neglecting many other parameters involved during actual part building stage [1-7].

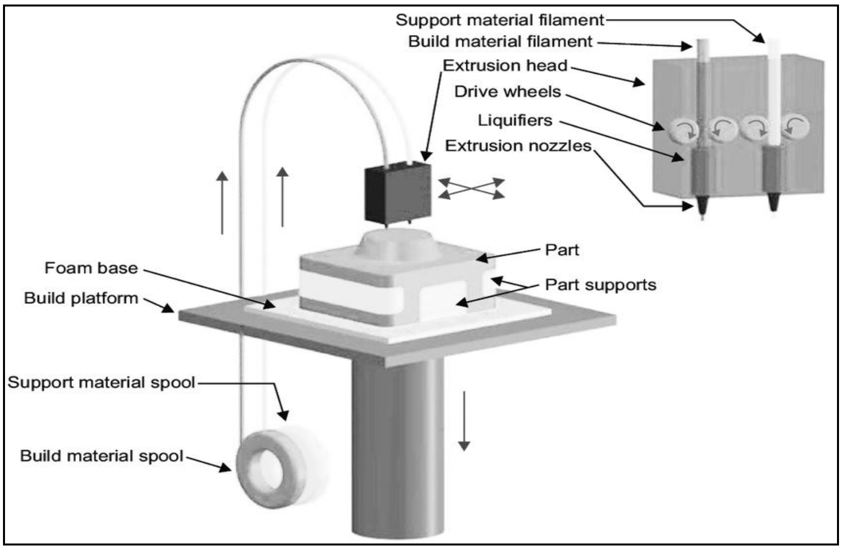

Fig. 1 FDM process

The present study focus on assessment of compressive strength and tensile strength of part fabricated using fused deposition modelling (FDM) technology. The whole experimentations are planned in Taguchi method using L27 Orthogonal array. From the experimental data, the process parameters such as layer thickness, part build orientation, raster angle, raster width, and air gap which significantly influence the dimensional accuracy and mechanical strength of processed part are to be optimized. Therefore, the present study considers the same process parameters as above to study their effect on compressive strength and tensile strength and subsequent optimization of process parameters to maximize the responses using Taguchi based Utility concept and MOORA technique for multi-objective optimization of part build characteristics.

II. EXPERIMENTAL ANALYSIS AND METHODOLOGY

A. Material Used for Fabrication

The material used for test specimen fabrication is acrylonitrile butadiene styrene (ABS M30). It contains 90-100% acrylonitrile/butadiene/styrene resin and may also contain mineral oil (0-2%), tallow (0-2%) and wax (0-2%). Acrylonitrile is a synthetic monomer produced from propylene and ammonia; butadiene is a petroleum hydrocarbon obtained from the C4 fraction of steam cracking; styrene monomer is made by dehydrogenation of ethyl benzene - a hydrocarbon obtained in the reaction of ethylene and benzene. ABS is made by polymerizing styrene and acrylonitrile in the presence of poly-butadiene. The result is a long chain of poly-butadiene criss-crossed with shorter chains of poly (styrene-co-acrylonitrile). ABS-M30 is 25-70% stronger, has greater tensile, impact and flexural strength than standard ABS. Layer bonding is significantly stronger than that of standard ABS M30, an ideal material for conceptual modelling, functional prototyping, manufacturing tools and production parts.

TABLE I
PROPERTIES OF COMMERCIALLY AVAILABLE ABS M30

Parameter	Value
Density	1040 kg/m^3
Hardness Rockwell	109.5 HRC
Tensile Strength, Ultimate	36 MPa
Tensile Strength, Yield	32 MPa
Modulus of elasticity	2.413 GPa
Elongation at Break	7 %
Layer thickness	0.18 - 0.25 mm

B. Specimen Fabrication

The 3D models of specimens are generated using CATIA V5 R21 solid modelling software and exported as STL file to FDM software (Insight). Here, factors are set as per experiment plan. Software breaks the STL model into individual slices and generate tool path. After this, data is sent to the FDM hardware for modelling. The article forming material (ABS M30), in the form of a flexible strand of solid material is supplied from a supply source spool to the head of the machine. Specimens are fabricated using FORTUS 400mc machine for respective characteristic measurement.

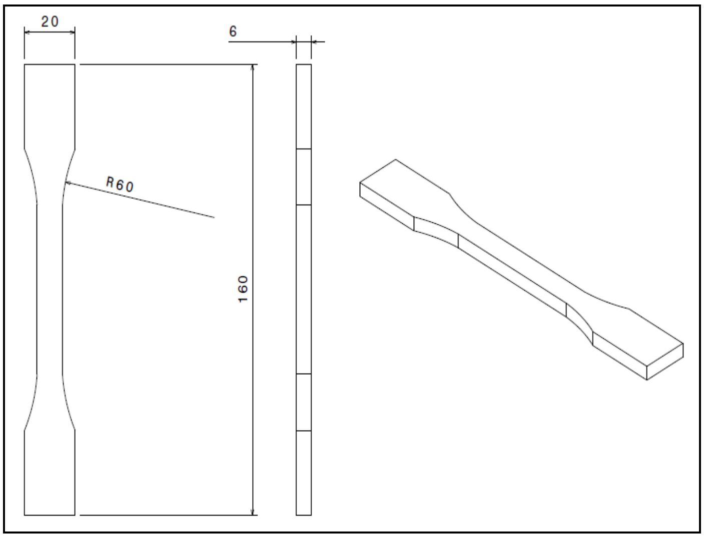

Fig. 2 Dimension of the test specimen (mm)

C. Design of Experiments

Here, five parameters of FDM process namely, layer thickness, orientation, raster angle, raster width, and air gap are identified as significant factors and hence are selected to study their influence on output responses. The levels of factors are selected in accordance with the permissible minimum and maximum settings recommended by the equipment manufacturer, experience, and real industrial applications. Fixed parameters and control parameters are provided in Table II and Table III respectively.

TABLE II
FIXED PARAMETERS [1-7]

Parameter	**Value**
Part fill style	Perimeter/raster
Counter width	0.4064 mm
Part interior style	Solid normal
Visible surface	Normal raster
X Y & Z shrink Factor	1.0038
Perimeter to raster air gap	0.0000 mm

TABLE III
CONTROL PARAMETERS & THEIR LEVELS [1-7]

Parameters	**Symbol**	**Levels**		
		1	**2**	**3**
Layer thickness	A	0.127 mm	0.178 mm	0.254 mm
Orientation	B	0^0	15^0	30^0
Raster angle	C	0^0	30^0	60^0
Raster width	D	0.4064 mm	0.4654 mm	0.5064 mm
Air Gap	E	0.000 mm	0.004 mm	0.008 mm

The tensile test of the test specimens was executed using "Instron 1195 series IX" automated material testing system with crosshead speeds of 1 mm/s. Similarly, compressive strength at break of the test specimens was done using same machine used for tensile test with crosshead speed of 2 mm/min and full scale load range of 50 KN [3, 5].

D. Multi objective optimization on the basis of the ratio analysis method (MOORA)

The MOORA method (Multi objective optimization on the basis of the ratio analysis) has been used to disregard unsuitable substitutions by selecting the most appropriates an also by collation the selection parameter. It is a decision making method, where the objectives were restrained for every pronouncement of outcomes from a set of available alternatives. The MOORA method can be functional in numerous forms of complex multi objective optimization problems. In MOORA method the recital of the diverse output responses is arranged in a decision matrix as specified in Equation (i) [10, 11].

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdot\cdot & \cdot\cdot & x_{1n} \\ x_{21} & x_{22} & \cdot\cdot & \cdot\cdot & x_{2n} \\ :: & :: & :: & :: & :: \\ x_{m1} & x_{m1} & \cdot\cdot & \cdot\cdot & x_{mn} \end{bmatrix} \qquad \text{(i)}$$

Where, x_{ij} is the performance measure of the i^{th} alternative on j^{th} attribute, *m* is the number of alternatives, and *n* is the number of attributes.
A ratio system will be formed by normalizing the data of decision matrix which can be calculated by using the equation (ii).

$$x_{ij}^{*} = x_{ij} / \left[\sum_{i=1}^{m} x_{ij}^{2}\right]^{\frac{1}{2}} \qquad (j = 1, 2, \ldots\ldots n) \qquad \text{(ii)}$$

Where, x_{ij}^{*} represents the normalized value *x* which is a dimensionless number which lies between 0 and 1 i^{th} alternative on j^{th} attribute.
After that, the normalized value will be added for maximization problem or subtracted in case of minimization problems. In some cases, some of the attributes have more importance than others, and to deliver even more importance to these attributes, they are multiplied by their corresponding weight. After the consideration of weight, the equation will be:

$$y_i = \sum_{j=1}^{g} w_j x_{ij}^{*} - \sum_{j=g+1}^{g} w_j x_{ij}^{*} \qquad \text{(iii)}$$

where, *g* is the maximized number of attribute, (n-g) is the attributes to be minimized and w_j is the weight of j^{th} attribute. y_i is the normalized assessment value of the i^{th} alternative relating to all the attributes. After calculation of normalized assessment value, ranking of y_i is done from highest to lowest value to know the best alternate among the entire attributes. Thus, highest y_i value is the best alternative among all since ranking of the y_i is the final preference. [10, 11].

E. Utility concept

Utility can be defined as the convenience of an object in response to the prospects of the users. It is the measure of the characteristic of an artefact to meet the users' requirements. The overall usefulness of an object can be represented by a unified index termed as utility which is the sum of the individual performance characteristics attributes of a particular product [12-19].

If y_j is the measure of performance of jth attribute (criterion) and there are n alternatives in the entire selection space, then the joint utility function can be expressed as [12-19]:

$$U(y_1, y_2, \ldots, y_n) = f(U_1(y_1), U_2(y_2), \ldots, U_n(y_n)) \qquad \text{(iv)}$$

where $U_j(y_j)$ is the utility of jth attribute and n is the number of evaluation criteria. The overall utility function is the sum of individual utilities if the attributes are autonomous, and is given as follows:

$$U(y_1, y_2, \ldots, y_n) = \sum_{j=1}^{n} U_j(y_j) \qquad \text{(v)}$$

The overall utility function after assigning weights to the attributes can be expressed as:

$$U(y_1, y_2, \ldots, y_n) = \sum_{j=1}^{n} w_j U_j(y_j) \qquad \text{(vi)}$$

A preference scale for each attribute is constructed for defining its utility value. The predilection numbers vary from 0 to 9 (denoting the lowest and highest performance value). Thus, a preference number of 0 represents the just suitable attribute and the best value of the attribute is denoted by preference number 9 [12-19]. The preference number (P_j) for jth attribute can be stated on a logarithmic scale as follows:

$$P_j = A_j \times \log\left(\frac{y_j}{y_j'}\right) \qquad \text{(vii)}$$

where y_j and y_j' are the observed and the just acceptable values, and A_j is a constant for jth attribute. For y_j', the minimum value is taken for beneficial criteria, while the maximum value is considered for non-beneficial criteria. The value of A_j can be found by the condition that if $y_j = y_j^*$ (where y_j^* is the best value for jth attribute), then $P_j = 9$ [12-19]. Therefore,

$$A_j = \frac{9}{\log\left(\frac{y_j^*}{y_j'}\right)} \qquad \text{(viii)}$$

The overall utility value (U) can now be computed as follows:

$$U = \sum_{j=1}^{n} w_j P_j \quad \text{subject to the constraint that } \sum_{j=1}^{n} w_j = 1 \qquad \text{(ix)}$$

III. RESULTS AND DISCUSSIONS

Samples are prepared by using Taguchi's experimental design which is shown in Table IV. As per design of experiment, 27 experimental runs are carried out in FDM setup. After experimentation the Compressive Strength and Tensile strength are recorded in Table IV along with the L27 orthogonal array of input parameters.

TABLE IV
ORTHOGONAL ARRAY L27 OF THE EXPERIMENTAL RUNS AND RESPONSES

Expt. No.	A	B	C	D	E	Compressive Strength (Mpa)	Tensile Strength (Mpa)
1.	0.127	0	0	0.4064	0	12.98	14.34
2.	0.127	0	0	0.4064	0.004	11.92	13.28
3.	0.127	0	0	0.4064	0.008	12.88	13.29
4.	0.127	15	30	0.4654	0	14.02	16.64
5.	0.127	15	30	0.4654	0.004	12.96	15.58
6.	0.127	15	30	0.4654	0.008	13.91	15.60
7.	0.127	30	60	0.5064	0	16.07	16.24
8.	0.127	30	60	0.5064	0.004	15.01	15.18
9.	0.127	30	60	0.5064	0.008	15.97	15.19
10.	0.178	0	30	0.5064	0	12.11	14.26
11.	0.178	0	30	0.5064	0.004	11.05	13.20
12.	0.178	0	30	0.5064	0.008	12.00	13.22
13.	0.178	15	60	0.4064	0	13.36	15.11
14.	0.178	15	60	0.4064	0.004	12.30	14.05

15.	0.178	15	60	0.4064	0.008	13.25	14.06
16.	0.178	30	0	0.4654	0	13.66	15.78
17.	0.178	30	0	0.4654	0.004	12.60	14.72
18.	0.178	30	0	0.4654	0.008	13.55	14.73
19.	0.254	0	60	0.4654	0	12.42	13.39
20.	0.254	0	60	0.4654	0.004	11.36	12.33
21.	0.254	0	60	0.4654	0.008	12.32	12.34
22.	0.254	15	0	0.5064	0	12.41	14.50
23.	0.254	15	0	0.5064	0.004	11.35	13.45
24.	0.254	15	0	0.5064	0.008	12.31	13.46
25.	0.254	30	30	0.4064	0	12.68	14.44
26.	0.254	30	30	0.4064	0.004	11.62	13.38
27.	0.254	30	30	0.4064	0.008	12.57	13.39

A. Optimization using MOORA Technique

Now, MOORA optimization method is applied to find out the optimal parameters for FDM process. The normalization of the output responses is done conferring to Equation (ii). After that the normalized assessment values were calculated. Equal percentage of weight is considered for compressive strength and tensile strength and the sum of all the weights will be 1. The MOORA overall assessment value is calculated using equation (iii) and ranked according to the highest value of the overall assessment value. Table 5 shows the shows the normalized assessment values of the responses and overall assessment value and their ranking according to the highest value.

TABLE V
NORMALIZED INDIVIDUAL ASSESSMENT VALUES AND OVERALL ASSESSMENT VALUE

Run No.	Compressive Strength	Tensile Strength	y_i	Rank
1.	0.0963	0.0964	-0.0001	12
2.	0.0885	0.0893	-0.0008	13
3.	0.0955	0.0894	0.0061	5
4.	0.1040	0.1119	-0.0079	25
5.	0.0962	0.1048	-0.0086	26
6.	0.1032	0.1049	-0.0017	14
7.	0.1192	0.1092	0.0100	2
8.	0.1114	0.1021	0.0093	3
9.	0.1185	0.1022	0.0163	1
10.	0.0898	0.0959	-0.0061	22
11.	0.0820	0.0888	-0.0068	24
12.	0.0890	0.0889	0.0001	11
13.	0.0991	0.1016	-0.0025	15
14.	0.0912	0.0945	-0.0032	17
15.	0.0983	0.0946	0.0037	6
16.	0.1013	0.1061	-0.0048	19
17.	0.0935	0.0990	-0.0055	21
18.	0.1005	0.0991	0.0015	8
19.	0.0922	0.0900	0.0021	7
20.	0.0843	0.0829	0.0014	9
21.	0.0914	0.0830	0.0084	4
22.	0.0921	0.0975	-0.0054	20
23.	0.0842	0.0904	-0.0062	23
24.	0.0913	0.0905	0.0008	10
25.	0.0940	0.0971	-0.0031	16
26.	0.0862	0.0900	-0.0038	18
27.	0.0466	0.0901	-0.0435	27

In the above table, it can be seen that by using the MOORA method for a particular values of input parameter in experiment no. 9 has the highest overall assessment value. Therefore, experiment no. 2 is an optimal parameter combination for FDM build part. Hence, factor setting with Layer thickness (A), part orientation (B), Raster angle (C), raster width (D), air gap (E) should be maintained at 0.127mm, 30^0, 60^0, 0.5064mm, 0.008mm respectively can be recommended for maintaining a higher compressive strength and tensile strength of the FDM build part according to MOORA technique optimization.

B. Optimization using Utility Concept

For optimization of FDM process parameters using Utility concept, first equations (vii) and (viii) was used to construct the preference scales for compressive strength and tensile strength.

1) *For compressive strength,*
X*: Optimum value of compressive strength 16.071 MPa
X': Minimum acceptable value of compressive strength 11.05 MPa
(assumed, as all the observed values of compressive strength in Table V are in between 11.05 and 16.07).
Using these values and equations (vii) and (viii), the preference scale for compressive strength is,

$$P_{compressive} = 55.2654 \log(X_{compressive}/11.05) \qquad (x)$$

2) *For construction of preference scale for tensile strength*
X*: Optimum value of tensile strength 16.7109 MPa
X': Minimum acceptable value of tensile strength 12.33 MPa
(assumed, as all the observed values of tensile strength in Table V are in between 12.33 and 16.64).
Using these values and equations (vii) and (viii), the preference scale for tensile strength is,

$$P_{tensile} = 68.2097 \log(X_{tensile}/12.33) \qquad (xi)$$

3) *The weights to the selected quality characteristics have been assigned as*
$W_{compressive}$: Weight assigned to compressive strength (0.5)
$W_{tensile}$: Weight assigned to tensile strength (0.5)

The value of the overall utility value has been calculated using the equation (ix). Table VI shows the Utility data calculate using above equations.

TABLE VI
UTILITY DATA BASED ON MULTIPLE RESPONSES

Sl. No.	Preference number (P_j)		Utility Value (U)
	Compressive Strength	Tensile Strength	
1.	3.8752	4.4629	4.1691
2.	1.8330	2.1928	2.0129
3.	3.6772	2.2193	2.9482
4.	5.7192	8.8767	7.2979
5.	3.8341	6.9314	5.3827
6.	5.5358	6.9539	6.2449
7.	8.9999	8.1547	8.5773
8.	7.3641	6.1597	6.7619
9.	8.8401	6.1829	7.5115
10.	2.1971	4.3051	3.2511
11.	0.0000	2.0224	1.0112
12.	1.9846	2.0490	2.0168
13.	4.5557	6.0112	5.2835
14.	2.5730	3.8610	3.2170
15.	4.3632	3.8860	4.1246
16.	5.0947	7.3007	6.1977
17.	3.1579	5.2453	4.2016
18.	4.9066	5.2692	5.0879
19.	2.8169	2.4375	2.6272
20.	0.6784	1.4854	1.0817
21.	2.6099	0.0284	1.3191
22.	2.7975	4.8036	3.8006
23.	0.6572	2.5605	1.6089
24.	2.5904	2.5866	2.5885
25.	3.3014	4.6741	3.9878
26.	1.2076	2.4208	1.8142
27.	3.0986	2.4470	2.7728

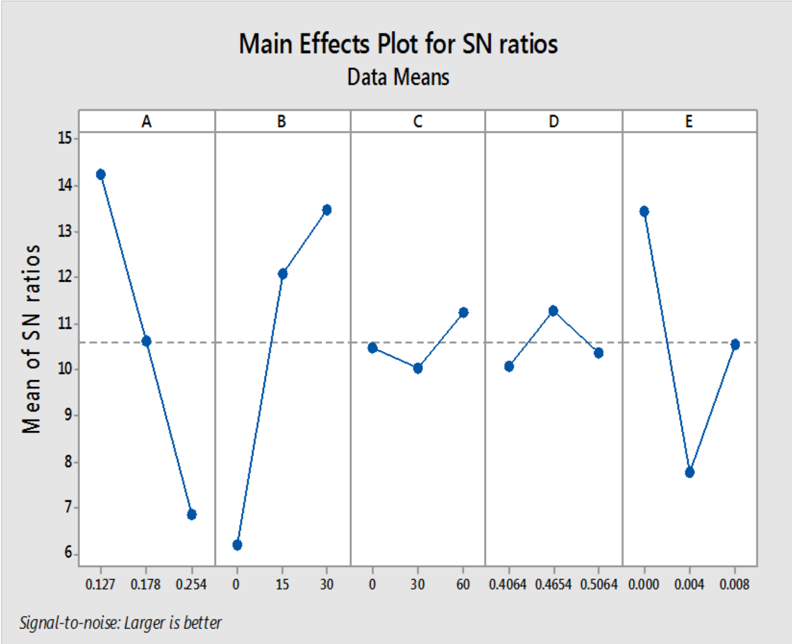

Fig. 3 SN-ratio graph with factors and their levels

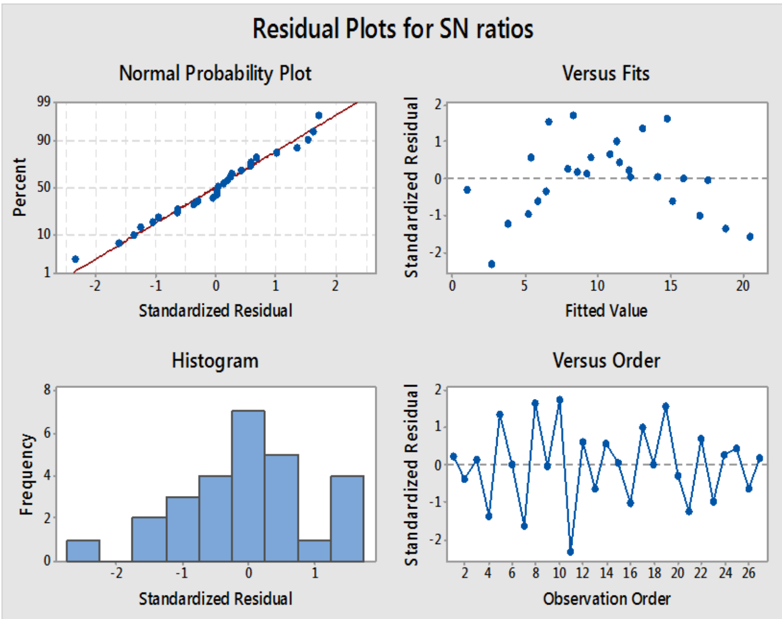

Fig. 4 Residual plot for SN-ratio graph

TABLE VII
THE RESPONSE TABLE FOR UTILITY VALUE

Level	A	B	C	D	E
1	14.272	6.197	10.478	10.092	13.431
2	10.643	12.078	10.030	11.302	7.778
3	6.835	13.475	11.242	10.356	10.541

Delta	7.437	7.277	1.212	1.209	5.653
Rank	1	2	4	5	3

Figure 3 shows the SN-ratio plot for the Utility value value for the levels of the FDM process parameters. Essentially, the larger the Utility value, the better is the multiple performance characteristics. In Table VII and Fig. 3, the combination of A1, B3, C3, D2 and E1 shows the largest value of the SN ratio for the factors A, B, C, D and E respectively. Therefore, A1 B3 C3 D2 E1 i.e. Layer thickness of 0.127 mm, part orientation of 30^0, Raster angle of 60^0, raster width of 0.4654mm and air gap of 0.0004mm is the optimal parameter combination for improving compressive strength and tensile strength of the FDM build part.

Table VIII gives the results of the analysis of variance (ANOVA) for the calculated values of Utility factor of compressive strength and tensile strength. According to Table 8, factor B, part orientation with contribution of 37.91 % is the most significant controlled parameters for fabrication of FDM processed part followed by factor A, Layer thickness with 35.15%, factor E, air gap with 20.31%, factor D, raster width with 1.03% and factor C, Raster angle with 0.95% of contribution if the maximization of compressive strength and tensile strength are simultaneously considered.

S = 1.436   R-Sq = 95.3%   R-Sq(adj) = 92.4%

TABLE VIII
ANOVA RESULT FOR UTILITY FACTOR

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%
A	2	248.941	124.471	60.39	0.000	35.15
B	2	268.467	134.234	65.13	0.000	37.91
C	2	6.755	3.378	1.64	0.225	0.95
D	2	7.281	3.641	1.77	0.203	1.03
E	2	143.837	71.918	34.90	0.000	20.31
Error	16	32.976	2.061			4.66
Total	26	708.257				

C. Confirmation Experiment

The confirmation experiments were conducted using the optimum combination of the FDM process parameters obtained from Taguchi analysis. These confirmation experiments were used to predict and validate the improvement in the quality characteristics for FDM build part. The optimal conditions using Utility concept is A1 B3 C3 D2 E1 respectively. The final phase is to verify the predicted results by conducting the confirmation test. The estimated utility factor can be determined by using the optimum parameters as

$$\mu_{predicted} = a_{2m} + b_{1m} - 3\mu_{mean} \quad \text{(xii)}$$

where a_{2m} and b_{1m} are the individual mean values of the utility factor with optimum level values of each parameters and μ_{mean} is the overall mean of utility factor. The predicted mean ($\mu_{predicted}$) at optimal setting is found to be 8.9360.

TABLE IX
CONFIRMATORY TEST RESULTS

Optimization technique	Optimal setting	Predicted Optimal S/N ratio	Experimental Optimal S/N ratio
Desirability Function Analysis	A1 B3 C3 D2 E1	8.9360	8.4573

From the confirmation experiment performed with the same experimental setup, it may be noted that there is good agreement between the estimated value and the experimental value for Utility concept approach. Hence, the obtained parameter setting of FDM process can be treated as optimal. Here, it can be found that the part orientation is influencing on the compressive strength and tensile strength of FDM processed part.

IV. CONCLUSIONS

In this study, the FDM process was used to fabricate Acrylonitrile-Butadiene-Styrene (ABS M30) parts. The process parameters were optimized at a common level setting using MOORA technique and Utility concept. Purposeful relationship between process parameters and the responses (compressive strength and tensile strength) for FDM built parts has been established using both the optimization techniques. Based on experiment studies carried out for selecting optimum combination of process parameters for FDM part, some of the important conclusions are as follows-

1) The optimal levels of process parameters for maximum compressive strength and tensile strength for FDM processed part are shown in table X. It is interesting to observe that after applying both the optimization technique, layer thickness, part orientation and Raster angle have same setting of 0.127 mm, 30^0, 60^0 respectively.

TABLE X
OPTIMAL PARAMETERS USING TWO OPTIMIZATION METHODS

	MOORA Technique	**Utility Concept**
Layer thickness	0.127 mm	0.127 mm
Orientation	30^0	30^0
Raster angle	60^0	60^0
Raster width	0.5064 mm	0.4654 mm
Air Gap	0.008 mm	0.000 mm

2) To control the compressive strength and tensile strength of the FDM built part, the contribution of part orientation is largest in comparison with other process parameters.
3) The equation for predicting multi-response performance index is validated by conducting confirmation experiment.

The present study has perceived that part orientation is the chief controlling factor for attaining higher compressive strength and tensile strength. Thus, this study opens up further scope of optimization of the Fused Deposition Modelling characteristics with a larger number of process parameters, along with their influences on convoluted geometrical parts, for attaining a better part fabrication superiority more rapidly.

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