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Parametric Optimization Study of ABS Material Using FDM Technique for Fatigue Life Prediction

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Abstract - Additive Manufacturing (AM) techniques have received more attention in today's manufacturing scenario due to its fascinating benefits to design and manufacturing engineers like no requirement of process planning and tool design, reduced lead time and highly skilled labour for its operation. The work presented in this paper, mainly focuses on optimizing the FDM process parameters for the Taguchi's L_9 Orthogonal Array based 3D printed ABS plastic subjected to rotating bending fatigue test. The three different parameters Infill Density, Layer Height and Print speed are considered for optimization. The results obtained from the experimental work are analyzed by Taguchi based Grey Relational Analysis procedure to find out the optimum process setting and the most significant factor over the output responses. The calculated values of MRPI by GRA have shown the optimum process setting for high Fatigue Strength with A1B3C3 (0.1 mm Layer Thickness, 80% Infill Density and a Print Speed of 75 mm/s).Through ANOVA it is observed that Layer Thickness is found to be most significant factor with contribution of 52.78% and Printing Speed is the insignificant factor over the output responses from the selected input variables.

Index Terms : ABS, Failure Cycles, Fused Deposition Modeling, Grey Relational Analysis, Rotating Bending Fatigue Test

1. INTRODUCTION

1.1 Fused Deposition Modelling (FDM)

Fused **D**eposition **M**odelling (FDM) is the low cost solid based rapid prototyping technique developed by Scott Crump in 1988 and the patent was awarded by USA in 1992. Stratsys Inc an USA based firm which leads in supplying FDM machineries with different ranges in according to the market need. As per the Global Scenario of Fused Deposition Modelling, Stratasys has got more than 60% market share of FDM in India and having more than 200+ FDM Systems Installed in Indian Market in various segments like Education, Defense, Government, Automotive, Aerospace, Consumer Goods and Heavy Industries. Balance 30% market share is of other RP Technologies. The Figure1 shows the percentage use of RP technology in various domains worldwide [1].

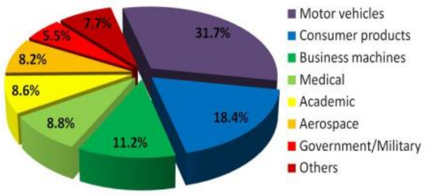

Figure1: Percentage Use of RP Technology World-wide

The principle of FDM is based on surface chemistry, thermal energy and layer manufacturing technology. Fused Deposition Modeling (FDM) is second most widely used rapid prototyping technology, after Stereolithography (uses laser). In FDM a plastic filament is unwound from a coil and supplies material to an extrusion nozzle which moves over the table in the required geometry and deposits a thin bead of extruded plastic to form each layer of the required geometry [2].The process involves many parameters such as Layer Height, Raster Width, Raster Angle, Infill Density, Envelope Temperature, Tip Diameter, Volumetric Flow Rate, Deposition Speed and so on. The FDM process can print the part in three different directions X (Horizontal) ,Y (Flat) and Z (Upright) and it can also print a part at an inclined position by providing support structures to the main part. The built orientation has a strong influence over the final properties of the part printed. The FDM process is compatible in printing various materials including ABS, PC, PC-ABS blend and PolyPhenylSulfone (PPSF). The 3D model of the object is created by using any solid modelling software and it is taken as an input by the slicing software which converts the model into layers for printing. The slicing software prepares the G – code according to the input model and the machines print the model as per the G code. The present study considers Acronitrile Butadiene Styrene (ABS) material in the form of filament in Blue color for specimen preparation which has a density of 1.04 g/cm^3 , with Young's modulus value of 1031 MPa and 6.5 MPa as tensile strength [3]. FDM parts are tougher and more durable than those produced by SLA. ABS parts are sufficiently resistant to heat, chemicals, and moisture that allows FDM parts to be used for limited to extensive functional testing, depending upon the application [4].

2. LITERATURE SURVEY

Ludmila Novakova et.al [4] 2012 have studied and reported the basic and advancement in the materials used for FDM process. The authors have stated that the basic materials for FDM process includes ABS plus, ABS-M30 , PC-ABS , PPSF and so on . They also reported that the FDM technique also uses some advanced metallic and ceramic materials for 3D printing includes Silicon Oxide, PZT, Aluminum Oxide, Hydroxypatite and Stainless Steel. Lamborghini is one customer which uses FDM technique to manufacture car parts with advanced FDM materials.

Sandeep Raut et.al[5] 2014 investigated the effect of FDM process parameters on mechanical properties and total cost of FDM parts. The authors have considered built orientation to find its effect over the mechanical properties such as tensile strength and bending strength or flexural strength. The authors have observed and concluded that parts built with Y-axis at 0° built orientation has good tensile strength and minimum cost and the parts fabricated with X-axis at 0° orientation has good flexural strength and medium cost.

Fahraz Ali et.al [6] 2014 have studied the effect of seven different FDM parameters such as Slice height, road width, raster angle, number of contours, air gap, STL deviation and angle over the parameters like build time , material usage and surface roughness of FDM built part. The authors have used L18 Orthogonal Array to build the parts by FDM and they have plotted Signal to Noise ratio for the results obtained and found the optimum values for all the seven different parameters. The authors have concluded that in order to minimize model build time larger slice height of 0.2540 mm , larger road width 0.6604 mm and positive air gap was more effective. The optimal values for build time, support and model material consumption are 13 minutes, 0.737 cm^3 and 10.799 cm^3, respectively. The optimal experimental values can bring a savings of 67% for model build time, 25% for support material, 33% for model material and 80% improvement of surface quality.

N.Mohammed Raffic et.al [7] 2017 have studied the effect of FDM process parameters on vibration properties of PET-G and ABS plastics. The authors have considered Infill Density, Layer Thickness and Printing Speed with two different levels and created L_4 Orthogonal Array using Minitab. The authors have prepared a specimen in rectangular shape and conducted impact hammer testing. The authors have observed that the changes in FDM parameters have shown considerable effect in frequency and amplitude of the specimen. The authors have concluded that for ABS material 50 % Infill density , Layer thickness 0.15 mm and 55 mm/s speed are the optimized values and for PET-G 100 % Infill density , Layer thickness 0.20 mm and 55 mm/s speed is optimum.

Madhuri Chaudhari et.al [8] 2018 have reported about the comparative study of parts built using FDM by varying Layer thickness , Infill density , Built orientation and Post processing treatment. By using those four parameters with three different levels L_9 Orthogonal Array is prepared and measured the surface finish of the specimens produced. The authors have plotted S/N ratio for PRSR Ra, Time and Cost. The authors have concluded that the use of soluble support is best suited compared to other methods for printing critical shaped models. In case of increase in productivity layer thickness 0.30 mm and 20 % infill density can be adopted and for less cost cold vapour treatment is best suited.

3. MECHANICAL TESTING

Mechanical testing of components is highly essential to ensure the reliability and durability of the parts produced by any manufacturing process. The various mechanical properties of any part that has to be verified are Tensile Strength, Compressive Strength , Fatigue Strength , Impact Strength and so on .The values of such parameters are generally evaluated by conducting experimental work rather than by using analytical methods. In the present study the number of failure cycles of a 3D printed ABS plastic specimen is considered for study. In order to evaluate the above said parameter one of the standard test called Rotating Bending Fatigue test may be conducted.

The term Fatigue can be understood when structures are subjected to repeated cyclic loadings for a long period and it can undergo progressive damage which shows itself by the formation and propagation of cracks. This damage is called fatigue and is represented by a loss of resistance with time. One familiar testing method to understand fatigue failure is rotating bending fatigue test. In rotating bending fatigue test to create a failure on the specimen, a constant-stationary force is applied on the specimen, which creates a constant bending moment. A stationary moment applied to a rotating specimen causes the stress at any point on the outer surface of the specimen to go from zero to a maximum tension stress, back to zero and finally to a compressive stress. Thus, the stress state is one that is completely reversed in nature.

4. ORTHOGONAL ARRAYS (OA)

Taguchi Orthogonal Array (OA) design is a type of general fractional factorial design. It is a highly fractional orthogonal design that is based on a design matrix proposed by Dr. Genichi Taguchi and allows you to consider a selected subset of combinations of multiple factors at multiple levels. Taguchi Orthogonal arrays are balanced to ensure that all levels of all factors are considered equally. For this reason, the factors can be evaluated independently of each other despite the fractionality of the design. In the present study three different parameters Layer Thickness (LT), Infill Density (ID) and Print Speed (S) are considered with three different levels. Hence 3^3 is the type of 3 Level design with three factors involved and L_9 Orthogonal Array is considered. The Table1 shows the L_9 Orthogonal Array design for three factors with three levels.

Table1: L_9 Orthogonal Array

Trial No	A	B	C

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

5. EXPERIMENTAL WORK

5.1 Specimen Preparation

The specimens are prepared by using Makerpi machine made from china which has a build envelope of 450 x 450 x 830 mm with bed size of 200 x 200 x 480 mm. The envelope temperature is maintained between 180° - 250°. The Figure.2 shows the Photographic view of Makerpi FDM machine.

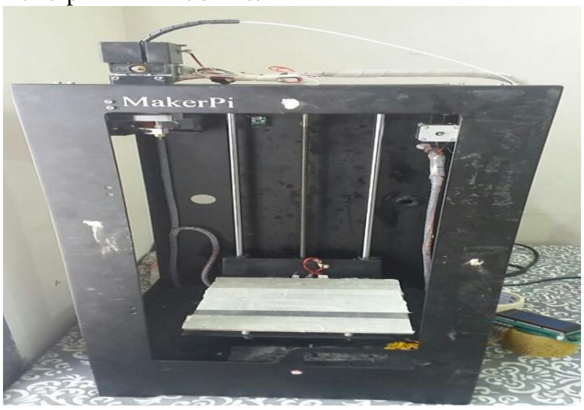

Figure2: Makerpi FDM Machine

The specimen for conducting the rotating bending fatigue test is prepared by considering three different FDM parameters such as Infill Density, Layer Height and Print Speed. The parameters are considered with three different levels and the same is being inputted to Minitab 18.0 for the preparation of Orthogonal Array (OA). L_9 (3^3) Orthogonal Array is developed with Minitab 18.0 as the parameters are considered with three different levels for preparing the specimen.

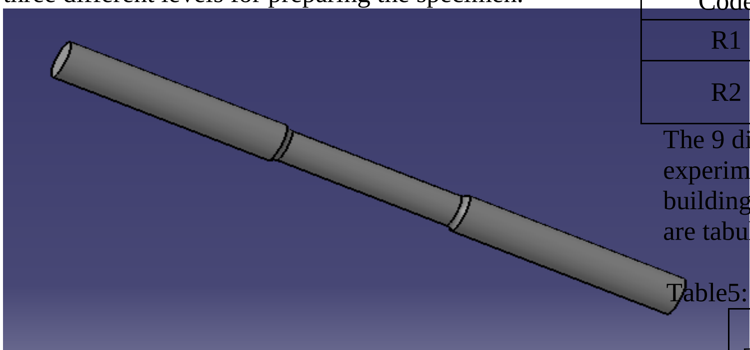

Figure3: 3D Model of Fatigue Specimen

The Table 2 Shows the 3 different printing parameters and their levels considered. The specimen is of cylindrical form with a length of 180 mm and it has two diameters 12 mm at the holding portion and 10 mm at the centre region. The 3D model of the specimen is prepared by using CATIA V5R20 which is presented in the above Figure.3.

Based upon the input given to Minitab 18.0 the software has prepared the Orthogonal Array table for preparing the specimen and the specimens are prepared following the Minitab 18.0 Orthogonal Array Table. The specimens are prepared by using ABS filament of 1.75mm diameter by extruding through the nozzle with 0.4mm diameter in FDM machine. Table 3 shows the experimental design matrix as per L9 Orthogonal Array. The output responses considered are shown in Table 4.

Table2 : FDM Process Parameters and Levels

Printing Parameter	Low Value	Medium Value	High Value
Layer Height (A) (mm)	0.1	0.2	0.3
Infill Density (B) (%)	40	60	80
Speed (C) (mm/s)	25	50	75

Table3: Experimental Design Matrix

Trial.No	A	B	C	A	B	C
1	1	1	1	0.1	40	25
2	1	2	2	0.1	60	50
3	1	3	3	0.1	80	75
4	2	1	2	0.2	40	50
5	2	2	3	0.2	60	75
6	2	3	1	0.2	80	25
7	3	1	3	0.3	40	75
8	3	2	1	0.3	60	25
9	3	3	2	0.3	80	50

Table4: Output Response Table

Response Code	Output Response	Unit
R1	Model Building Time	Mins
R2	No of Cycles to Failure	-

The 9 different specimens have been printed as per the experimental design matrix and the values of Model building Time and the cost for printing the specimen are tabulated in Table 5.

Table5: Model Building Time and Material Consumed

Trail No	Building Time (Secs)	Cost (Rs)
1	207	828

2	244	976
3	283	1132
4	103	412
5	123	492
6	143	572
7	72	288
8	86	344
9	98	392

6. EXPERIMENTAL SETUP

In the present work we have conducted a beam type test. The machine consists a DC electric motor for its operation to rotate the fatigue specimen. The machine has provision to add different loads ranging between 1Kg to 100 Kg to the specimen while rotating. The machine consist a cycle counter to count the number of revolutions that the specimen can rotate without failure. The Figure 4 shows the experimental setup used for conducting the fatigue test.

Figure 4: Experimental Setup

7. EXPERIMENTAL PROCEDURE

In the present work the 9 different 3D printed specimens are tested for the number of cycles to failure by applying a constant load of 4 Kg. The specimens are fixed in the machine and rotated. The cycle counter fixed to the rotating specimen displays the number of rotations the specimen have withstood the load applied without undergoing failure. A stop watch is used to calculate the time taken by the specimens to undergo failure. The specimens have undergone failure by breaking into two parts at different regions of the specimen. The Figure 5 (a), (b), (c) shows the images of broken specimens 1-9. The Table 5 shows the number of failure cycles for the 9 different specimens and the time taken.

Table5: Failure Cycles and Time Taken

Trial No	Number of Cycles for Failure	Time (Mins)
1	37819	482
2	54948	695
3	156200	1949
4	70439	914
5	125251	1632
6	59852	755
7	17708	132
8	49646	628
9	82236	1033

Figure5 (a): Fracture Regions of Specimen No 1, 2, 3

Figure5 (b): Fracture Regions of Specimen No 4, 5, 6

Figure5(c): Fracture Regions of Specimen No 7, 8, 9

8. ANALYSIS OF EXPERIMENTAL RESULTS

The data obtained through the specimen preparation and the experimental work are considered for statistical treatment using Taguchi approach to find out the respective influencing parameter. Taguchi's method has been extensively used by many authors to optimize the process parameters of FDM [13].Grey Relational Analysis (GRA) is a technique which is commonly used along with Taguchi's OA design data for finding out the optimal process settings. In the present work GRA is used to find the optimal process settings by adopting the following steps [14].

Step 1: Calculate the Signal to Noise Ratio (S/N Ratio) by selecting the appropriate type. In case of Model Building Time (R1), Smaller the best is preferred and for the Number of Failure Cycles (R2) Larger the best is considered.

Step 2: Convert the calculated S/N ratio to its normalized form by using the standard equations.

Table6: S/N Ratio and Normalized Values

Trial No	S/N Ratio		Normalized S/N Ratio (x_i)	
	R1	R2	R1	R2
1	-46.32	91.55	0.7712	0.3485
2	-47.75	94.80	0.8915	0.5201
3	-49.04	103.87	1.0000	1.0000
4	-40.26	96.96	0.2616	0.6342
5	-41.8	101.96	0.3911	0.8986
6	-43.11	95.54	0.5013	0.5594
7	-37.15	84.96	0.0000	0.0000
8	-38.69	93.92	0.1295	0.4735
9	-39.82	98.30	0.2246	0.7053

Table7 Deviation Sequence and Grey Relation Coefficient

Trial No	DeviationSequence $(\Delta 0)$		Grey Relation Coefficient ($\xi i(k)$)	
	R1	R2	R1	R2
1	0.2288	0.6515	0.6861	0.4342
2	0.1085	0.4799	0.8217	0.5103
3	0.0000	0.0000	1.0000	1.0000
4	0.7384	0.3658	0.4037	0.5775
5	0.6089	0.1014	0.4509	0.8314
6	0.4987	0.4406	0.5006	0.5316
7	1.0000	1.0000	0.3333	0.3333
8	0.8705	0.5265	0.3648	0.4871
9	0.7754	0.2947	0.3920	0.6292

For the Smaller-the-better (SB) condition,

$$x_i(k) = \frac{Max\ Yi(k) - Yi(k)}{Max\ Yi(k) - Min\ Yi(k)} \quad (1)$$

For the Larger-the-better (LB) condition,

$$x_i(k) = \frac{Yi(k) - Min\ Yi(k)}{Max\ Yi(k) - Min\ Yi(k)} \quad (2)$$

$x_i(k)$ = Value after Grey Relation Generation

Max $Yi(k)$ and Min $Yi(k)$ = Largest and Smallest values of $Yi(k)$ for the k ^ith^ performance

The Table 6 shows the calculated S/N ratio and its normalized value from the equations 1 and 2

Step 3: Calculate the Deviation Sequence for R1 and R2 using equation 6.3

$$\Delta 0i = x0(k) - xi(k) \quad (3)$$

Step 4: Calculate the Grey Relation Coefficient by using the standard relation

$$\xi i(k) = \frac{\Delta min + \xi \Delta max}{\Delta 0i + \xi \Delta max} \quad (4)$$

Step 5: Calculate the Grey Relation Grade and consider the same as Multiple Response Performance Index (MRPI)
Step 6: Find the average values of MRPI for the individual factors and the larger value implies the optimal parameter values and calculate the Mean MRPI to find out the optimal process settings.
Step 7: Conduct ANOVA to find out the influence of controllable factors on the responses at 5% significance level (i.e., 95 % confidence level based on *F* value and *P*-value). A P-value of < 0.05 means that the factors have high influence on the responses.
The Table 7 shows the calculated Deviation sequence and Grey Relation coefficient for the Reponses R1 and R2

The Table 8 shows the Grey Relational Grade for the respective trials

Table8: Calculated Grey Relational Grade

Trial No	GreyRelational Grade	Rank
1	0.5602	4
2	0.6660	2
3	1.0000	1
4	0.4906	7
5	0.6411	3
6	0.5161	5
7	0.3333	9
8	0.4260	8
9	0.5106	6

From the calculation of Grey Relational Grade and its ranking the trial no 3 holds the top rank and trial no 7 holds the last rank. The obtained value of GRG has to be considered as MRPI in Grey Relational Analysis method. The larger MRPI value implies the optimum process setting. The mean MRPI values are calculated to find the best level in individual factors. From the calculation of Mean MRPI it is found that A1B3C3 (0.1 mm Layer Thickness , 80% Infill Density and Print Speed 75 mm/s). The Table 9 shows the calculated Mean MRPI values.

Table 9: Mean Multiple Response Performance Index

Factors	Levels			
	1	2	3	Max-Min
A	**0.742**	0.5492	0.4233	**0.3188**
B	0.461	0.5777	**0.6755**	0.2142
C	0.501	0.5557	**0.6581**	0.1574

From the calculated MRPI values, ANOVA is conducted to find the most influencing factor among the three factors. It is observed that Layer Thickness is the most influencing factor than Infill density and Print Speed with a maximum contribution of 52.78%. The P-value of Layer Thickness and Infill density are less than 0.05 and considered to be significant factors. The print speed has got P-value less than 0.05 is considered to be insignificant as per ANOVA results. The regression equation for MRPI is used for calculating the predicted values of MRPI to plot a graph between the calculated and predicted for different trials .Table 10 shows the MRPI Experimental and Predicted values and they are in good agreement. The Table 11 shows the ANOVA results of different factors and their significances.

MRPI = 0.412 - 1.594 Layer Thickness + 0.00535 Infill Density + 0.00315 Speed (5)

Table10: MRPI Experimental and Predicted

Trial No	MRPI Exp	MRPI Predicted
1	0.56	0.55
2	0.67	0.73
3	1.00	0.92
4	0.49	0.46
5	0.64	0.65
6	0.52	0.60
7	0.33	0.38
8	0.43	0.33
9	0.51	0.52

Table11: ANOVA Results

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Cont %
A	1	0.1524	0.152418	25.1	0.004	**52.78**
B	1	0.06882	0.068822	11.33	0.02	23.83
C	1	0.03715	0.037146	6.12	0.056	12.86
Error	5	0.03036	0.006072			10.51
Total	8	0.28875				100

9. CONCLUSIONS

The following conclusions may be drawn from the experimental work and further statistical analysis carried out

1. Through Taguchi based Grey Relational Analysis the optimal process setting is found to be A1B3C3 (0.1mm Layer Thickness, 80% Infill Density and Print Speed 75 mm/s) for the higher fatigue strength of the material and Trial No 3 is found to have the same process settings which also have shown the maximum value for the number of cycles to failure.
2. The optimal settings for low model building time are found to be A3B1C1 (0.3mm Layer Thickness, 40% Infill Density and Print Speed 25 mm/s) and the time is found to be 58 mins through Ultimaker CURA software.
3. From the calculated values of Mean Multi Response Performance Index (MRPI) the Layer Thickness is found to be the most significant factor than infill density and speed.
4. As per ANOVA results , the factor A (Layer Thickness) is found to have maximum contribution of 52.78% which is in good correlation with Mean MRPI value calculated
5. ANOVA results have revealed that Layer Thickness and Infill Density are significant factors with P-value less than 0.05 and Printing Speed is found to be the insignificant factor with P-value more than 0.05.

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