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Optimizing Flexible Behaviour of Bow Prototype Using Taguchi Approach

[1]J. Laeng, [2]Zahid A. Khan and [2]S.Y. Khu
[1]School of Mechanical Engineering, The University of Western Australia,
35, Stirling Highway, Crawley, Western Australia 6009, Australia
[2]School of Mechanical Engineering, Universiti Sains Malaysia,
Engineering Campus 14300 Seri Ampangan, Nibong Tebal, Penang, Malaysia

Abstract: This study presents the application of the Taguchi method, a powerful tool to process optimization for quality, to find the optimal process parameters for Fused-deposition Modeling (FDM) rapid prototyping machine that was used to produce flexible Acrylonitrile-Butadiene-Styrene (ABS) bow and arrow prototype. In order to achieve optimum performance of the bow so as to obtain the maximum throwing distance of the arrow from it, Orthogonal Array (OA), main effect analysis, signal-to-noise (S/N) ratio and analysis of variance (ANOVA) are employed to investigate the process parameters. Through this study, not only can the optimal FDM parameter combinations to be obtained, but also the main process parameters that affect the performance of the prototype can be found. Experiments were carried out to confirm the effectiveness of this approach. From the results, it is found that FDM parameters, especially air gap, slice height and raster angle have the most significant impact on the elastic performance of the flexible ABS prototype. The optimum levels of parameters at different angle of displacement of the bow are also presented.

Key words: Rapid prototyping, flexible ABS bow and arrow, fused deposition modeling, Taguchi method

INTRODUCTION

In the development of a new product, there is a need to produce a single example or prototype of a designed part or system so that large amount of capital commitment to new production facilities or assembly lines is financially justified. A new technology which considerably speeds up the iterative product development process is the concept and practice of rapid-prototyping. Rapid-prototyping is a fast growing activity within industry. It can offer incredible time-to-market savings with all the financial benefits involved[1].

Since the introduction of the first commercial Rapid Prototyping (RP) machine widely known as Stereolithography in 1986, a wide range of RP machines have been commercialized and many more newer systems continue to be developed in various parts of the world[2]. Rapid-prototyping systems continue to become more economical and at the same time more accurate and faster as compared to the conventional processes such as casting and molding method studies have been conducted by many researchers to improve and to optimize the process, so as to obtain high quality parts produced on a wide range of commercial RP machines[3-8].

Fused-Deposition Modeling (FDM) process is an additive rapid-prototyping operation that builds the parts in layers. It builds parts slice by slice. In FDM process, a gantry-robot-controlled extruder head moves in two principal directions over a table. The table can be raised or lowered as needed. A thermoplastic or wax filament is extruded through the small orifice of a heated die. The initial layer is placed on a foam foundation by extruding the filament at a constant rate while the extruder head follows a predetermined path. When the first layer is completed, the table is lowered so that subsequent layers can be superposed[9]. Process parameters such as the air gap between adjacent tracks, raster angle, raster width, slice height of deposited layers, orientation of the part, contour width and so on, will influence the performance of parts produced on an FDM machine. Some studies have been done to determine the optimum surface finish of parts produced by FDM 1650 machine[6].

A compliant (or flexible) mechanism is a mechanism that is composed of at least one component (member) which is sensibly deformable (flexible or compliant) compared to the other rigid links[10]. The compliant mechanisms, therefore, gain their mobility by transforming an input form of energy into output motion via

Corresponding Author: J. Laeng, School of Mechanical Engineering, The University of Western Australia, 35, Stirling Highway, Crawley, Western Australia 6009, Australia
Tel: +61 8 6488 3601 Fax: +61 8 6488 1024

deformation of the body. Children toys such as sling shot and catapult are examples where compliant mechanisms are widely used. RP technologies will be widely used as the manufacturing trends are heading towards shorter product life cycles and the designs are becoming more complicated.

In this study an attempt has been made to analyze the various combinations of rapid prototyping parameters, in order to strive for the optimum performance of compliant plastic prototype. Four FDM parameters i.e., air gap, raster angle, raster width and slice height, each with three levels were investigated. Other variables such as humidity and temperature were kept constant. In the following, an overview of the Taguchi method is given followed by the description of orthogonal array experiment using the Taguchi method to determine and to analyze the optimal FDM parameters. Results are presented and finally the paper concludes with a summary of the study.

MATERIALS AND METHODS

The Taguchi method: Dr. Genichi Taguchi of Nippon Telephones and Telegraph Company, Japan, has developed a partial factorial design called Taguchi Method. This method, indeed, is a powerful tool to design optimization for high quality systems. It provides a simple, efficient and systematic approach to optimize designs for performance, quality and cost. The methodology is valuable when the design parameters are quantitative and discrete. It is a special variant of Design of Experiment (DOE) that distinguishes itself from classic DOE in the focus on optimizing design parameters to minimize variation before optimizing design to hit mean target values for output parameters. The method is applicable over a wide range of engineering fields that spans over processes and manufacture raw materials, sub-systems, products for professional and consumer markets worldwide[11-13].

The Taguchi Method uses a special design of Orthogonal Array (OA) to study the entire parameter space with a minimum number of experiments only[14,15]. This is especially vital for RP where cost to produce prototypes is still high. Based on the average output value at each parameter level, main effect analysis is performed. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the main effect and ANOVA analysis, the optimal combination of the process parameters can be predicted. Finally, a confirmation test is conducted to verify the optimal process parameters obtained from the parameter design. The blend of DOE with optimization of control parameters to obtain the best result is achieved in the Taguchi Method.

OPTIMIZATION OF FUSED DEPOSITION MODELING PARAMETERS

Selection of FDM parameters and their levels: The FDM3000 rapid prototyping machine with Insight 3.1 software was used in the study. Four parameters, each at three levels as presented in Table 1 were taken into consideration. It can be noted that raster angle is specified as 0°/90°, 45°/−45° and 30°/60° in Table 1. The 0°/90° angle means that FDM machine fabricates the alternate layers of the prototype on the horizontal plane by changing direction at 0° and 90° angles from the coordinate of the machine. Similarly, 45°/−45° and 30°/60° indicated the same deposition pattern followed by the machine. The interactions between the parameters were not considered and other factors such as temperature and humidity were kept constant. To select an appropriate orthogonal array for the experiments, the total degrees of freedom need to be determined. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. For example, a three-level process parameter counts for two degrees of freedom. The total degrees of freedom are obtained by multiplying the degrees of freedom of each process parameter to the number of parameters. Therefore, in this study, four parameters, each with three levels counted for eight degrees of freedom. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. Obviously the appropriate orthogonal array in this case was the standard L_9, with four columns and nine rows. The L_9 orthogonal array used for this study is shown in Table 2.

Table 1: FDM parameters and their levels

No.	Symbol	FDM parameter	Unit	Level 1	Level 2	Level 3
1	A	Air gap	--	Solid Fine	Sparse	Double wide
2	B	Raster angle	degree	0/90	45/-45	30/60
3	C	Raster width	mm	0.406	0.568	0.729
4	D	Slice height	mm	0.178	0.254	0.305

Table 2: Experimental layout using an L_9 orthogonal array

	L_9 (3^4)			
Experiment No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

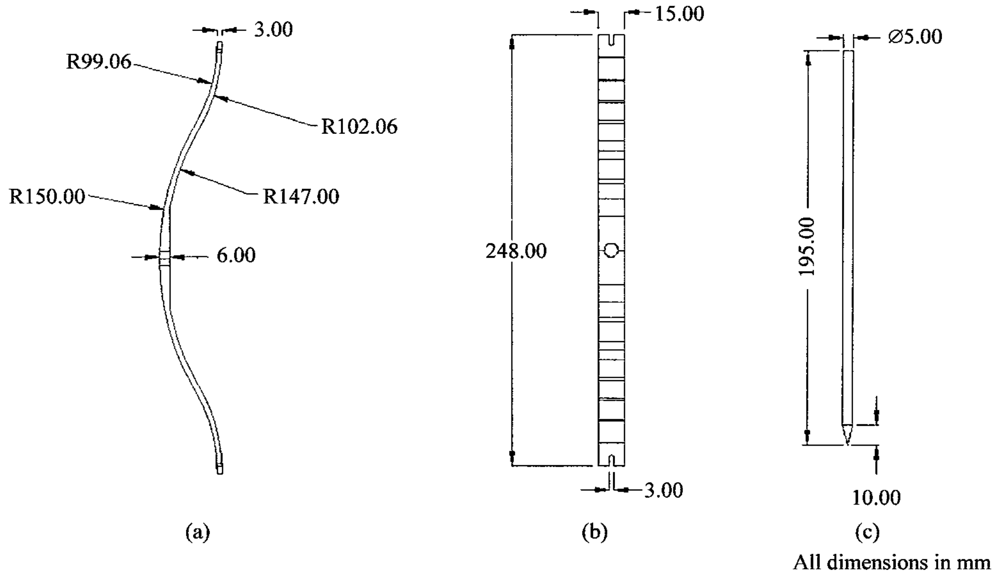

Fig. 1: a) Side view of the bow design, b: Top view of the bow design, c: Top view of the arrow design

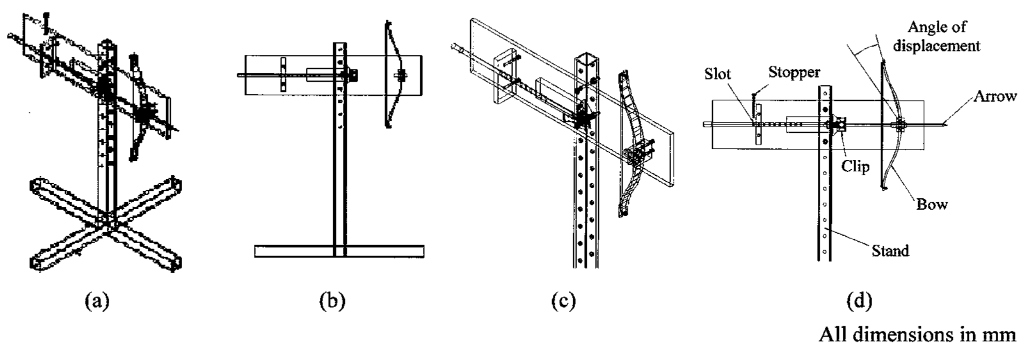

Fig. 2: a) Isometric view of the experimental setup for bow testing, b: Side view of the experimental setup for bow testing, c) Detail isometric view of the experimental setup, d) Detail side view of the experimental setup

Testing of bow and arrow: The side as well as top view and dimensions of the selected bow design are shown in Fig. 1a and b. Similarly, the top view along with the dimensions of the selected arrow design is shown in Fig. 1c. Nine samples of the bow were produced on an FDM 3000 machine using ABS (Acrylonitrile-Butadiene-Styrene) material according to the parameters and their levels as indicated in Table 2. One sample of the arrow was also produced by the same machine and from the same material which was subsequently used with the bows for testing their elastic behavior. The weight of the arrow was 3.2 g. After all the prototypes were produced, experiments were conducted to test the performance of each bow. In order to conduct the experiments, first, a non-elastic string made of cotton was attached to the bow and then the bow was fixed on a specially designed fixture. The isometric view, side view and other details of the experimental setup are shown in Fig. 2a-d. During the experiment, the fixture was fixed at a height of 1.16 m from the floor on a steel stand. Bow was inserted into the holder of the fixture. The arrow along with the string was held in a clipper which was rigidly attached to a movable rod. Thus, when the rod was moved it caused movement of the arrow as well as string which in turn caused bending of the bow. The movable rod had multiple slots and its movement could be stopped by inserting a stopper in any slot. The movable rod was moved to a distance of 6, 8 and 10 cm, respectively from the neutral position of the string i.e., when the string was not stretched and bending angles of the bow were measured. These angles were found to be 10°, 15° and 20°, respectively and henceforth, these angles are referred to as angle of displacement. After bending the bow at a desired angle of displacement, the clip was pressed to release the arrow. Sheets of plain white paper were spread on the floor and red colour was put on the arrow head so that the arrow left a red mark upon landing on the sheets. The experiments were conducted in a random order to avoid the influence of experimental setup[14]. Following the procedure discussed above, three throws of the arrow were performed for each experiment and for each angle of displacement of the bow. The same arrow was used in all the experiments. All experiments were conducted in a room with the same environmental conditions, i.e., moisture level, temperature, still air, so as to eliminate their inconsistent influence on the flight of arrow from one experiment to another. The performance of the bow was measured in terms of throwing distance achieved by the arrow. The differences among the distances achieved reflect different level of flexibility of the bows.

RESULTS AND DISCUSSION

The procedure stated above was used for testing the performance of each bow and the results of average throwing distance for 10°, 15° and 20° angle of displacements were obtained and presented in Table 3.

Main effect analysis: For performing the main effect analysis, average throwing distance achieved by the arrow upon being released from the bows, which were produced according to the experimental plan of the orthogonal array (Table 2), at each angle of displacement was calculated and the results are shown in Table 3. It can be seen from Fig. 3 that on the basis of average throwing distance, the best combination of parameters and their levels for the optimum performance of the bow for 10° angle of displacement is $A_1B_3C_3D_1$ since it results in maximum average throwing distance. The parameters and their levels, i.e., $A_1B_3C_3D_1$ once again appear to be the best combination for 15° angle of displacement as it is evident from Fig. 4. Finally, it can be observed from Fig. 5 that the best combination of parameters and their levels for 20° angle of displacement is $A_1B_1C_3D_2$

Table 3: Average distances achieved at various angles of displacement

Experiment No.	Distance achieved (cm) 10°	15°	20°
1	329.33	502.83	746.77
2	321.33	499.33	724.67
3	344.67	526.50	722.67
4	274.50	412.33	594.67
5	321.83	487.50	569.33
6	317.77	443.50	542.50
7	329.50	493.00	744.67
8	312.00	476.67	641.67
9	331.50	497.33	684.00

Analysis of variance (ANOVA): The purpose of the analysis of variance (ANOVA) was to investigate which of the FDM parameters significantly affected the quality characteristic. In the analysis of variance many quantities such as degrees of freedom, sum of squares, mean squares, etc. are computed and organized in a standard tabular format. In order to perform ANOVA first, the total sum of squared deviations, SS_T was calculated from the following formula[15]:

$$SS_T = \sum_{i=1}^{n} y_i^2 - C.F. \quad (1)$$

where, n is the number of experiments in the orthogonal array, y_i is the throwing distance of i th

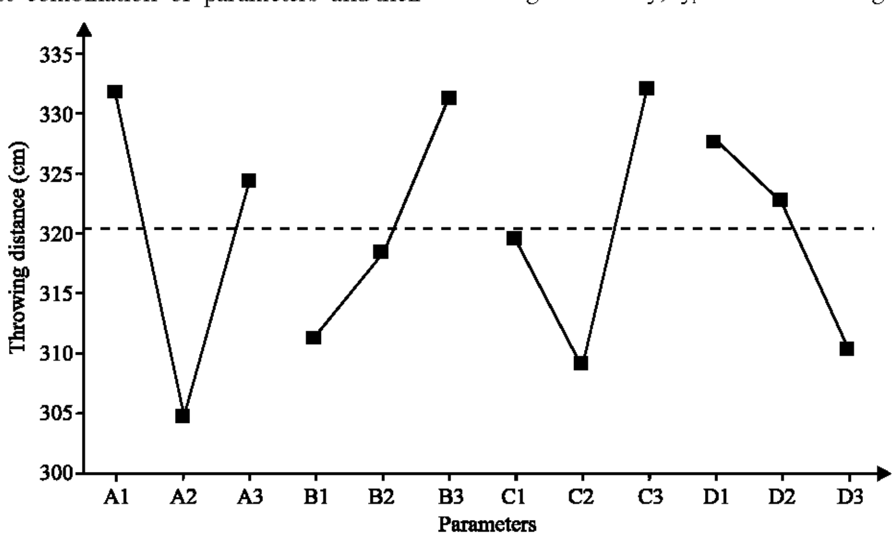

Fig. 3: Main effect graph for 10° angle of displacement

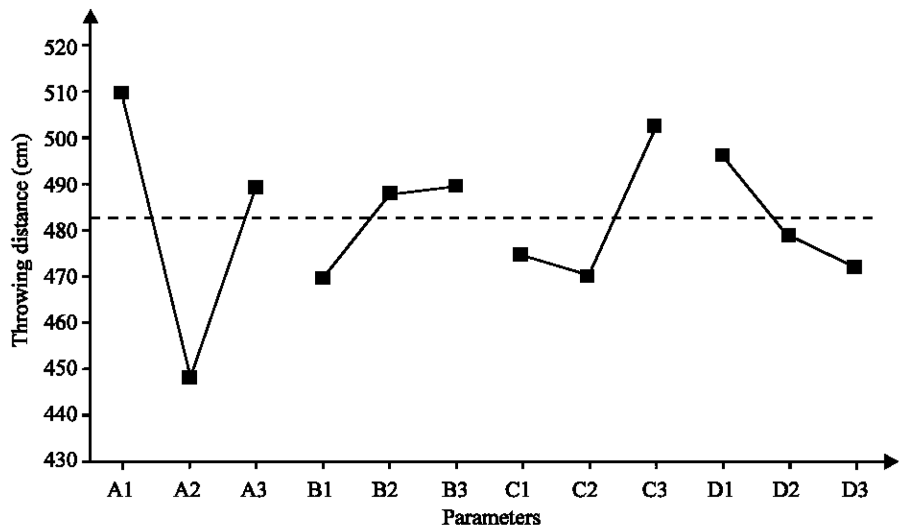

Fig. 4: Main effect graph for 15° angle of displacement

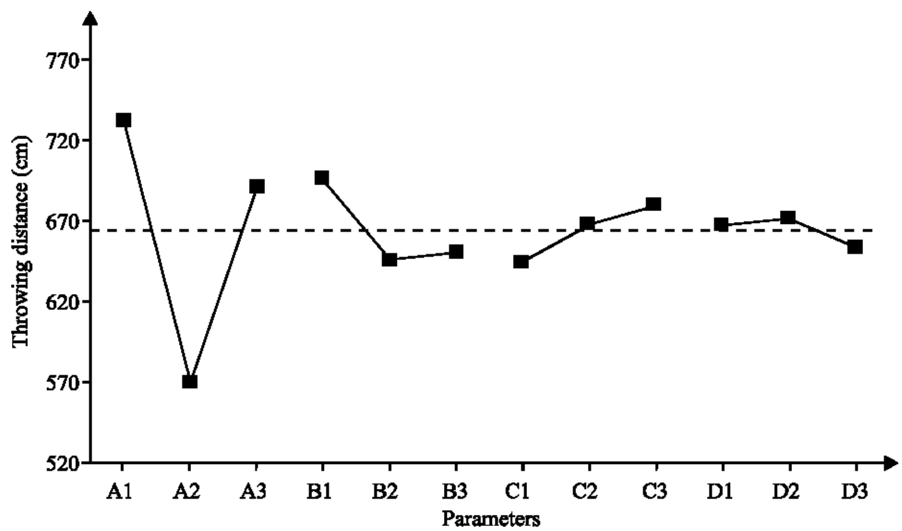

Fig. 5: Main effect graph for 20° angle of displacement

experiment and C.F. is the correction factor. C.F was calculated as[14]:

$$C.F. = \frac{T^2}{n} \qquad (2)$$

where, T is the total of the throwing distances.

It should be noted that the bow produced from each experiment was used three times to throw the arrow at each angle of displacement and thus the value of n (27) was used in the calculation.

The total sum of squared deviations, SS_T was decomposed into two sources: the sum of squared deviations, SS_d due to each process parameter and the sum of squared error, SS_e. The percentage contribution, P by each of the process parameter in the total sum of squared deviations, SS_T was found as a ratio of the sum of squared deviations, SS_d due to each process parameter to the total sum of squared deviations, SS_T.

Statistically, there is a tool called F test to see which process parameters have significant effect on the quality characteristic. For performing the F test, the mean of squared deviations, SS_m due to each process parameter were calculated. SS_m measures the distribution of the data about the mean of the data and it equals to the sum of squared deviations, SS_d divided by the number of degree of freedom associated with the process parameters. Then, the F value for each process parameter is simply the ratio of the mean of squared deviations, SS_m of that parameter

Table 4: ANOVA for 10° angle of displacement

Symbol	FDM parameter	Degree of freedom	Sum of squares	Mean Square	F-value	Contribution, p (%)
A	Air gap	2	3522.28	1761.14	50.03	35.87
B	Raster angle	2	1883.97	941.99	26.76	19.19
C	Raster width	2	2361.95	1180.98	33.55	24.06
D	Slice height	2	1417.13	708.57	20.13	14.43
All other /error		18	633.53	35.20		6.45
Total		26	9818.86			100.00

Table 5: ANOVA for 15° angle of displacement

Symbol	FDM parameter	Degree of freedom	Sum of squares	Mean Square	F-value	Contribution, p (%)
A	Air gap	2	17814.89	8907.45	76.47	58.42
B	Raster angle	2	2192.39	1096.20	9.41	7.19
C	Raster width	2	5618.67	2809.34	24.12	18.43
D	Slice height	2	2769.39	1384.70	11.89	9.08
All other /error		18	2096.61	116.48		6.88
Total		26	30491.95			100.00

Table 6: ANOVA for 20° angle of displacement

Symbol	FDM parameter	Degree of freedom	Sum of squares	Mean Square	F-value	Contribution, p (%)
A	Air gap	2	128441.46	64220.58	970.54	85.14
B	Raster angle	2	13835.24	6917.62	104.54	9.17
C	Raster width	2	5856.02	2928.01	44.25	3.88
D	Slice height	2	1537.46	768.73	11.62	1.02
All other /error		18	1191.07	66.17		0.79
Total		26	150861.25			100

to the mean of squared error, SS_e. Usually, when F>4, it means that the change of process parameter has a significant effect on the quality characteristic[11].

It can be seen from Table 4 that for 10° angle of displacement, all four parameters i.e., air gap, raster angle, raster width and slice height have significant influence on the performance of the bow. The percent contributions in descending order are air gap (35.87), raster width (24.06), raster angle (19.19) and slice height (14.43%). Similarly, the results presented in Table 5 shows that for 15° angle of displacement, all the four parameters are statistically significant. The parameter air gap has the most significant contribution among the four parameters (58.42). The contribution of raster width is 18.43 followed by the contribution of slice height (9.08%). Raster angle contributes only 7.19% and has the least significant effect on the performance for this angle of displacement. Based on the main effect and ANOVA analyses, the optimal parameters for both 10° and 15° angles of displacement are $A_1B_3C_3D_1$ (i.e. ,air gap - solid fine, raster angle − 30/60°, raster width − 0.729 mm and slice height − 0.178 mm).

Finally, it can be seen from Table 6 that for 20° angle of displacement, once again all the four parameters are statistically significant. It also shows that air gap has the most significant contribution to the quality characteristic (85.14%). The contributions of other parameters in descending order are raster angle (9.07 or 9.17), raster width (3.88%) and slice height (1.02%). Based on the main effect and ANOVA analyses, the optimal parameters and their levels are $A_3B_3C_3D_1$ (i.e. air gap - double wide, raster angle − 30/60°, raster width − 0.568 mm and slice height − 0.178 mm).

Analysis of the signal to noise (S/N) ratio: The signal-to noise ratio (S/N ratio) measures the sensitivity of the quality characteristics being investigated to those uncontrollable external influencing factors (noise factors). A higher S/N ratio is always desired because it implies that the effect of signal is much higher than that of noise factors. The quality characteristic is the distance achieved by the arrow. For this study the quality characteristic is "the-bigger-the-better" which indicates that larger throwing distance is desirable. In order to perform S/N ratio analysis, Mean Squared Deviation (MSD) needs to be calculated first. MSD is a quantity that reflects the deviation from the target value. For "the-bigger-the-better" quality characteristic, the MSD and S/N ratio were computed as follows:

$$MSD = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \quad (3)$$

$$S/N = -10\ Log_{10}(MSD) \quad (4)$$

where, y_i is the throwing distance for i th experiment.

Using the above two formulas the S/N ratios it can be seen from Table 7 and Table 8 that for both 10° and 15° angles of displacement, experiment number 3 yields the largest S/N ratio and for this experiment the combination

Table 7: S/N ratio for 10° angle of displacement

Experiment No.	Average distance y_{avg} (cm)	MSD (10^{-6})	S/N ratio
1	329.33	9.22	50.35
2	321.33	9.69	50.14
3	344.67	8.43	50.74
4	274.50	13.27	48.77
5	321.83	9.66	50.15
6	317.77	9.91	50.04
7	329.50	9.22	50.35
8	312.00	1.03	49.88
9	331.50	9.11	50.40

Table 8: S/N ratio for 15° angle of displacement

Experiment No.	Average distance y_{avg} (cm)	MSD (10^{-6})	S/N ratio
1	502.83	3.96	54.03
2	499.33	4.02	53.95
3	526.50	3.61	54.43
4	412.33	5.88	52.30
5	487.50	4.22	53.75
6	443.50	5.09	52.93
7	493.00	4.12	53.85
8	476.67	4.40	53.56
9	497.33	4.05	53.93

Table 9: S/N ratio for 20° angle of displacement

Experiment No.	Average distance y_{avg} (cm)	MSD (10^{-6})	S/N ratio
1	746.77	1.79	57.46
2	724.67	1.91	57.20
3	722.67	1.92	57.18
4	594.67	2.83	55.48
5	569.33	3.09	55.11
6	542.50	3.40	54.68
7	744.67	1.80	57.44
8	641.67	2.43	56.15
9	684.00	2.14	56.70

of parameters and their levels is $A_1B_3C_3D_3$ as indicated in Table 2. Table 9 reveals that for 20° angle of displacement, experiment number 1 results in the maximum S/N ratio and for this experiment the combination of parameters and their levels is $A_1B_1C_1D_1$. These results are different from those obtained from main effect analysis and do not represent optimum combination of parameters and their levels. However, they indicate minimum variation in the performance around the target value.

Confirmation tests: Once the optimal combination and levels of the process parameters at each angle of displacement was obtained, the final step was to verify the estimated result against experimental value. It may be noted that it is not necessary to conduct confirmation test for every angle of displacement. If the optimal combination of parameters and their levels coincidently match with one of the experiments in the OA, it is automatically verified and no confirmation test is required. Estimated value of throwing distance at optimum condition was calculated from the following formula[15]:

$$y_{opt} = m + (m_{Aopt} - m) + (m_{Bopt} - m) + (m_{Copt} - m) + (m_{Dopt} - m) \quad (5)$$

$$m = \frac{T}{n} \quad (6)$$

where, m is the average performance, T is the grand total of average throwing distance for each experiment, n is the total number of experiments and m_{Aopt}, m_{Bopt}, m_{Copt} and m_{Dopt} are the average throwing distance for parameters A, B, C and D at their optimum level, respectively.

Results of Table 10 showed that the estimated values do not correspond to any experiment of the OA as indicated in Table 2. Therefore, these optimum combinations need to be further verified. For this purpose, confirmation tests were carried out for each angle of displacement.

Two bows for the combination of parameters and their levels $A_1B_3C_3D_1$ and $A_1B_1C_3D_2$, respectively were

Table 10: Estimated value against experimental result

Bending angle (°)	Estimated value (cm)	Experimental result (cm)
10	361.83	Does not correspond to any experiment in the orthogonal array
15	553.89	Does not correspond to any experiment in the orthogonal array
20	785.92	Does not correspond to any experiment in the orthogonal array

Table 11: Confirmation test result for 10° angle of displacement

	Optimal condition			
	Estimation	Experiment	Difference	Difference (%)
Level	A_1, B_3, C_3, D_1	A_1, B_3, C_3, D_1	-	
Distance achieved (cm)	361.83	363.00	1.17	0.32
S/N ratio	-	46.43	-	

Table 12: Confirmation test result for 15° angle of displacement

	Optimal condition			
	Estimation	Experiment	Difference	Difference (%)
Level	A_1, B_3, C_3, D_1	A_1, B_3, C_3, D_1	-	
Distance achieved (cm)	553.89	552.80	1.09	0.20
S/N ratio	-	50.07	-	

Table 13: Confirmation test result for 20° angle of displacement

	Optimal condition			
	Estimation	Experiment	Difference	Difference (%)
Level	A_1, B_1, C_3, D_2	A_1, B_1, C_3, D_2	-	
Distance achieved (cm)	785.92	784.60	1.32	0.17
S/N ratio	-	53.12	-	

again produced by using the FDM 3000 machine and from the same material. The bow produced for parameter combination of $A_1B_3C_3D_1$ was used in the confirmation test for both 10° and 15° angles of displacement whereas the bow for parameter combination $A_1B_1C_3D_2$ was used in the confirmation test for 20° angle of displacement. After producing the bows, three throws of the same arrow were performed from each of them and the average throwing distance achieved by the arrow was computed. Subsequently, the average throwing distance was compared with the estimated value of the throwing distance calculated earlier. It is evident from Table 11-13 that the difference between experimental result and the estimated value for all three angles of displacement is small. In terms of percentage, the difference is only 0.32% for 10° angle of displacement, 0.20% for 15° and 0.17% for 20° angle of displacement. Thus, these results verified the optimum combination of parameters and levels obtained from the experiment.

CONCLUSIONS

Based on the results of the study, following conclusions can be drawn:

- The optimum combination of parameters and their levels for both 10° and 15° angles of displacement are $A_1B_3C_3D_1$ (i.e. air gap- solid fine, raster angle −30°/60°, raster width − 0.729 mm and slice height − 0.178 mm).
- The percent contributions of air gap, raster angle, raster width and slice height for 10° angle of displacement are 35.87, 19.19, 24.06 and 14.43, respectively.
- The percent contributions of air gap, raster angle, raster width and slice height for 15° angle of displacement are 58.42, 7.19, 18.43 and 9.08, respectively.
- The optimum parameters combination and their levels for 20° angle of displacement are $A_1B_1C_3D_2$ (i.e. air gap - double wide, raster angle − 30°/60°, raster width − 0.568 mm and slice height − 0.178 mm).
- The percent contributions of air gap, raster angle, raster width and slice height for 20° angle of displacement are 85.14, 9.17, 3.88 and 1.02, respectively. The value of all these parameters also represent at 10° and 15° angle.
- The combination of parameters and their levels $A_1B_3C_3D_3$ yield the optimum quality characteristic with minimum variance about the target for 10° and 15° angles of displacement. Whereas, this combination is $A_1B_1C_1D_1$ for 20° angle of displacement.

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