COMPARATIVE STATISTICAL ANALYSIS FOR PREDICTION OF DEPTH OF CUT IN CO2 LASER MACHINING

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Abstract- The present study investigates the relationships and parameter interactions between three controllable variables on depth of cut in CO_2 laser cutting of acrylic material using three statistical methods. Laser power, traverse speed and number of pass of laser probe are selected as independent variables. The three statistical methods considered were Full Factorial (FF), Response Surface Method (RSM) and Taguchi method for predicting the relation between response and the variables. The predicted models were developed using adjusted sum of square method and finalized by linear multiple regression technique. The ANOVA test has also been carried out to study the effect of main variables and their interaction effects on the response as well as to check the adequacy of the models at 95% confidence level. The final models were checked by complete residual analysis and finally were experimentally verified. It was found and the average deviation of depth of cut between predicted and actual values with full factorial method was found to be 0.0225 mm, with RSM method, it was found to be 0.052 mm and with Taguchi, it was -0.07667 mm.

Index Terms- Laser beam machining, full factorial method, response surface method, Taguchi method, ANOVA.

I. INTRODUCTION

The laser beam machining (LBM) uses a high intense coherent and monochromatic beam, which is focused on to the work-piece surface to a very small spot by means of focusing lens. Due to extreme heat generation at the laser spot zone on the material's surface, reaching to melting temperature, melting and vaporization of work material takes place leaving a crater on the incident area of the beam. A stream of gas, like atmospheric air, oxygen, nitrogen, argon etc is used to blow the molten metal from the machining zone and also to minimize the heat affected zone. The schematic diagram of laser beam cutting is shown in figure 1 [1]. Using a laser method allows one to eliminate some inconveniences like environment chemical pollution or limitations of the treated material. Knowing that laser texturing is a complex process, it is necessary to identify the operating parameters having a significant influence on the performance indicators [2]. As the laser processing aims the highest quality excellence, one must obey an optimized combination of parameters [3] as follows: power density; transversal laser beam mode; traverse speed; number of passes, etc. The laser parameters listed above lead to complex interactive relations.

Many experiments involve the analysis of effects of one or more factors in a system being studied.

According to Montgomery [4], the method of varying one of the factors at a time and keep the others fixed is not adequate when there is a possibility of the influence of one factor over the other. In this case, the most appropriate is the use of different statistical techniques like full factorial, response surface method, taguchi, etc where all the possible combinations of the factors are investigated in a complete run of experiments. Miroslav Radovanovic, et al [5] have observed that laser cutting, as multi-input and multi-output process, is affected by many process parameters and their interactions.

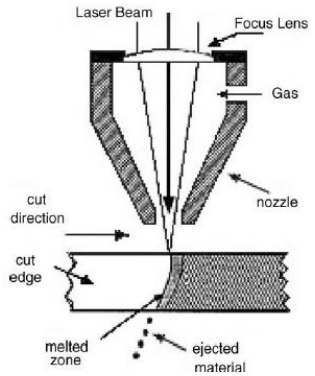


Fig. 1 A schematic of the laser beam interaction with the material

It was found that design of experiments approach is superior from unplanned approach because it is a systematic and scientific way of planning the experiments, collection and analysis of data with limited use of available resources. Yilbas [6] employed a full factorial design to identify the main and first order interaction effects on the hole quality in single pulse laser cutting including taper, inlet cone, exit cone, surface debris and mean hole diameter. Tam et al [7] optimised the laser deep hole drilling of Inconel 718 using Taguchi method containing an orthogonal array design to minimise the drilling time. Almeida et al [8] performed factorial analysis for optimizing the cutting of titanium using Nd:YAG laser process. Their study found that superficial hardness of the cut area increases as well as a noticeable formation of nitrogen

precipitates under a thin layer of a melted zone. Ghoreishi, M. et al [9] investigated the influence of parameters on hole taper and circularity for two different materials using RSM and it was noted that the pulse frequency has a bigger effect on the responses for stainless steel compared to mild steel in which the pulse frequency had no significant effect. Bappa Acherjee et al [10] performed an investigative study to find the effects of the laser parameters to the responses for laser transmission welding of acrylic. The process parameters studied were laser power, welding speed, clamp pressure and size of the beam. The results shows that lap shear strength and weld seam width can be increased by increasing the laser power meanwhile an increase in welding speed will reduce the values of both responses. D. Dhupal, et al [11] investigates the relationship of processes parameters of pulsed Nd:YAG laser-turning operation on aluminum oxide (Al_2O_3). The central composite design (CCD) were utilized to plan the experiments and lamp current, pulse frequency, pulse width, assist air pressure and cutting speed of work piece were considered as process parameters. Kamalu and Byrd [12] assessed the effects of lens focal length, position of the focal plane relative to the material surface and laser energy on laser drilling performance 2^3 factorial design. K. Huehnlein,et al [13] carry out an optimization study of laser cutting thin ceramic layers using a design of experiment approach. They employed full factorial method and response surface methodology, which investigates the local and global optima of the process and which identifies relevant interactions between the influencing variables. Benyounis K. Y. et al [14] performed a multi-response optimization study on laser welding of austenitic stainless steel and the effects of laser power, welding speed and focal point position on the tensile strength, impact strength and joint-operating cost were observed. A. M. Varsi et al [15] investigates the relationship of process parameters of CO_2 laser cutting of acrylic material for predicting depth of cut using statistical methods like full factorial and response surface methodology for single pass traveling of laser probe on the workpiece with power and traverse speed as process parameters. This paper presents a study to compare different statistical approaches like full factorial, response surface methodology and taguchi method for predicting depth of cut during laser beam machining on CO_2 laser. The process parameters like laser beam power, traverse speed and number of passes are considered by keeping assist gas pressure of air as constant.

II. EXPERIMENTATION AND PREDICTIVE MODEL

The experiments were carried out on CO_2 laser of continuous-wave type along with 5 cm focal length lens producing laser beam of 0.015 cm diameter. A blower system is used to expel the molten material away from the machined zone.

The work-piece material considered is an acrylic sheet of 10 mm thickness since its absorptivity is unity. The cutting parameters considered are laser power (p) from 10 to 100% of maximum capacity 25 watt, cutting speed (v) from 10 to 100% of maximum capacity of 42 ips (1066 mm/sec) and the number of pass (n) from 1 to 10. The present work attempts creation of cavity of 10 mm diameter with fill option so that laser machine can create circular cavity of 10 mm with certain value of depth based on the set parameter combinations for multiple pass of laser probe. The data of depth values by varying power, traverse speed and number of pass is obtained by carrying out experiments on CO_2 laser and the reported values are used to develop a predictive model. Since, depth of cut (D) is a function of power (p), cutting speed (v) and number of pass (n), a predictive model was developed using multi-variable regression analysis [16].

Calculating the depth from the predicted model and doing the regression with the experimental depth value, the value of average error comes to be 35.6% which shows variation of predicted model from the actual to be moderate [17].

III. STATISTICAL ANALYSIS

The traditional method of experimentation i.e. varying one factor at a time (OFAT) and studying its effects would be quite tedious and uneconomical especially if the number of variables is large. Furthermore, such experiments cannot predict the presence of interactions between the different factors. With a properly designed experiment, it should be possible to determine, with a much reduced number of experiments, the effect of changing any one variable with the same accuracy as if only one factor has been varied at a time, and interaction effects between the factors [18]. Statistical analysis of laser machining is used in many areas such as laser cutting, laser drilling, etc. for better understanding of the relationship between laser parameters and responses. Out of number of statistical methods available, three methods are discussed below.

A. Full Factorial Method

Factorial designs allow for the simultaneous study of the effects that several factors may have on a process. When performing an experiment, varying the levels of the factors simultaneously rather than one at a time is efficient in terms of time and cost, and also allows for the study of interactions between the factors. The range and level of experimental variables investigated in this study are shown in table I.

Table I Experimental ranges and levels of the independent variables

Factors	Levels	Level Values		
		-1	0	+1
P	3	46	73	100
V	3	37	64	91
n	3	2	5	10

The experiments were carried out by l^k factorial design where l = number of levels and k = number of factors. In this study, 3^3 design will be implemented giving 27 experimental runs and for more accuracy in the design, number of replicates selected is 2 giving total 54 experimental runs which is shown in table II. Analysis of the influence of every control factor on the response was carried out statistically. The influence of each factor on the response is obtained from the F- values from the ANOVA table III.

Table II Experimental data based on 3^3 factorial design with 2 replicates

Runs	P %	V %	n	Depth (D), mm	Runs	P %	V %	n	Depth (D), mm
1	100	91	5	0.125	28	46	64	5	0.025
2	73	91	5	0.025	29	46	91	5	0.001
3	73	64	2	0.025	30	73	91	2	0.001
4	73	64	10	0.275	31	73	37	2	0.150
5	100	37	2	0.325	32	46	64	10	0.075
6	73	64	5	0.125	33	100	37	2	0.330
7	46	64	2	0.025	34	46	64	10	0.075
8	73	91	10	0.100	35	46	64	2	0.025
9	100	64	5	0.325	36	100	91	2	0.025
10	73	37	10	1.100	37	46	91	10	0.001
11	46	91	2	0.001	38	46	37	2	0.100
12	73	64	10	0.275	39	100	37	5	0.775
13	73	91	5	0.020	40	100	37	5	0.780
14	46	37	5	0.250	41	73	37	5	0.500
15	100	64	10	0.600	42	73	37	2	0.150
16	46	91	2	0.001	43	73	91	10	0.100
17	73	64	5	0.130	44	73	64	2	0.025
18	100	91	5	0.125	45	46	37	10	0.400
19	100	64	5	0.326	46	46	91	5	0.001
20	46	91	10	0.001	47	73	37	10	1.100
21	73	37	5	0.500	48	46	64	5	0.025
22	100	37	10	1.525	49	100	91	10	0.275
23	46	37	5	0.250	50	100	91	2	0.025
24	46	37	2	0.100	51	100	37	10	1.525
25	100	64	10	0.600	52	46	37	10	0.410
26	73	91	2	0.001	53	100	64	2	0.150
27	100	64	2	0.150	54	100	91	10	0.275

Table III Analysis of Variance for Depth of Cut (D) using Sum of Square

Source	DF	Sum of Square	Mean Square	F	P
P	2	1.17808	0.58904	145.57	0.000
V	2	2.55306	1.27653	315.48	0.000
n	2	1.42838	0.71419	176.50	0.000
P*V	4	0.37268	0.09317	23.03	0.000
P*n	4	0.41244	0.10311	25.48	0.000
V*n	4	0.84399	0.21100	52.15	0.000
Error	35	0.14162	0.00405		
Total	53	6.93025			

The statistical significance of the model equation is evaluated by the F-test carried out at 95% ($\alpha = 0.05$) confidence level. The Fα values for main effects and interaction effect are obtained from the standard tables. The standard values are $F_{0.05,2,35} = 3.32$ and $F_{0.05,4,35} = 2.69$. From table 3, the value of $F > F\alpha$ indicates that the main effects (power, speed and number of pass) and their interaction effects are significant. The goodness of the fit of the model is checked by the value of Residual (R^2). Residual is the difference between observed and predicted value. In this case, the value of $R^2 = 96.9$ % which revealed that the model is a good fit to the data and only 3.1% of the total variations is not explained by the model. The application of full factorial method expressed in the form of regression is an empirical relationship between depth of cut (D) and tested variables which is given by eq. (1).

$$D = 0.107 + 0.00668P - 0.00943V + 0.0493n \quad (1)$$

Table IV Analysis of Variance for regression model

Source	DF	Sum of Square	Mean Square	F	P
Regression	3	4.9344	1.6448	41.21	0.000
Residual Error	50	1.9958	0.0399		
Total	53	6.9303			

Table IV shows the ANOVA values for the regression model shown by eq. (1). The *p*-value from ANOVA table IV indicates that the model is significant. The main effects plot in Fig. 2 shows that with increase in power and number of passes and with decrease in speed, the depth of cut increases.

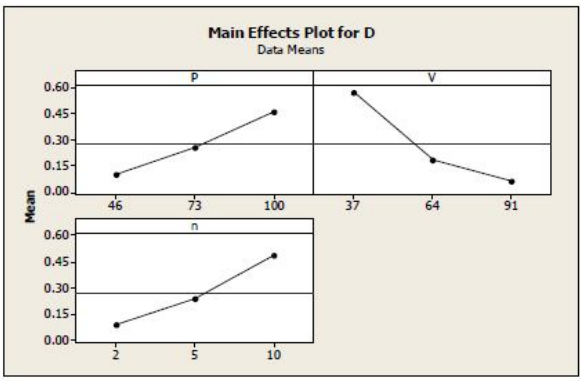


Fig. 2 Main effects plot

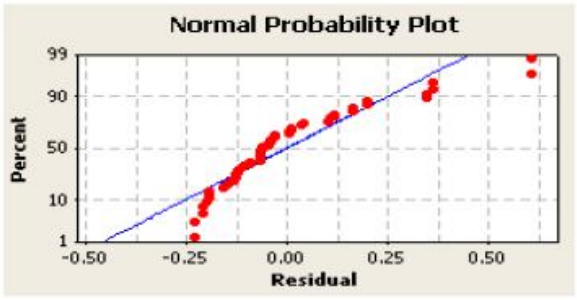


Fig. 3 Normal probability plot

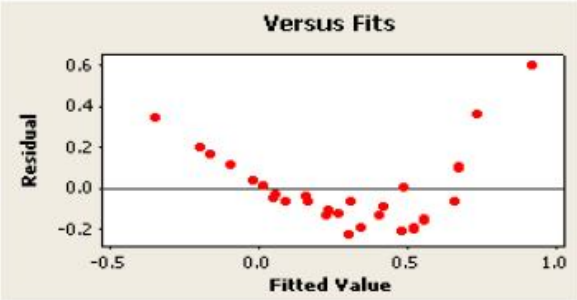


Fig. 4 residual versus fit plot

From the normal probability plot shown in Fig. 3, it can be seen that the residuals appear to follow a straight line. No evidence of non-normality, skew-ness or unidentified variables exists. From the residual versus fit plot shown in Fig. 4, it is seen that there are adequate distributions of data points nearer the fitted lines and therefore, it is concluded that the developed model estimates the responses satisfactorily.

B. Response Surface Method (RSM) with Central Composite Design (CCD)

The RSM is a collection of experimental design techniques and regression methods. The discussion on interaction effects between the factors is very crucial and can reveal how the process can be controlled in order to achieve the desirable process outputs. One useful class of such designs, which are economical in the number of experiments required, is the RSM with CCD [19]. The experiment was decided to be performed with RSM method with 2 replicates. The range and level of experimental variables investigated in this study are shown in table V.

Table V Experimental ranges and levels of the independent variables

Factors	Levels	Level Values	
		Upper	Lower
P	2	100	46
V	2	91	37
n	2	2	10

The experiments were carried out with the 2^3 factorial designs as per central composite design shown in table VI. Here, the value of α is 1.

Table VI Experimental data based on central composite design (CCD)

Runs	P %	V %	n	Depth (D), mm	Runs	P %	V %	n	Depth (D), mm
1	100	37	2	0.325	21	73	91	6	0.025
2	73	64	6	0.150	22	100	91	10	0.275
3	73	64	6	0.150	23	100	64	6	0.375
4	46	91	2	0.001	24	73	64	6	0.150
5	100	91	2	0.025	25	46	37	2	0.100
6	73	64	6	0.150	26	73	64	6	0.160
7	73	64	10	0.275	27	46	37	10	0.400
8	73	64	6	0.150	28	73	64	2	0.025
9	46	64	6	0.050	29	100	37	2	0.325
10	73	64	6	0.160	30	73	37	6	0.625
11	73	64	2	0.025	31	73	91	6	0.030
12	73	64	6	0.170	32	100	37	10	1.525
13	46	91	10	0.001	33	100	91	10	0.275
14	46	91	10	0.001	34	46	64	6	0.050
15	100	64	6	0.375	35	73	64	6	0.150
16	100	91	2	0.025	36	46	37	10	0.400
17	73	37	6	0.625	37	46	91	2	0.001
18	100	37	10	1.525	38	73	64	6	0.150
19	73	64	6	0.150	39	73	64	6	0.170
20	73	64	10	0.275	40	46	37	2	0.100

The response surface analysis was carried out statistically and the ANOVA results are shown in table VII. Here also, the F-test is carried out at 95% (α = 0.05) confidence level. The Fα values for main effects and interaction effect are obtained from the standard tables. The standard values are $F_{0.05,9,39}$ = 2.12 and $F_{0.05,3,39}$ = 2.84. From table VII, the value of F for linear, quadratic and interaction sources indicates that their effects are highly significant. The goodness of the fit of the model is checked by the value of Residual (R^2). In this case, the value of R^2 = 96.6 % which revealed that the model is a good fit to the data and only 3.4% of the total variations is not explained by the model. The regression model is given by eq. (2).

Table VII Analysis of Variance for Depth of Cut

Source	DF	Sum of Square	Mean Square	F	P
Regression	9	4.25755	0.47306	95.69	0.000
Linear	3	2.97828	0.99276	200.81	0.000
Square	3	0.28134	0.09378	18.97	0.000
Interaction	3	0.99793	0.33264	67.28	0.000
Residual Error	30	0.14831	0.00494		
Lack-of-Fit	5	0.14760	0.02952	1035.8	0.000
Pure Error	25	0.00071	0.00003		
Total	39				

$$D = 0.251 + 0.0028P - 0.015V + 0.062n + 0.00005P^2 + 0.00022V^2 - 0.0014n^2 - 0.00018P.V + 0.0013P.n - 0.0014V.n \quad (2)$$

The trend of the main effect plot was found to be same as that of full factorial method indicating that as power and number of passes increases and speed decreases, the depth of cut increases. Also the normal probability plot and residual versus fit plot in Fig. 5 and Fig. 6 respectively shows similar type of trend as observed in the case of full factorial method.

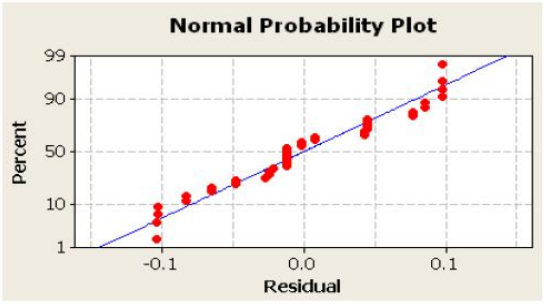


Fig. 5 Normal probability plot

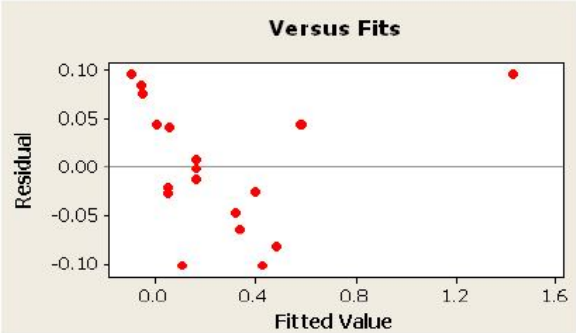


Fig. 6 Residual versus Fit plot

C. Taguchi method

An attempt was made to carry out experiments based on Taguchi method for statistical comparison with the above two methods. L_{27} orthogonal array based Taguchi method was adopted with three levels of each of the three process parameters giving 27 experimental runs. The orthogonal array of 27 experimental runs is shown in Table VIII.

Table VIII L_{27} Orthogonal array and experimental results of the responses

Runs	P %	V %	n	Depth (D), mm	Runs	P %	V %	n	Depth (D), mm
1	46	37	2	0.100	15	73	64	10	0.280
2	46	37	2	0.150	16	73	64	10	0.275
3	46	37	2	0.180	17	73	91	2	0.001
4	46	64	5	0.025	18	73	91	2	0.001
5	46	64	5	0.026	19	73	91	2	0.001
6	46	64	5	0.024	20	100	37	10	1.525
7	46	91	10	0.001	21	100	37	10	1.528
8	46	91	10	0.001	22	100	37	10	1.530
9	46	91	10	0.001	23	100	64	2	0.150
10	73	37	5	0.500	24	100	64	2	0.160
11	73	37	5	0.550	25	100	64	2	0.155
12	73	37	5	0.580	26	100	91	5	0.125
13	73	64	10	0.275	27	100	91	5	0.126
14	46	37	2	0.100	-				

The Taguchi analysis was also carried out statistically and the ANOVA results are shown in table IX.

Table IX Analysis of Variance for Depth of Cut

Source	DF	Sum of Square	Mean Square	F	P
P	2	1.36136	0.68068	22.81	0.000
V	2	2.51781	1.25890	42.19	0.000
n	2	1.21978	0.60989	20.44	0.000
Error	20	0.59673	0.02984		
Total	26				

Here also, the F-test is carried out at 95% ($\alpha = 0.05$) confidence level. The standard value is $F_{0.05,2,26} = 3.39$. From table IX, the value of F for linear source indicates that their effects are significant. The value of $R^2 = 86.4$ % revealed that the model is a moderate fit to the data and 13.6% of the total variations is not explained by the model. One of the reasons for this variation may be due to the lack of interaction terms and their effects which are not considered for the present set of experimental data. The regression model for the above set of experiment is given by eq. (3).

$$D = 0.035 + 0.0101P - 0.0129V + 0.0639n \qquad (3)$$

The trend of the main effect plot was found to be same as that of the above two methods. From the normal probability plot and residual versus fit plot in Fig. 7 and Fig. 8 shows a moderate variation of the trend as compared to the above two methods.

IV. COMPARATIVE ANALYSIS

The comparative analysis of the statistical methods is very interesting to know about the validity of the models predicted by all the above methods by calculating the difference between actual depth and predicted depth and then finally comparing all the three models by some validation points for unknown values of the parameters like power, speed and number of passes.

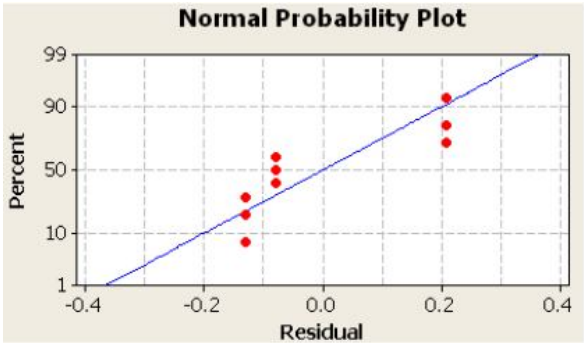


Fig. 7 Normal probability plot

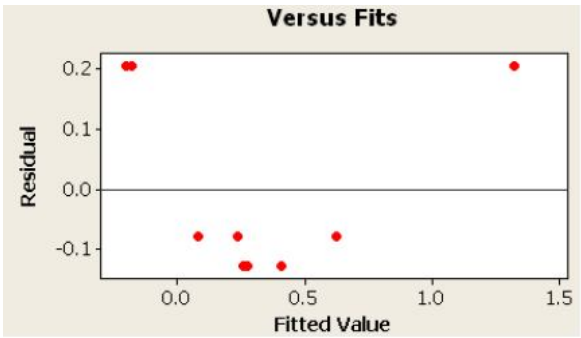


Fig. 8 Residual versus Fit plot

Using the regression equation for the depth of cut by full factorial method, the predicted depth was calculated and then deviation with the actual depth value was obtained. The value of average deviation was found to be 0.0225 mm which shows a good agreement of the predicted model with the experimental data. This result also shows that the predicted model is a linear fit to the data but this model does not show any effect of quadratic terms. Further, using the regression equation for the depth of cut by RSM with CCD, the value of average deviation was

found to be 0.052 mm which shows that the average deviation is almost near to full factorial method and also this method takes into account the effect of quadratic terms which is highly significant for the present experimental data. Similarly, by using the regression equation for the depth of cut by Taguchi, the value of average deviation was found to be -0.07667 mm. This shows some deviation than the above two methods and also this method does not involve the quadratic terms since this method is suitable for more number of process parameters. Finally, comparisons of all the three models were done simultaneously using some unused set of parameters like power, speed and number of passes which is shown in table X, table XI and table XII. The values of process parameters for validation purpose are kept constant for all the three models. It can be seen from the table X and table XI that the average deviation of depth of cut for both the models are found to be almost same showing the good convergence of both the model with the experimental data.

Table X Validation data for Full Factorial model

Order of Exp.	P %	V %	n	Pred. depth, mm	Actual depth, mm	Deviation, mm
1	95	19	3	0.71	1.1	0.39
2	82	55	7	0.48	0.475	-0.005
3	64	28	4	0.47	0.55	0.08
4	58	35	5	0.41	0.38	-0.03
5	75	28	3	0.52	0.52	0
6	85	40	2	0.46	0.25	-0.1
					Avg.	0.0225

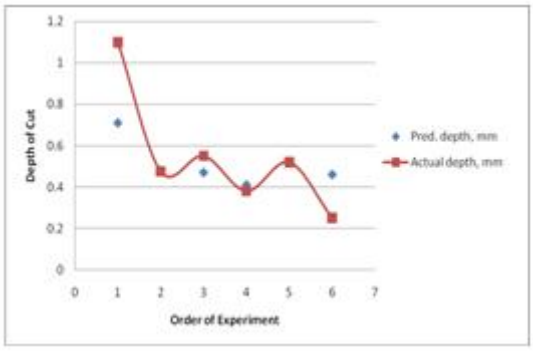


Fig. 9 Comparison of predicted and actual values of depth of cut for FF model

Table XI Validation data for RSM model

Order of Exp.	P %	V %	n	Pred. depth, mm	Actual depth, mm	Deviation, mm
1	95	19	3	0.95	1.1	0.15
2	82	55	7	0.425	0.475	0.05
3	64	28	4	0.483	0.55	0.067
4	58	35	5	0.374	0.38	0.006
5	75	28	3	0.49	0.52	0.03
6	85	40	2	0.241	0.25	0.009
					Avg.	0.052

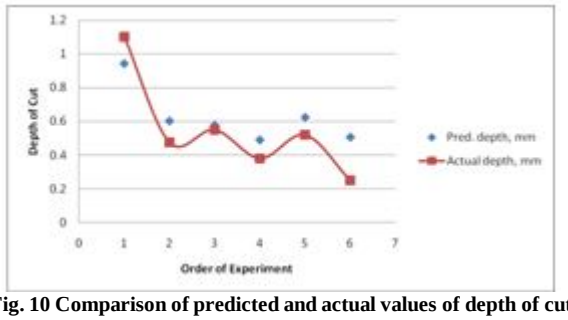


Fig. 10 Comparison of predicted and actual values of depth of cut for RSM model

From the Fig. 9 and Fig. 10, it can be said that there is a good agreement between predicted and actual values of depth of cut, statistically acceptable for 95% confidence level.

Table XII Validation data for Taguchi model

Order of Exp.	P %	V %	n	Pred. depth, mm	Actual depth, mm	Deviation, mm
1	95	19	3	0.9411	1.1	0.1589
2	82	55	7	0.601	0.475	-0.126
3	64	28	4	0.5758	0.55	-0.0258
4	58	35	5	0.4888	0.38	-0.1088
5	75	28	3	0.623	0.52	-0.103
6	85	40	2	0.5053	0.25	-0.2553
					Avg.	-0.07667

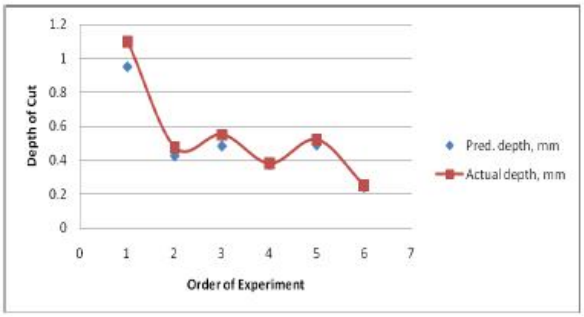


Fig. 11 Comparison of predicted and actual values of depth of cut for Taguchi model

Table XII shows the validation data for the Taguchi method and it can be seen that the value of average deviation is slightly high as compared to other two methods. Also, much variation is observed in the predicted and actual value depicted in Fig. 11. This variation may be due to lack of quadratic terms effect as well as less number of process parameters and their levels.

CONCLUSION

The present study has demonstrated the application of DOE methods like full factorial, response surface method with central composite design and Taguchi method for statistically studying the effect of process parameters like power, speed and number of pass of laser probe on the depth of cut for laser machining on

acrylic material. The statistical model for depth of cut is obtained by all the three techniques. From all the three models, FF and RSM adequately fits the data as compared to Taguchi method since it shows some variation than the above two methods. The value of residual for RSM method is found to be 96.6 % whereas for full factorial method, it is found to be 96.9 % and for Taguchi, value of residual is 86.4 %. By FF method, the predicted model is a linear fit to the data but shows the absence of quadratic terms which is shown by RSM method for the present experimental data. By comparative analysis, the average deviation of depth of cut with full factorial method is found to be 0.0225 mm, with RSM method, it is found to be 0.052 mm and with Taguchi, it is -0.07667 mm which shows that there is a good agreement between predicted and actual values of depth of cut, statistically acceptable for 95% confidence level for FF and RSM method whereas little deviation is observed in Taguchi method. However, Taguchi involves lesser experimental runs as compared to other methods, but due to less number of process parameters and their few levels does not able to show influence of quadratic as well as interaction effects for the present experimental data.

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