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PREDICTION OF DEPTH OF CUT IN SINGLE PASS IN CO_2 LASER USING STATISTICAL METHODS

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Abstract: ***The present paper investigates the relationship of process parameters of CO_2 laser cutting of acrylic material for predicting depth of cut using statistical methods. The process parameters considered during laser beam machining are power and traverse speed for single pass of laser probe. Since depth of cut is a function of power and transverse speed during laser cutting, full factorial method and response surface method with central composite design have been employed to predict the relation between response and variables. 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. The validity of the models have also been checked through experiments and the average deviation of depth of cut with full factorial method is found to be -2.26 x 10^{-5} which shows that the model is a linear fit to the data and may have minor effect of quadratic terms for the present experimental work.***

Keywords: ***Design of experiment, full factorial method, interaction effects, laser beam machining, response surface method.***

INTRODUCTION

In any engineering industries or organization, experiments are used to study the performance of the processes and systems. The process or system can be represented by the model as shown in figure 1. The objective of the experiment is to establish the relationship between the variables/factors and the response/output and also to determine the optimum set of parameters for variables so that the variation in the output is minimum. Statistics is the study of the collection, analysis, interpretation, presentation, and organization of data. A basic statistical approach is by implying design of experiment [1].

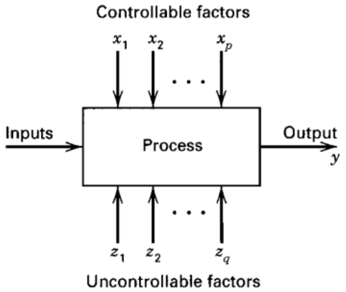

Fig. 1 General model of a process or system

A mathematical model showing the relation between parameters and response are developed by using statistical techniques like regression analysis and ANOVA test is carried out to check adequacy of the model [2]. Avanish Kr. Dubey, et al reviewed the different approaches used for experimental investigations carried out to study the effect of various factors/process parameters on the performance of Nd:YAG laser beam cutting. By using different DOE techniques, efficiency of experimentation is increased by reducing the loss of quality. The factorial design method is simple and has all combination of experimental runs. RSM is the best method of parameter optimization with reduced number of experimentation without affecting the accuracy of results but qualitative variables cannot be optimized [3]. Miroslav Radovanovic, et al have observed that laser cutting, as multi-input and multi-output process, is affected by many process parameters and their interactions. So they focused on reviewing the experimental investigation concerned with analysis on effects of laser input process parameters on cut quality. 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 [4]. Among the most famously used DOE techniques are response surface modeling with central composite design, Taguchi's method and factorial design. In factorial experiments, combination of two or more levels of more than one factor is the treatment. That is, every level of one factor is combined with every level of other factors. Full factorial design with two or three level is one of the good choices for most experiment whereas multi-level is expensive and unproductive. Almeida et al 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 [5]. Yilbas B. S performed a parametric study using factorial design method to study the effect of pulse length, focus setting, energy and material thickness on hole diameter and taper. The thickness of the work piece was found to be the most important criteria. Pulse length influences hole diameter the most but focus setting is even more important for an improved hole geometry with increase focus setting. An increase in pulse energy found to increase the hole diameter also [6]. Response Surface Methodology (RSM) is a collection of mathematical and statistical technique that is useful for the modeling and analysis of problems in which a response is influenced by several variables and the objective is to optimize the response. The most commonly used RSM design is the Central Composite Design (CCD). Mathew J. et al investigated response surface methodology (RSM) technique for optimization of carbon fibre reinforced plastics composite laser cutting where the reaction of HAZ and taper of the cut to cutting speed, pulse energy, pulse duration, pulse repetition and gas pressure. Cutting speed, pulse energy, pulse duration and pulse repetition were found to significantly influence the HAZ while gas pressure affects the cut kerf width the most [7]. Ghoreishi, M. et al 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 [8]. Kuar, A.S. et al analyzed laser machining of Zirconia and used RSM to determine the optimal setting for the process parameters for achieving minimum HAZ and hole taper. Lamp current was found to have the most significant effect on both of the responses in which a linear increase can be obtained. Minimum HAZ and hole taper is a direct result from low current setting [9]. Choudhury, I. A. et al used RSM CCD technique to develop a predictive model to analyze the effects of the laser power, cutting speed and compressed air pressure against the HAZ, surface roughness for three different polymer materials (PP, PC, PMMA). The results of the experiment showed that the HAZ is directly proportional to the laser power and inversely proportional to cutting speed and compressed air pressure. It was observed that the quality of cut of PMMA is much better than PC and PP [10]. Bappa Acherjee et al 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 responses investigated are lap-shear strength and weld seam width. 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 [11]. Soveja A. et al. studied on laser texturing by combining RSM CCD technique and Taguchi method to identify the key parameters that contribute to productivity and surface quality. The results of their study show that frequency and energy of the pulse have the most influence in the laser texturing process. MRR is linearly proportional to pulse energy and frequency while the surface roughness is inversely affected by them. It is predicted that the model can function with a 95% confident level [12]. Benyounis K. Y. et al 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. It was noted that the laser power increases the tensile strength until it reaches a central value after which the tensile strength began to drop [13]. D. Dhupal, et al 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. It was found that proper control of the process parameters lead to achieve minimum upper deviation, lower deviation and depth of laser-turned micro-grooves produced on cylindrical workpiece of Al_2O_3 [14]. G. Kibria, et al studied the effect of process parameters during Nd:YAG laser micro-turning operation of alumina ceramic materials using Taguchi methodology . The process parameters considered during machining are laser beam average power, pulse frequency, workpiece rotational speed and feed rate. Analysis of Variance (ANOVA) was performed to find out the significant process parameters during laser micro-turning process. The percentage errors in the responses were found to be very less which shows good agreement of the predicted model with the experimental data [15]. The objective of the Taguchi method is to determine the optimum settings of input parameters, neglecting the variation caused by uncontrollable factors or noise factors [16]. Here, in the present work, the factors to be considered during laser beam machining by CO_2 laser are power and transverse speed. Since, factors are only two; Taguchi method cannot be employed effectively as the results are vague. So, DOE technique like full factorial method and response surface method with central composite design is employed to study the effect of factors and their interactions on the response and finally comparison is made between the two techniques.

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). 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 single pass of laser probe. The data of depth values for varying pressure and traverse speed 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) and cutting speed (v), a predictive model was developed using multi-variable regression analysis [17]. Calculating the depth from the predicted model and doing the regression with the experimental depth value, the value of average error comes to be 4.5% which shows good convergence from the actual one [18].

III. STATISTICAL APPROACH USING DOE

DOE of laser machining is used in many areas such as laser cutting, laser drilling, laser texturing and laser micro-drilling for better understanding of the relationship between laser parameters and responses.

1. Full Factorial Method

A prior knowledge and understanding of the process and the process variables under investigation are necessary for achieving a more realistic model. The range and level of experimental variables investigated in this study are shown in table 1.

Table 1 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

The experiments were carried out by l^k factorial design where l = number of levels and k = number of factors. In this study, 3^2 design will be implemented giving 9 experimental runs and for more accuracy in the design, number of replicates selected is 3 giving total 27 experimental runs which is shown in table 2.

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

Run Order	P	V	Observed value (D)
1	46	64	0.0025
2	73	37	0.1000
3	100	91	0.0250
4	73	64	0.0500
5	46	37	0.0500
6	46	37	0.0500
7	100	91	0.0250
8	100	64	0.1000
9	46	91	0.0025
10	100	91	0.0250
11	73	37	0.1000
12	73	91	0.0020
13	46	91	0.0001
14	100	37	0.1750
15	73	64	0.0500
16	100	37	0.1750
17	46	64	0.0025
18	100	64	0.1000
19	100	37	0.1750
20	100	64	0.1000
21	46	91	0.0001
22	73	91	0.0002

23	46	64	0.0001
24	73	91	0.0022
25	46	37	0.0500
26	73	37	0.1000
27	73	64	0.0500

Analysis of the influence of every control factor on the response was carried out using MINITAB 16 software package. The influence of each factor on the response is obtained from the F- values from the ANOVA table 3.

Table 3 Analysis of Variance for D using Adjusted SS

Source	DF	Seq SS	Adj MS	F	P
P	2	0.031015	0.015507	27618.46	0.000
V	2	0.044692	0.022346	39798.66	0.000
P*V	4	0.008366	0.002092	3725.06	0.000
Error	18	0.000010	0.000001		
Total	26	0.084083			

The statistical significance of the model equation is evaluated by the F-test The F-test is carried out at 95% ($\alpha = 0.05$) confidence level. The $F\alpha$ values for main effects and interaction effect are obtained from the standard tables. The standard values are $F_{0.05,2,18} = 3.55$ and $F_{0.05,4,18} = 2.93$. From table 3, the value of $F > F\alpha$ indicates that the main effects (power and speed) and their interaction effect is significant. 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 as follows:

$$D = 0.0621 + 0.00153\ P - 0.00184\ V \text{ ----------------------------- } (1)$$

Table 4 Regression values

Predictor	Coefficeint	T	P
Constant	0.06211	3.65	0.001
P	0.0015272	8.94	0.000
V	-0.0018372	-10.76	0.000

S = 0.0195651 R-Sq = 89.1% R-Sq(adj) = 88.2%

Table 5 Analysis of Variance for regression model

Source	DF	SS	MS	F	P
Regression	2	0.074896	0.037448	97.83	0.000
Residual Error	24	0.009187	0.000383		
Total	26	0.084083			

Table 4 and table 5 shows the regression values and ANOVA for the regression equation shown by equation 1. The *p*-value from ANOVA table 5 indicates that the model is significant. The goodness of the fit of the model is also checked by the value of Residual (R^2). Residual is the difference between observed and predicted value. In this case, the value of $R^2 = 89.1$ % which revealed that this regression is statistically significant and only 10.9% of the total variations is not explained by the model. The residual plots for the response D is shown in figure 2. From the normal probability plot, 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 Versus Fits plot, it can be seen that the residuals appear to be randomly scattered about zero. No evidence of non-constant variance or missing terms exists. From the Versus Order plot, it can be seen that the residuals appear to be randomly scattered about zero. No evidence exists that the error terms are correlated with one another. Thus, from the figure 2, it can be inferred that the model is a good fit of the data. Also, the main effects plot in figure 2 shows that with increase in power and decrease in speed, depth of cut increases.

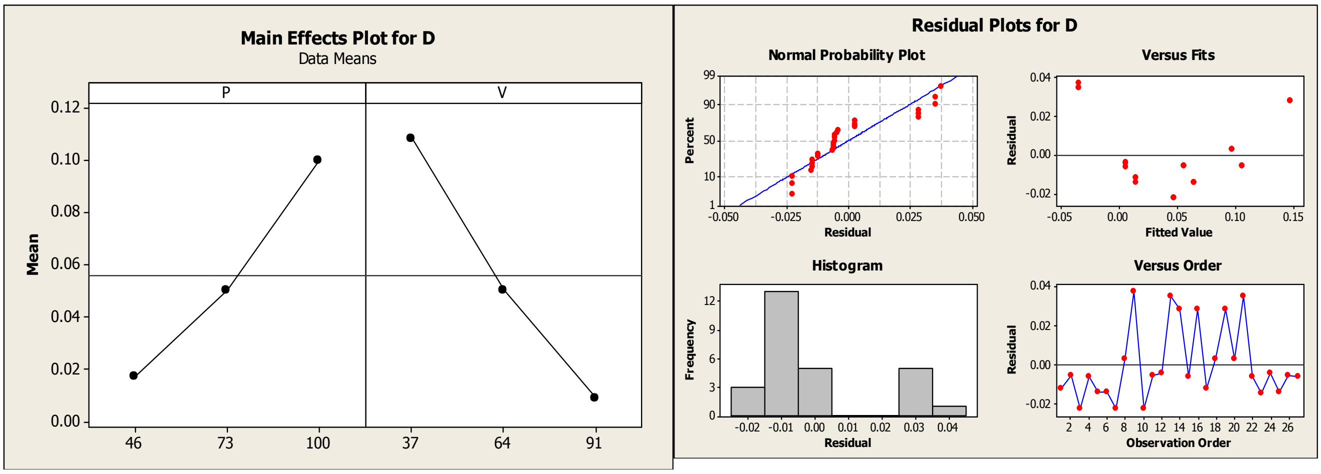

Fig. 2 Main effects plot and Four- in- one residual plots

2. Response Surface Method with Central Composite Design

Initially the experiment was decided to be performed RSM method with 2 replicates. But the results show higher variations in the model in terms of low value of residual indicating lacking of the model to fit the data. Hence, it was decided to conduct the experiment with 3 replicates. The range and level of experimental variables investigated in this study are shown in table 6.

Table 6 Experimental ranges and levels of the independent variables

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

The experiments were carried out with the 2^2 factorial designs as per central composite design shown in table 7 with 3 replicates. Here, the value of α is 1.414.

Table 7 Experimental design based on central composite design (CCD)

Run	Independent Variables				Response D
	Coded Values		Real Values		
	P	V	P	V	
1	-α	0	34.82	64	0.001
2	0	α	73	102.2	0.010
3	-α	0	34.82	64	0.001
4	0	0	73	64	0.050
5	0	0	73	64	0.055
6	0	α	73	102.2	0.001
7	1	-1	100	37	0.175
8	0	0	73	64	0.050
9	-1	1	46	91	0.002
10	1	1	100	91	0.025
11	0	-α	73	25.8	0.120
12	-1	-1	46	37	0.050
13	0	0	73	64	0.050

14	0	-α	73	25.8	0.125
15	-1	1	46	91	0.002
16	0	0	73	64	0.052
17	0	0	73	64	0.050
18	0	α	73	102.2	0.002
19	-1	-1	46	37	0.053
20	-α	0	34.8	61	0.001
21	0	0	73	64	0.054
22	α	0	111.2	64	0.130
23	1	-1	100	37	0.174
24	0	0	73	64	0.055
25	0	0	73	64	0.050
26	-1	1	46	91	0.001
27	0	0	73	64	0.050
28	0	0	73	64	0.053
29	1	1	100	91	0.025
30	0	0	73	64	0.052
31	1	1	100	91	0.024
32	0	0	73	64	0.055
33	-1	-1	46	37	0.052
34	α	0	111.2	64	0.100
35	1	-1	100	37	0.175
36	0	0	73	64	0.050
37	0	0	73	64	0.054
38	α	0	111.2	64	0.130
39	0	-α	73	25.8	0.120

The response surface analysis was carried out on MINITAB 16 software package and the ANOVA results are shown in table 8.

Table 8 Analysis of Variance of D

Source	DF	Seq SS	Adj MS	F	P
Regression	5	0.095808	0.019162	461.64	0.000
Linear	2	0.087292	0.043646	1051.51	0.000
Interaction	1	0.007490	0.007490	180.45	0.000
Residual Error	33	0.001370	0.000042		
Lack-of-Fit	3	0.000634	0.000211	8.61	0.000
Pure Error	30	0.000736	0.000025		
Total	38	0.097178			

Here also, the F-test is 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 $F_{0.05,2,30} = 3.32$ and $F_{0.05,1,30} = 4.17$. From table 8, the value of F > Fα the main effects (power and speed) and their interaction effect is significant.

The regression equation is given by

$$D = 0.0606 + 0.00146\,P - 0.00169\,V \quad \text{---------------} \ (2)$$

Table 9 Regression values

Predictor	Coefficeint	T	P
Constant	0.06063	4.87	0.000
P	0.0014554	11.62	0.000
V	-0.0016944	-13.52	0.000

S = 0.0165718 R-Sq = 89.8% R-Sq(adj) = 89.3%

Table 10 Analysis of Variance for regression model

Source	DF	SS	MS	F	P
Regression	2	0.087292	0.043646	158.93	0.000
Residual Error	36	0.009887	0.000275		
Total	38	0.097178			

Table 9 and table 10 shows the regression values and ANOVA for the regression equation shown by equation 2. The *p*-value from ANOVA table 9 indicates that the model is 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 = 89.8 % which revealed that this regression is statistically significant and 10.2% of the total variations is not explained by the model. The residual plots for the response D is shown in figure 3. Similar types of observations are found in the residual plots of response surface method as it was observed in full factorial method. Hence it can be said that the model is a good fit to the data.

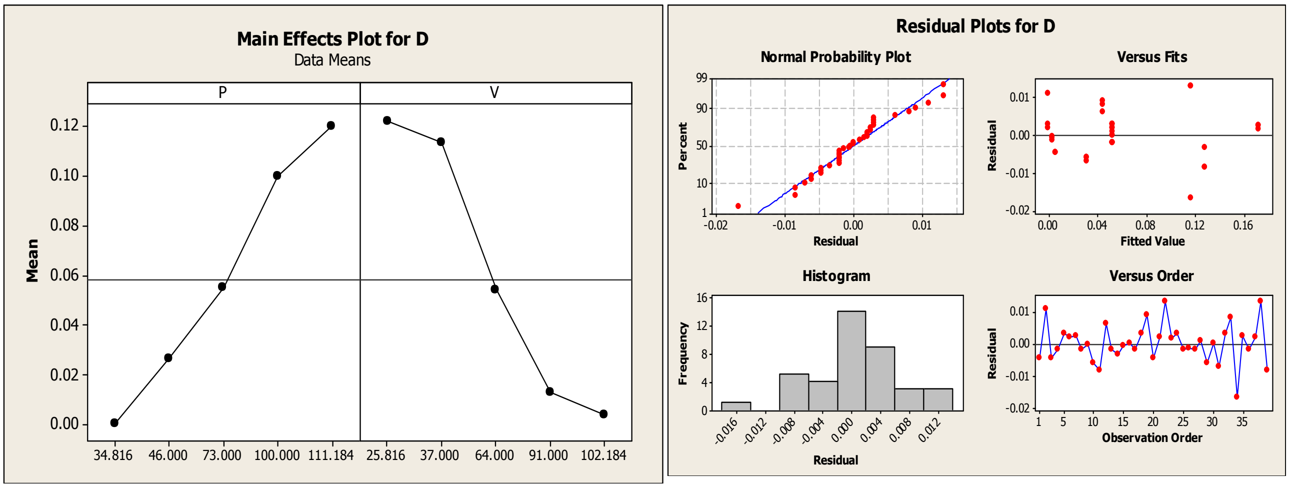

Fig. 3 Main effects plot and Four- in- one residual plot

IV COMPARATIVE ANALYSIS

Apart from the above statistical analysis using full factorial and response surface method, an attempt was made to validate both the models by calculating the difference in the actual depth and predicted depth and then finally comparing both the models by some validation points like unknown values of the parameters like speed and power and analyzing the output.

1. Full Factorial method:

The regression equation for the depth of cut is given by equation 1. Using this equation the predicted depth is calculated and the deviation with the actual depth value is shown in table 11.

Table 11 Deviation of depth using full factorial method

Sr. No.	P	V	Actual Depth	Predicted Depth	Deviation
1	46	64	0.0025	0.01472	-0.01222
2	73	37	0.1	0.10571	-0.00571
3	100	91	0.025	0.04766	-0.02266
4	73	64	0.05	0.05603	-0.00603
5	46	37	0.05	0.0644	-0.0144
6	46	37	0.05	0.0644	-0.0144

7	100	91	0.025	0.04766	-0.02266
8	100	64	0.1	0.09734	0.00266
9	46	91	0.0025	-0.03496	0.03746
10	100	91	0.025	0.04766	-0.02266
11	73	37	0.1	0.10571	-0.00571
12	73	91	0.002	0.00635	-0.00435
13	46	91	0.0001	-0.03496	0.03506
14	100	37	0.175	0.14702	0.02798
15	73	64	0.05	0.05603	-0.00603
16	100	37	0.175	0.14702	0.02798
17	46	64	0.0025	0.01472	-0.01222
18	100	64	0.1	0.09734	0.00266
19	100	37	0.175	0.14702	0.02798
20	100	64	0.1	0.09734	0.00266
21	46	91	0.0001	-0.03496	0.03506
22	73	91	0.0002	0.00635	-0.00615
23	46	64	0.0001	0.01472	-0.01462
24	73	91	0.0022	0.00635	-0.00415
25	46	37	0.05	0.0644	-0.0144
26	73	37	0.1	0.10571	-0.00571
27	73	64	0.05	0.05603	-0.00603
				Avg.	-2.26×10^{-5}

From the table 11, it can be seen that a negligible deviation is observed between the actual value and the predicted value and the average deviation is found to be zero 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 and does not have any effect of quadratic terms in the present experimental data and for the confirmation, the analysis was also carried out with RSM method.

2. Response Surface Method with Central Composite Design

The regression equation for the depth of cut is given by equation 2. Using this equation the predicted depth is calculated and the deviation with the actual depth value is shown in table 12.

Table 12 Deviation of depth using RSM method

S. No.	P	V	Actual Depth	Predicted Depth	Deviation
1	34.82	64	0.001	0.003277	-0.00228
2	73	102.2	0.01	-0.00554	0.015538
3	34.82	64	0.001	0.003277	-0.00228
4	73	64	0.05	0.05902	-0.00902
5	73	64	0.055	0.05902	-0.00402
6	73	102.2	0.001	-0.00554	0.006538
7	100	37	0.175	0.14407	0.03093
8	73	64	0.05	0.05902	-0.00902
9	46	91	0.002	-0.02603	0.02803

10	100	91	0.025	0.05281	-0.02781
11	73	25.8	0.12	0.123578	-0.00358
12	46	37	0.05	0.06523	-0.01523
13	73	64	0.05	0.05902	-0.00902
14	73	25.8	0.125	0.123578	0.001422
15	46	91	0.002	-0.02603	0.02803
16	73	64	0.052	0.05902	-0.00702
17	73	64	0.05	0.05902	-0.00902
18	73	102.2	0.002	-0.00554	0.007538
19	46	37	0.053	0.06523	-0.01223
20	34.8	61	0.001	0.008318	-0.00732
21	73	64	0.054	0.05902	-0.00502
22	111.2	64	0.13	0.114792	0.015208
23	100	37	0.174	0.14407	0.02993
24	73	64	0.055	0.05902	-0.00402
25	73	64	0.05	0.05902	-0.00902
26	46	91	0.001	-0.02603	0.02703
27	73	64	0.05	0.05902	-0.00902
28	73	64	0.053	0.05902	-0.00602
29	100	91	0.025	0.05281	-0.02781
30	73	64	0.052	0.05902	-0.00702
31	100	91	0.024	0.05281	-0.02881
32	73	64	0.055	0.05902	-0.00402
33	46	37	0.052	0.06523	-0.01323
34	111.2	64	0.1	0.114792	-0.01479
35	100	37	0.175	0.14407	0.03093
36	73	64	0.05	0.05902	-0.00902
37	73	64	0.054	0.05902	-0.00502
38	111.2	64	0.13	0.114792	0.015208
39	73	25.8	0.12	0.123578	-0.00358
				Avg.	-0.00072

From the table 12, it can be seen that a negligible deviation is observed between the actual value and the predicted value but the value of average deviation is more than that observed with full factorial method which shows that there is no need for carrying out the statistical analysis using RSM method. Finally, comparisons of both the models were done simultaneously using some unknown set of parameters like power and speed which is shown in table 13 and table 14. It can be seen from the table 13 and table 14 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 13 Validation data for Full Factorial model

S. No.	P	V	Exp. depth	Depth by FF method	Deviation
1	55	46	0.025	0.06161	-0.0366
2	64	37	0.15	0.09194	0.05806
3	73	28	0.125	0.12227	0.00273

4	82	73	0.025	0.05324	-0.0282
5	91	19	0.375	0.16637	0.20863
				Avg.	0.040914

Table 14 Validation data for RSM model

S. No.	P	V	Exp. depth	Depth by RSM method	Deviation
1	55	46	0.025	0.06316	-0.03816
2	64	37	0.15	0.09151	0.05849
3	73	28	0.125	0.11986	0.00514
4	82	73	0.025	0.05695	-0.03195
5	91	19	0.375	0.16135	0.21365
				Avg.	0.041434

IV CONCLUSION

The present study has demonstrated the application of DOE techniques like full factorial method and response surface method with central composite design for statistically studying the effect of parameters like power and speed on the depth of cut for single pass laser beam machining. The statistical model for depth of cut is obtained by both the techniques and both the model adequately fits to the data. The value of residual for RSM method is found to be 89.8% whereas for full factorial method, it is found to be 89.1% which shows slight higher accuracy of the RSM model. But by comparative analysis, the average deviation of depth of cut with full factorial method is found to be -2.26×10^{-5} and with RSM method, it is found to be -0.00072 which shows that the predicted model is a linear fit to the data which is confirmed by full factorial method and there is a negligible influence of quadratic terms observed by RSM method for the present experimental data. Also, a validation test is carried out which shows a good convergence of both the models with experimental data for single pass cutting using CO_2 laser.

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