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Parametric Analysis of Cutting Parameters for Laser Beam Machining Based on Box-behnken Design

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Abstract

Laser beam machining (LBM) is one of the advanced machining processes which are used for shaping almost whole range of engineering materials. In LBM, surface roughness is one of important response which affects the quality characteristics of product. In this research work, the effect of process parameters such as cutting speed, frequency and duty cycle on surface roughness (Ra) for mild steel material in laser cutting is discussed. L-27 orthogonal array was selected for full factorial design to better understanding of interaction between process parameters. The values of surface roughness for mild steel were calculated using model equations and Box-Behnken design of Response Surface Methodology (RSM) is used to parametric analysis.

Keywords: Laser Beam Machining (LBM), Surface Roughness, Response Surface Methodology.

1. Introduction

Emergence of advanced engineering materials, stringent design requirements, and intricate shape and unusual size of work piece restrict the use of conventional machining methods. Hence, it was realize to develop some nonconventional machining methods known as advanced machining processes. LBM is one of the advanced machining processes which are used for shaping almost whole range of engineering materials. Major applications of laser beam is in cutting of metals and non- metals, soft and difficult to machine (DTM) materials. The laser is directed at the required surface and moved around to cut the materials in the desired shape. LBM being a non conventional machining process requires high investment and offers poor efficiency, so high attention is required for better utilization of resources. The values of process parameters are determined to yield the desired product quality and also to maximize the process performances. In LBM, there are many factors such as beam parameters, material parameters and machining parameters which affects the various quality characteristics, e.g. surface roughness, Heat Affected Zone (HAZ), recast layer, etc. Design experimental approach is superior from other approach because it is a systematic and scientific way of planning the experiments, collection and analysis the data with limited use of available resources. Nd: YAG and CO_2 are most widely used for LBM application. Form the early days of the high power laser, Nd: YAG laser were only available in pulsed mode while CO_2 laser were available both in pulsed and continuous (CW) mode. But now a day, both laser types are available as pulsed and CW [2, 3].

Sivarao et al.[4] have experimentally investigated the effect of surface roughness on mild steel having thickness 6 mm with various parameters such as cutting speed, frequency and duty cycle and find a RSM based model equation. They found that surface roughness was highly affected by cutting speed and duty cycle; hence these two are the most affecting parameters and concluded that at high cutting speed and low duty cycle, best roughness can be achieved. After comparison of the data between the calculated and observed values for surface roughness they found that the deviation error between the predicted and observed values is not more than 15%, it means that mathematical model obtained for surface roughness is reliable.

In this research work, the effect of process parameters such as cutting speed, frequency and duty cycle on surface roughness (Ra) for mild steel material in laser cutting is discussed. L-27 orthogonal array was selected for full factorial design to better understanding of interaction between process parameters. The values of surface roughness for mild steel were calculated using model equations and Box-Behnken design of response surface methodology is used to parametric analysis.

2. Response Surface Methodology

The response surface methodology is a widely adopted tool for the quality engineering field. The Response surface methodology [5] is a collection of mathematical and statistical techniques that are useful for modeling, analysis and optimizing the process in which response of interest is influenced by several variables and the objective is to optimize this response. Response Surface Methodology uses quantitative data from appropriate experiments to determine and simultaneously solve multi-variable equations. The response surface methodology comprises regression surface fitting to obtain approximate responses, design of experiments to obtain minimum variances of the responses and optimizations using the approximated responses.

In most of the RSM problems the form of relationship between the response and the independent variable is unknown. Thus the first step in RSM is to find a suitable approximation for the true functional relationship between Y and set of independent variables employed. Usually a second order model is utilized in RSM.

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_{i<} \sum_{j=2}^{k} \beta_{jj} X_i X_j \qquad (1)$$

The β coefficients, used in the above model can be calculated by means of using least squares technique. The second order model is normally used when the response function is not known or nonlinear. [6, 7, 8]

3. Experimental Setup & Cutting Conditions

In this study, the material used mild steel having length of 6 m, width of 0.15 m and thickness of 6 mm. To make it easier to measure work piece, shearing machine was used to cut the material in to 1000 mm x 150 mm size work piece. The experiments have been conducted by researchers (Sivarao et. al.2010) with different factors and process variables in laser cutting are discussed. L-27 orthogonal array design was selected for full factorial design to better understanding of interaction between process parameters. The identified cutting parameters during experiments were cutting speed (v), frequency (f), and duty cycle (D) and the output response was surface roughness (R_a).The Cutting parameter and their level indicated in table 1.

Table 1: Control parameter and their level.

Symbol	Cutting Parameters	Level 1	Level 2	Level 3
v	Cutting speed (mm/min)	800	1000	1200
f	Frequency (Hz)	1000	1400	1800
D	Duty Cycle (%)	60	67.5	75

Table 2: L27 Orthogonal Array.

Trial No.	Column Factors												
1	1	2	3	4	5	6	7	8	9	10	11	12	13
2	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	2	2	2	2	2	2	2	2	2
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2

14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

4. Results and Discussion

Present work incorporates a derived model equation by researchers (Sivarao et. al.2010) [4] for Ra in laser cutting. With the help of this regression analysis and optimization will be done in table 2.

$$Ra = 2.74 - (0.0110 \times v) + (0.00117 \times f) + (0.261 \times D) \qquad (2)$$

Table 3: The Result of Ra under different process parameter.

Experiment No.	**Cutting speed (mm/min)**	**Frequency (Hz)**	**Duty cycle (%)**	**Surface roughness (Ra)**
1	800	1000	60.00	10.770
2	800	1000	67.50	12.727
3	800	1000	75.00	14.685
4	800	1400	60.00	11.238
5	800	1400	67.50	13.195
6	800	1400	75.00	15.153
7	800	1800	60.00	11.706
8	800	1800	67.50	13.663
9	800	1800	75.00	15.621
10	1000	1000	60.00	8.570
11	1000	1000	67.50	10.527
12	1000	1000	75.00	12.485
13	1000	1400	60.00	9.038
14	1000	1400	67.50	10.995
15	1000	1400	75.00	12.953
16	1000	1800	60.00	9.506

17	1000	1800	67.50	11.463
18	1000	1800	75.00	13.421
19	1200	1000	60.00	6.370
20	1200	1000	67.50	8.327
21	1200	1000	75.00	10.285
22	1200	1400	60.00	6.838
23	1200	1400	67.50	8.795
24	1200	1400	75.00	10.753
25	1200	1800	60.00	7.306
26	1200	1800	67.50	9.263
27	1200	1800	75.00	11.221

After calculating the values of the Ra for mild steel, nine important graphs can be plotted to analyze the effect of parameter on output parameter (Ra) shown in Fig. 1, Fig. 2 and Fig. 3 respectively. For Ra after using full factorial design, data is analyzed by response surface methodology's Box- Behnken technique, which suggested an array of 15 experiments in randomized run order, especially for 3 designs, in coded variable done on MINITAB 16software. Regression analysis for Ra versus cutting speed, frequency and duty cycle and ANOVA for Ra shown in table 4 and table 5 respectively.

As per the estimated regression coefficient, the model equation for Ra is

$$Ra = 10.9950 - 2.1999\ v + 0.4681\ f + 1.9575\ D + 0.0001\ v^2 + 0.0001\ f^2 + 0.0004\ D^2 + 0.0001\ vf - 0.000\ vD - 0.000\ fD \quad (5)$$

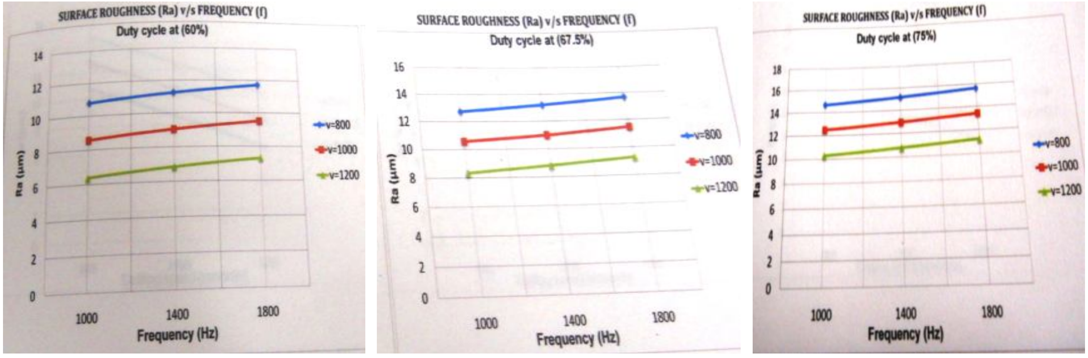

Fig. 1: Effect of frequency (f) on the Ra with three levels (60, 67.5, and 75%) of duty cycle (D)

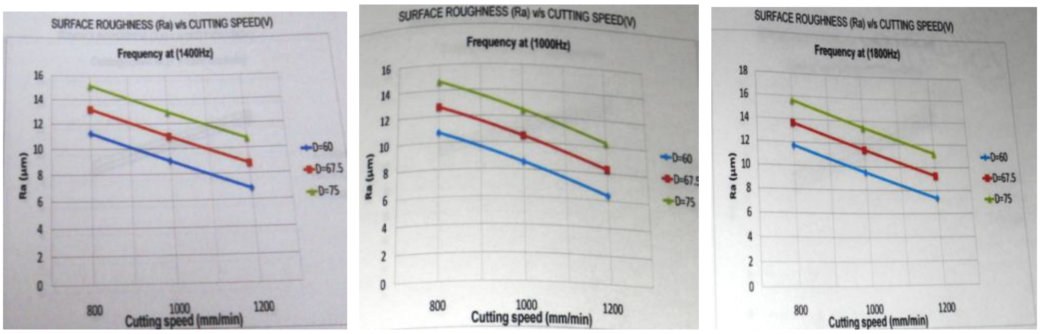

Fig. 2: Effect of Cutting speed (v) on the Ra with three levels (1000, 1400 and 1800 Hz) of frequency (f)

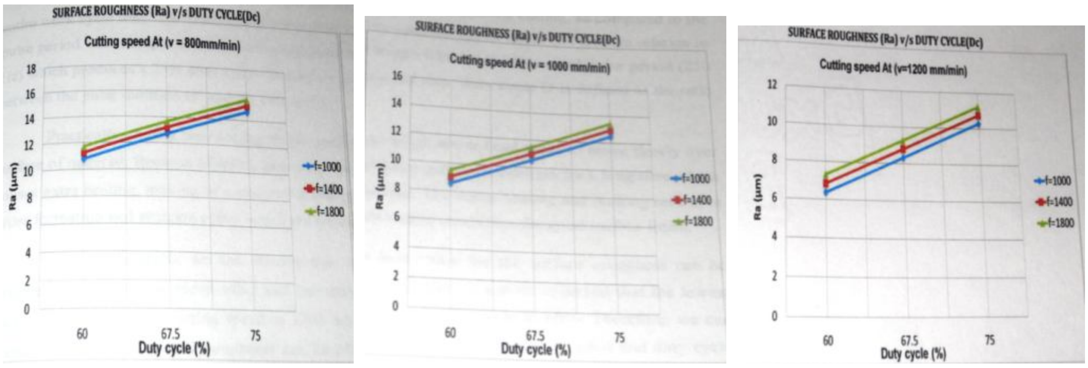

Fig. 3: Effect of duty cycle (D) on the Ra with three levels (800, 1000 and 1200 mm/min) of cutting speed (v)

Table 4: Regression Analysis for Ra versus Cutting speed, Frequency, Duty cycle.

Term	**Coefficient**	**SE Coef**	**T**	**P**
Constant	10.9950	0.000065	170333.808	0.000
Cutting speed	-2.1999	0.000040	-55654.506	0.000
Frequency	0.4681	0.000040	11841.146	0.000
Duty cycle	1.9575	0.000040	49521.268	0.000
Cutting speed * Cutting speed	0.0001	0.000058	1.074	0.332
Frequency* Frequency	0.0001	0.000058	1.074	0.332
Duty cycle* Duty cycle	0.0004	0.000058	7.519	0.001
Cutting speed*Frequency	0.0001	0.000056	2.236	0.076
Cutting speed* Duty cycle	-0.0000	0.000056	-0.000	1.000
Frequency * Duty cycle	-0.0000	0.000056	-0.000	1.000
S =0.000111803	PRESS=1.00000E-06	R-Sq=100.00%	R-Sq(pred)=100.00%	R-Sq(adj)=100.00%

Table 5: ANOVA for Ra.

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	9	71.1249	71.1249	7.9028	6.32221E+08	0.000
linear	3	71.1249	71.1249	23.7083	1.89666E+09	0.000
Cutting speed	1	38.7178	38.7178	38.7178	3.09742E+09	0.000
Frequency	1	1.75270	1.75270	1.75270	1.40213E+08	0.000
Duty cycle	1	30.6545	30.6545	30.6545	2.45236E+09	0.000
Square	3	0.0000	0.0000	0.0000	19.00	0.004
Cutting speed*Cutting speed	1	0.0000	0.0000	0.0000	1.15	0.332
Frequency * Frequency	1	0.0000	0.0000	0.0000	1.15	0.332
Duty cycle * Duty cycle	1	0.0000	0.0000	0.0000	56.54	0.001
Interaction	3	0.0000	0.0000	0.0000	1.67	0.288
Cutting speed*frequency	1	0.0000	0.0000	0.0000	5.00	0.076
Cutting speed * Duty cycle	1	0.0000	0.0000	0.0000	0.00	1.000
frequency* Duty cycle	1	0.0000	0.0000	0.0000	0.00	1.000
Residual Error	5	0.0000	0.0000	0.0000		
Lack-of- Fit	3	0.0000	0.0000	0.0000		
Pure Error	2	0.0000	0.0000	0.0000		
Total	14	71.1249				

According to the result, cutting speed's F- value of 3.09742E+09 implies the cutting speed is the most affecting parameter in deciding the surface quality. Value of "Prob.>F" less than 0.0500 indicates model terms are significant. In this case cutting speed, frequency, duty cycle and second order terms of duty cycle are the significant model terms. Value greater than 0.1000 indicates that the model terms are not significant. Result can be used to predict the surface roughness within the limits of the experiment.

5. Conclusion

In the theoretical study of Ra for mild, Response Surface Methodology is used to investigate the relationship between laser machining parameter with responses. The cutting parameters studied here are cutting speed, frequency and duty cycle. The dimensions of Ra for mild steel are directly proportional to the duty cycle and frequency and inversely proportional to cutting speed can be observed with the help of model equation. For mild steel the best value for the surface roughness (6.37μm) can be obtained at high cutting speed (1200 mm/min) value and low duty cycle value (60%). From the graph 1, 2 and 3 it is clear that surface roughness decreases with increase in cutting speed. Surface roughness increases with increase in the duty cycle. Frequency is not a major factor in influencing the outcome of the surface roughness. The effect of cutting speed and duty cycle on the surface roughness is more as compared to frequency.

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