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Response Surface Modelling of Bottom Kerf Deviation in Nd-YAG Laser Cutting of Al 6061-T6 Alloy Sheet

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Abstract: Laser beam cutting (LBC) is the most acceptable method for creating complex geometries in sheetmetal with close tolerances and high precision. The reflective nature of Al-alloy possesses problems to absorb the laser light. Hence, the shorter wavelength laser is advised for cutting of reflective sheetmetals. This paper presents the modelling of bottom kerf deviation during pulsed Nd-YAG laser cutting of Al 6061-T6 sheet. The deviation of laser cut in the study is examined by considering the four cutting parameters (lamp current, pulse width, pulse frequency and cutting speed). Experiments have been conducted using Box-Behnken design (BBD) and subsequently, experimental results have been analyzed for developing the response surface model. Further, the model has been used for parametric study.

Keywords: Al-alloy sheet, Cutting, Modelling, Nd-YAG laser, Response surface methodology.

I. Introduction

Due to the exceptional properties of Al-alloys, they are become preferred choice of several industries for specific applications. Al-alloys have the high strength to weight ratio, good formability, tensile strength and good corrosion resistance properties. In order to applications, various forms of Al-alloys are used in modern manufacturing industries in general but sheet form is used for structural work in aerospace industries in particular. To reduce the manufacturing costs of any structure, a trend has been driven towards the design of larger, thinner, and complex parts which can be assembled more easily without recourse to jigs and fixtures [1]. Such trends have directed for increasing the focus on the cutting of large thin-walled sections in Al-alloy sheets. There are number of alternatives to cut Al-alloy sheets but among the various sheet cutting processes laser beam cutting (LBC) offers significant advantages over others. It has the ability to cut complex geometries with close tolerances, high cutting speed and provides narrower heat affected zone (HAZ), and high-quality cut [2].

LBC is the two-dimensional (2D) configuration of laser beam machining (LBM) process where the process is completed by providing the relative motion between laser source and the sheet specimen. The schematic diagram of LBC setup is shown in (Fig. 1). As the LBC is the thermal energy based non-contact type machining process so it has the advantages of introducing no mechanical forces on the sheetmetal. Thus, all difficulties arising from mechanical cutting tools can be avoided. In LBC process, intense energy of laser light first heats up the surface of sheet metal and subsequently, sheetmetal is melted and the molten material is further removed with the help of assist gas such as (oxygen gas, nitrogen gas, argon gas) at required pressure [3-5]. During the expulsion of the molten metal from the kerf, some of the material is adhered to the bottom side of the kerf which causes unevenness. This non-uniformity of the kerf width at bottom side can be quantified in terms of bottom kerf deviation (BKD). Various researchers have been examined the geometrical quality characteristics of the laser cut kerf (i.e. Kerf width, Kerf taper & Kerf deviation) to analyze the effect of different input process parameters on these cut qualities.

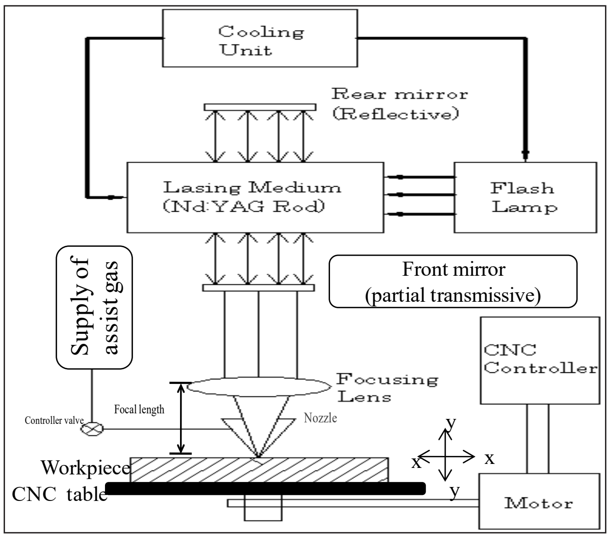

Fig. 1: Schematic Diagram of LBC System

Ghany and Newishy, found the variation in kerf width with the increment of cutting speed, laser power, pulse frequency and type of gas pressure during Nd-YAG laser cutting of austenitic stainless steel sheet of 1.2 mm thickness. They employed the laser in pulsed as well as continuous wave (CW) mode. Finally, they concluded that the kerf width is decreased by increasing the pulse frequency and cutting speed while increased with the laser power, focus position and gas pressure [6]. Thawari *et al.*, studied the effects of spot overlap in pulsed Nd-YAG laser cutting of nickel-based superalloy thin sheet (Hastelloy-X) having thickness 1 mm. They observed that the kerf width increases at top and bottom side while surface roughness decreases with the increment of spot overlap. They also found that the longest pulse duration (2 ms) considered in the study accountable to results in higher kerf taper [7]. Karatas *et al.*, investigated the effects of focal position on kerf width during CO_2 laser cutting of hot rolled and pickled steel sheets of 1.5 mm and 3.5 mm thickness [8].

Dubey and Yadava, optimized the kerf taper (KT) and material removal rate (MRR) during the pulsed Nd-YAG laser cutting of aluminum alloy (8011) sheet of 0.9 mm thickness using Computer Aided Robust Parameter design (CARPD) software. They found a considerable improvement in both the cut quality characteristics during optimization and analyzed that cutting speed is as most significant factor for MRR. However, pulse width is found to be the most significant factor for kerf taper [9]. Recently, kerf geometry has been investigated during cutting of aluminum alloy (Al-6061T6) sheet of 1 mm thickness by Leone *et al.*, using 150 MW multimode pulsed Nd-YAG laser [10]. They have considered beam travel direction, pulse duration and cutting speed as a laser cutting parameters. They have been found that the beam travel direction affects both the kerf width and taper angle and pulse duration affects the bottom kerf, taper angle and dross height.

Rao and Yadava, studied the effects of laser cutting parameters (oxygen pressure, pulse width, pulse frequency and cutting speed) during laser cutting of thin Ni-base superalloy sheet along straight as well as curved cut. They optimized kerf width, kerf taper, and kerf deviation simultaneously using grey relational analysis (GRA) with entropy measurement [11]. Dubey and Yadava, applied hybrid approach of TM and RSM for multi-objective optimization of laser beam cutting process, which is termed as TMRSM approach. They developed response surface model for KW and MRR where gas pressure, pulse width, pulse frequency and cutting speed were taken as laser cutting parameters [12]. Subsequently, Sharma and Yadava, applied hybrid approach of TM and RSM to develop the model for average kerf taper (AKT) and average surface roughness (ASR) along the straight profile cut and the model for AKT and average kerf deviation (AKD) along curved profile cut during pulsed Nd-YAG laser cutting of thin Al-alloy sheet [13-14].

In the present study, bottom kerf deviation (BKD) has been considered for modeling in pulsed Nd-YAG LBC of aluminum alloy (Al 6061-T6) sheet. Four input process parameters taken are lamp current (LC), pulse width (PW), pulse frequency (PF), and cutting speed (CS) for the study. First, experiments have been conducted on sheetmetal using Box-Behnken design (BBD) and the experimental results have been further utilized to develop the mathematical model. Subsequently, parametric influences have been studied using response surface model.

II. Experimentation and Measurements

Experiments for the present work are conducted on a pulsed Nd-YAG laser beam cutting system of 250 W (CNCPCT-300 model) available at Raja Ramanna Center for Advance Technology (RRCAT), Indore, India. Compressed gas is used as the assist gas for cutting which is passed through a conical nozzle of 1.5 mm diameter co-axially with the laser beam. Aluminum-alloy (Al-6061-T6) sheet of having thickness 1.3 mm is used for the study. The chemical composition of Al-6061-T6 alloy (% by weight) is shown in Table I. The nozzle diameter, focal length of lens (35 mm), stands off distance (SOD-2 mm), sheet material thickness and gas pressure (10 kg/cm^2) were kept constant throughout the experimentation.

Table 1: Chemical Composition of AL 6061-T6

Elements	Mg	Si	Cr	Mn	Fe	Cu	Zn	Ti	Al
% (by weight)	1.2	0.8	0.35	0.15	0.7	0.40	0.25	0.15	96

Lamp current (LC), pulse width (PW), pulse frequency (PF), and cutting speed (CS) are considered as cutting parameters for the LBC process. The range of these parameters is decided based on the pilot experimentation for through cutting of Al-6061-T6 alloy sheet. In the present study, three levels for each factor have been decided to conduct the experiments. The numerical values of these cutting parameters corresponding to each level have been given in Table II.

Table II: Laser Cutting Parameters and Their Levels

Laser Cutting Parameters	Levels		
	L1 (-1)	L2 (0)	L3 (+1)
LC (A)	240	260	280
PW (ms)	4	5	6
PF (Hz)	4	7	10
CS (mm/min)	20	40	60

After the selection of laser cutting parameters and deciding their levels, experiments are designed using Box-Behnken design (BBD). BBD is one of the types of rotatable second-order designs [15]. It has been chosen for the study due to shorter range of process parameters and to perform less experimental runs. Due to the wide acceptability of the design, it is used for the optimization of cut quality characteristics during LBC of different sheet materials [16-17]. In BBD, experiments under the extreme conditions are avoided because it does not contain combination of factors at which the factors are simultaneously at their highest and lowest levels [18].

The LBC of Al-alloy sheet is performed along straight cut profile. The cut profile is shown in (Fig. 2) in which cut length of straight cut is 19 mm. The bottom kerf widths (BKW) are measured using optical measuring microscope (Model: LEICA-S8APO) at 10x magnification available at RRCAT, Indore. Kerf widths at bottom side are measured at five different locations along the length of cut. The location of measurements is taken at equal distance (as shown in Fig. 2) and the experimental results of BKD corresponding to each experimental run has been tabulated in Table III.

Table III: Experimental Results based on BBD

Exp. No.	LC	PW	PF	CS	BKD (mm)
1	280	5	10	40	0.218
2	260	6	7	20	0.186
3	260	6	7	60	0.298
4	280	4	7	40	0.224
5	260	5	7	40	0.248
6	240	5	10	40	0.185
7	260	4	10	40	0.371
8	280	5	4	40	0.31
9	260	6	4	40	0.246
10	240	4	7	40	0.229
11	260	4	4	40	0.186
12	240	6	7	40	0.167
13	240	5	7	20	0.235
14	240	5	4	40	0.247
15	280	5	7	60	0.123
16	280	6	7	40	0.198
17	260	6	10	40	0.129
18	260	4	7	60	0.215
19	260	5	7	40	0.186
20	260	5	10	60	0.18
21	260	4	7	20	0.373
22	260	5	4	20	0.309
23	260	5	7	40	0.111
24	260	5	10	20	0.093
25	240	5	7	60	0.155
26	260	5	4	60	0.124
27	280	5	7	20	0.265

The aim of the research is to model the BKD. BKD along the length of cut can be computed using following equation:

$$\text{BKD (mm)} = \text{Maximum of BKW} - \text{Minimum of BKW} \quad (1)$$

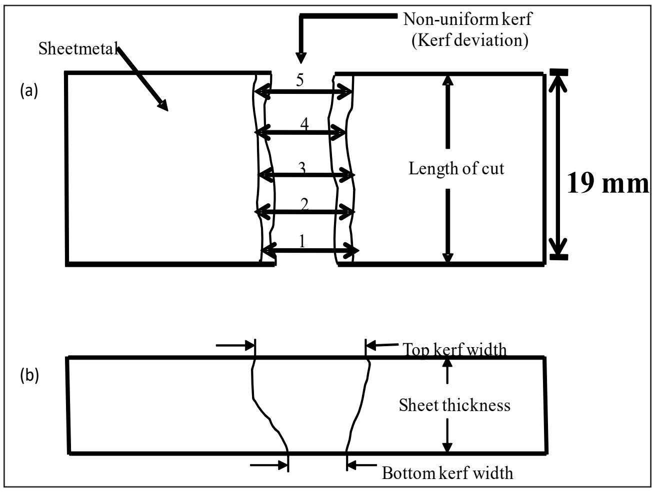

Fig. 2: Schematic Diagram of Laser Cut Specimen (a) Top View and (b) Front View

III. Response Surface Methodology (RSM)

RSM is a collection of mathematical and statistical technique which is useful for the modeling and analysis of the engineering problems. In RSM, following procedure has been followed: selection of parameters with significant effects, selection of proper experimental design, fitting of adequate mathematical model, checking the accuracy of the fitted model and evaluation of its prediction behavior with respect to the experimental data [18-19]. A polynomial model of the second order type has been expressed below to represent the functional relationship between laser cutting parameters and the response surface:

$$y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_i^2 + \sum \beta_{ij} x_i x_j \quad (2)$$

where, β_0, β_i, β_{ii} and β_{ij} all are the regression coefficients and x_i, $x_i x_j$ are the input variables that influence the responses. These regression coefficients are determined using regression analysis. In order to estimate the regression coefficients, experiment has been performed using Box-Behnken design (BBD). BBD is rotatable and used for a small number of factors (four or less). BBD is the more efficient design technique among other response surface designs like central composite design (CCD) and full factorial design. In BBD, less number of experiments is required for developing the models [25]. Further, the developed models have been tested to check the competency of the model by performing the analysis of variance (ANOVA).

IV. Results and Discussion

A. Modelling of BKD using RSM

The experiments have been conducted using BBD and the experimental results of BKD corresponding to each experimental run has been tabulated in Table III. Further, the experimental results have been used for developing mathematical models. The model for BKD during LBC of Al 6061 T-6 alloy sheet is developed using MINITAB software which is expressed as:

$$\begin{aligned} y_{BKD} &= 0.150333 - 0.007083 \times LC - 0.020417 \times PW - 0.003750 \times PF - 0.06697 \times CS \\ &+ 0.030875 \times LC^2 + 0.049625 \times PW^2 + 0.021375 \times PF^2 + 0.044125 \times CS^2 \\ &- 0.040500 \times LC \times PW - 0.042750 \times LC \times PF + 0.080500 \times LC \times CS \\ &- 0.001000 \times PW \times PF - 0.022750 \times PW \times CS + 0.059000 \times PF \times CS \end{aligned} \quad (3)$$

To test whether the data are fitted in the model or not, the calculated S value of the regression analysis for BKD is obtained as 0.02509, which is smaller. The R-Sq and R-Sq (adj) values for BKD are 94.6% and 88.4%, respectively. These values are tabulated in Table IV along with the regression coefficients.

Table IV: Regression Coefficients for BKD based on Coded Units

BKD			
Term	Coefficients	T-value	P-value
Constant	0.150333	10.377	0.000
LC	-0.007083	-0.978	0.347
PW	-0.020417	-2.819	0.016
PF	-0.003750	-0.518	0.614
CS	-0.066917	-9.238	0.000
LC*LC	0.030875	2.842	0.015
PW*PW	0.049625	4.567	0.001
PF*PF	0.021375	1.967	0.073
CS*CS	0.044125	4.061	0.002
LC*PW	-0.040500	-3.228	0.007
LC*PF	-0.042750	-3.407	0.005
LC*CS	0.080500	6.416	0.000
PW*PF	-0.001000	-0.080	0.938
PW*CS	-0.022750	-1.813	0.095
PF*CS	0.059000	4.702	0.001
S = 0.02509 , R-sq = 94.6%, R-sq (adj) = 88.4%			

The values of R-square and R-square (adjusted) are reasonably high for the model, therefore modelfit the data during LBC of Al-alloy sheet. Analysis of variance (ANOVA) and consequent F-value and P-value tests have been carried out to test the adequacy of developed BKD model and the results of ANOVA have been tabulated in Table V. Results show that the p-value of source of regression, liner effects, square effects and interaction effects has been found to be lower than the 0.05 for each response. Computed F-value of the lack-of-fit is found as: 1.80 which is lower than the critical value of the F-distribution 19.4 as found from the standard table at 95% confidence level [18].

Table V: Results of ANOVA for Response Surface Model

Source	BKD	
	F-value	P-value
Regression	15.14	0.000
Linear	23.63	0.000
Square	7.20	0.003
Interaction	14.77	0.000
Lack of fit	1.80	0.409

In order to determine the residuals of each individual experiment run, the regression model is used. Residuals are the difference between measured values and predicted values. The residuals are calculated and ranked in rising order. The normal probabilities of residuals for BKD are shown in Fig. 3. The data are spread roughly along the straight line, indicating that the data are normally distributed and it can be concluded that the developed model is valid. Fig. 4 shows the plot of residual versus fitted values where the maximum variation between measured and fitted values are found as: -0.10 and 0.15. These plots do not expose any obvious pattern and therefore the fitted model is adequate. The variation of residuals against the observation order is shown in the (Fig. 5). The plot shows that the residuals are distributed equally in both the positive and negative direction along the run. Hence, the data is said to be independent.

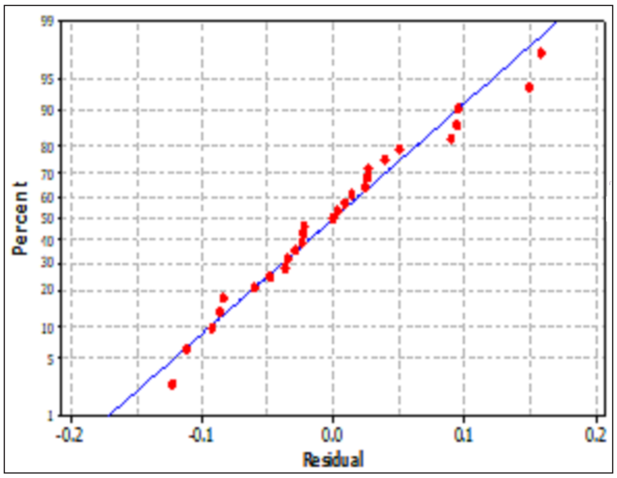

Fig. 3: Normal Probability Plot of BKD

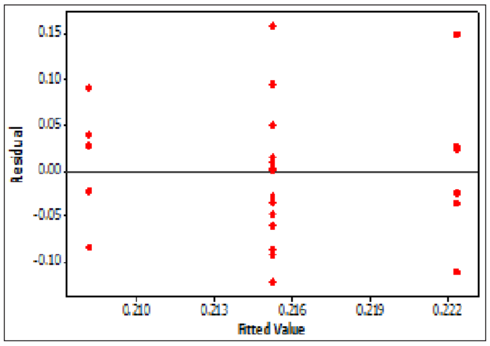

Fig. 4: Plot of Residuals versus the Fits for BKD

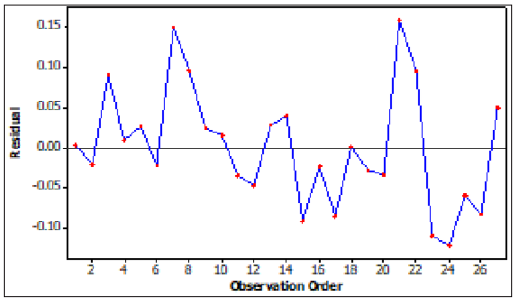

Fig. 5: Plot of Residual versus Observation Order for BKD

B. Analysis of Parametric Influence

In the present study pulsed Nd-YAG laser cutting of Al 6061 T-6 sheet has been carried out. During the process, lower values of BKD are preferred for obtaining the good quality laser cut. Hence, the influences of the laser cutting parameters (i.e. lamp current, pulse width, pulse frequency and cutting speed) on BKD during cutting operation have been analyzed. Fig. 6 shows the combined effects of lamp current and pulse frequency on BKD where the pulse width and cutting speed are kept constant at their central levels. From the figure, it can be observed that BKD decreases with the increment in lamp current at higher level of pulse frequency and also with the decrement of pulse frequency at lower value of lamp current.

The combined effects of lamp current and cutting speed on BKD are shown in (Fig. 7), where pulse frequency and pulse width are kept constant at their central levels. From the figure, it has been found that BKD decreases with the increment of lamp current at lower value of cutting speed. This is due to fact that the lower value of cutting speed gives the sufficient time to laser for interaction with the sheetmetal which gives the smooth cutting. The combined effects of pulse frequency and cutting speed on BKD are shown in Fig. 8. From this figure, it has been found that BKD decreases with the increment of pulse frequency at lower value of cutting speed.

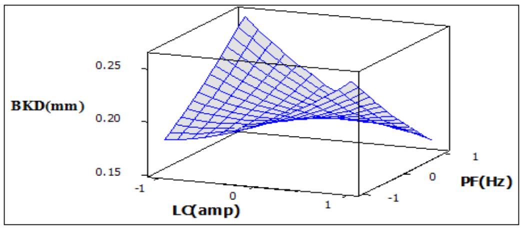

Fig. 6: Effect of Lamp Current and Pulse Frequency on the BKD

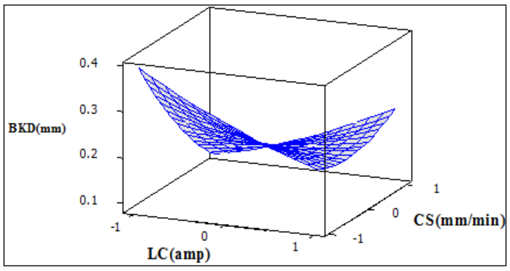

Fig. 7: Effect of Lamp Current and Cutting Speed on the BKD

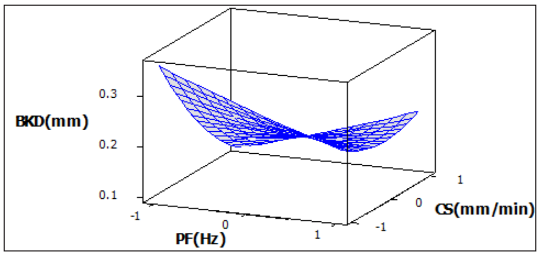

Fig. 8: Effect of Pulse Frequency and Cutting Speed on the BKD

V. Conclusion

In the present study, mathematical model for BKD has been developed in pulsed Nd-YAG laser cutting of aluminum alloy (Al-6061 T6) sheet using the RSM. The following conclusions have been drawn from the study:

- The developed second order response surface model for BKD has been found satisfactory. It is also found from the results of regression coefficients that the liner as well as square and interaction effects of input process parameters is significant for developed response surface model.
- From the parametric study it has been found that the combination of high level of pulse frequency and lamp current is most attractive to achieve the minimum bottom kerf deviation.

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