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Experimental Investigation of Kerf Width and Kerf Taper in Fiber Laser Cutting of Aluminium Alloy

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Abstract –*In order to examine the impact of process parameters on the laser cutting process, the laser cutting of Al 6061 is explored in this work using a fibre laser with variable laser power. The Kerf Width and Kerf Taper Angle are considered as a response characteristic. Response Surface Methodology (RSM) approach is used for experimental design. Box-Behnken Design (BBD) method of Response Surface Methodology (RSM) is used to plan the experiment.*

Keywords-*Laser Cutting, Response Surface Methodology, Laser Beam Machining, Kerf Width, Kerf Taper Angle.*

I -INTRODUCTION

Aluminum is one of the most adaptable, affordable, and beautiful metallic materials for a variety of applications, from soft, highly ductile wrapping foil to the most demanding engineering ones. This is due to the special combinations of qualities that aluminium and its alloys offer.The utilization of aluminium alloys as structural metals is second only to that of steel. [1]. Aluminium and its alloys are currently regarded as the top materials of choice utilised in many industries, including the automotive and aerospace industries, following steel[2][3].

One of the most common thermal energy-based advanced machining processes is laser beam machining (LBM), which uses laser energy instead of traditional mechanical energy. It is a two dimensional machining process in which material removal is achieved by focusing a highly intense laser beam on the work piece [4][6]. A laser beam with a high energy density provides highly targeted heating on a workpiece in the Laser Beam Machining method. The material is caused to melt, vaporize or ablate in order to remove the material from the piece at micron level. It is an energy-less thermal beam based non-contact tool with several unique advantages, such as a micro-machining potential, elimination of finishing operations, automation adaptability and increased material usage and faster machining [5].

II -LITERATURE REVIEW

In [4], the author employs top kerf deviation, bottom kerf deviation and top kerf width as output parameters and pulse width, pulse frequency, gas pressure, and cutting speed as input parameters. They used Taguchi methodology for modeling and fuzzy logic as optimization technique. In [10], author uses laser power, cutting speed, pulsing frequency and gas pressure used as input parameters and kerf width, cut edge surface roughness and heat affected zone used as output parameters. They used Taguchi-Fuzzy hybrid approach for modelling and optimization. Cutting speed and pulsing frequency are found as the significant parameters for the laser cutting of Aluminum alloy 5083.

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As input parameters in [11], the author employs pulse energy, pulse width and cutting speed,; as output parameters, material removal rate and surface roughness. According to experimental findings, the lowest surface roughness was 6.23 µm with the following parameters: V=1.2 mm/s, E=4.5 J, and w=0.5 ms. With input parameter values of V=1.8 mm/s, E=6.8 J, and W=0.5 ms for the material AA1200 aluminium alloy, the maximum MRR achievable is 57.494 mg/min. In [12], author uses Laser power and scanning speed are used as input parameters and area, perimeter as the output responses. To conduct their work, they used a L9 orthogonal array and the Taguchi method. In [13], author uses assistant gas flow, distance between surface of work piece and beam focus location (defocus), repetition rate frequency, and pumping current used as process parameters. Depth, width, and contrast of engraved zone considered as output parameters for the material Al-SiC composite. Central composite design method is used to design experiments based on the response surface methodology (RSM). The result shows that increasing of repetition rate frequency and pumping current simultaneously, leads to decreasing in width and depth of engraved zone, and increasing in assistant gas flow, leads to increasing in width and depth of engraved zone. In [14], author used Nd:YAG laser and Nitrogen as an assist gas. Pulse energy, pulse width and cutting speed, are considered as controllable input parameters. surface roughness, kerf width, kerf deviation, and material removal rate are measured as output parameters. ANN-PSO model combining Artificial Neural Networks (ANN) and Particle Swarm Optimization (PSO) was used for prediction and optimization.

III -PERFORMANCE PARAMETERS

The performance of laser machining mainly depends on appropriate selection of input process parameters. Due to converging–diverging shape of laser beam profile as shown in figure 1, kerf taper always exist during laser machining.

Kerf is the width of material that the process removes as it cuts through the plate. Each cutting process removes a different amount of material, or kerf. The more precise processes, like waterjet and laser, remove a smaller amount of kerf, which is one of the reasons of more precise.

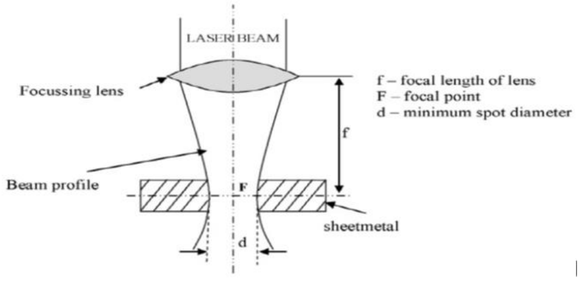

Fig. 1- Kerf taper in laser machining [4]

Figure 2 shows the schematic diagram of top and bottom kerf width. Figure 3 shows schematic diagram of kerf width. Kerf taper angle measurements of the all samples are measured by the use of profile projector. The quality control inspection team will find this tool, often referred to as a shadow graph, handy in a small parts machine shop or manufacturing line.The built-in projection screen is used to display the specimen's profile once it has been magnified by the projector. In order to observe or measure a straight edge of the machined object, the X-Y axis of this screen may normally be rotated 360 degrees to align with the grid.For more ease in calculating linear measures, this projection screen shows the specimen's profile and is magnified.The grid on the screen is matched up with an edge of the specimen to be examined.To determine the distance to other sites, straightforward measurements are made from there. On a magnified profile of the specimen, this is being done.Measuring using a profile projector's enlarged projection screen might be easier and less prone to error. The kerf taper angle is calculated by

$$\theta = \tan^{-1}\frac{(W_t - W_b)}{2h} (1)$$

where, W_t = kerf top width (mm), W_b = kerf bottom width (mm), h = thickness (mm)

The kerf top width is calculated by taking three reading at fixed interval from top surface of the specimen and its average is taken.

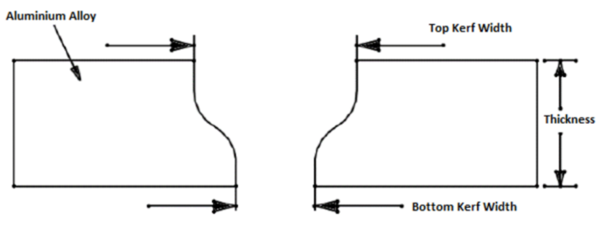

Fig. 2- Schematic representation of top and bottom kerf width

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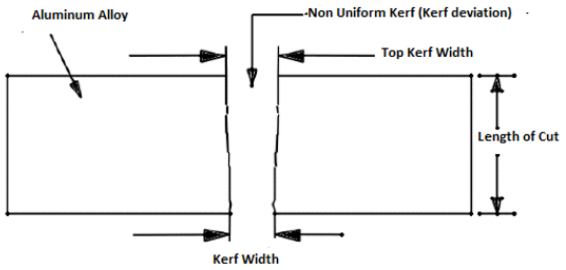

Fig. 3- Schematic representation of kerf width

IV-MATHEMATICAL MODEL

The relationship between the output and inputs can be expressed by a linear, second order (quadratic), or exponential equation when the kerf width values are viewed as the output and the cutting parameters as the inputs.

Linear model

It is possible to think of the dependent variable V as a linear combination of the independent variables Cutting Speed, Laser Power, and Gas Pressure. Therefore, the equation is as below:

$$V = k_0 + k_1 A + k_2 B + k_3 C (2)$$

where, A represents Laser Power, B represents Cutting Speed, C represents Gas Pressure.

Second order model

The association between the dependent variable V and the independent variables Cutting Speed,Laser Power, and Gas Pressure is apparently shown by the equation below.

$$V = k_0 + k_1 A + k_2 B + k_3 C + k_4 A^2 + k_5 B^2 + k_6 C^2 + k_7 AB + k_8 AC + k_9 BC (3)$$

EXPERIMENTATION

Specifications of Al 6061 Plate

Aluminium 6061

Sheet Dimensions – 250mm * 220mm* 12 mm

Sheet thickness – 12mm

Cut Part Dimensions 30 * 30 mm.

DOE Based Experimental Plan

Response surface methodology (RSM) approach [5][6] is used for experimental design. Design-Expert software is used for Response surface methodology (RSM) approach. Box-Behnken design (BBD) method of response surface methodology (RSM) is used to plan the experiment. In the present study, AMADA LCG3015AJ 6000W fibre laser is used. Laser machining is completed at M/s Anand Lasers, Pune, India. Material used is 12mm thick Al 6061 [Commercial Aluminium] with size of 250mm × 220mm × 12 mm. Nitrogen is used as assist gas. The square shape blocks with dimensions of 30mm × 30mm are cut by laser machine with different combinations of input parameters and the series of experiments are performed on 17 samples according to the experimental plan. Table 1 shows the levels of process parameters for LBM of Al 6061. Table2 shows experimental plan for LBM of Al 6061 material of specimen thickness 12 mm and data for kerf width. Table 3 shows Experimental data for kerf taper.

Table 1- Levels of Process Parameters for LBM

Process Parameter	Min	Max
Laser power (watt)	5500	6000
Cutting speed (mm/min)	1300	1700
Gas pressure (MPa)	1.4	1.8

Table 2- Experimental plan and Data for Kerf Width

Std	Run	Factor 1 A:Laser power (watt)	Factor 2 B:Cutting speed (mm/min)	Factor 3 C:Gas pressure (MPa)	Response 1 Kerf Width (mm)
7	1	5500	1500	1.8	0.24
17	2	5750	1500	1.6	0.265
16	3	5750	1500	1.6	0.27
5	4	5500	1500	1.4	0.23
8	5	6000	1500	1.8	0.29
4	6	6000	1700	1.6	0.235
2	7	6000	1300	1.6	0.35
14	8	5750	1500	1.6	0.265
3	9	5500	1700	1.6	0.23
13	10	5750	1500	1.6	0.25
1	11	5500	1300	1.6	0.28
12	12	5750	1700	1.8	0.225
15	13	5750	1500	1.6	0.275
11	14	5750	1300	1.8	0.31
10	15	5750	1700	1.4	0.23
9	16	5750	1300	1.4	0.26
6	17	6000	1500	1.4	0.235

Table 3- Experimental plan and Data for Kerf Taper

		Factor 1	Factor 2	Factor 3	Response 1
Std	**Run**	**A:Laser power (watt)**	**B:Cutting speed (mm/min)**	**C:Gas pressure (MPa)**	**Kerf Taper (degree)**
7	1	5500	1500	1.8	0.2476
17	2	5750	1500	1.6	0.2864
16	3	5750	1500	1.6	0.266
5	4	5500	1500	1.4	0.3647
8	5	6000	1500	1.8	0.2298
4	6	6000	1700	1.6	0.3348
2	7	6000	1300	1.6	0.2444
14	8	5750	1500	1.6	0.2742
3	9	5500	1700	1.6	0.3814
13	10	5750	1500	1.6	0.2506
1	11	5500	1300	1.6	0.2202
12	12	5750	1700	1.8	0.3509
15	13	5750	1500	1.6	0.2557
11	14	5750	1300	1.8	0.2208
10	15	5750	1700	1.4	0.4089
9	16	5750	1300	1.4	0.2533
6	17	6000	1500	1.4	0.2931

V-STATISTICAL ANALYSIS & DEVELOPMENT OF MODELS

Models are developed for all output parameters and analyzed using analysis of variance (ANOVA). Then models are validated by calculating percentage errors in predicted responses.

Analysis of Variance (ANOVA) is used to analyze models created in RSM. Table 4 shows ANOVA for kerf width. Table 5 shows ANOVA for Kerf Taper.

Table 4- ANOVA for Kerf Width

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0172	9	0.0019	17.51	0.0005	**significant**
A-Laser power	0.0021	1	0.0021	19.39	0.0031	
B-Cutting speed	0.0098	1	0.0098	89.97	< 0.0001	
C-Gas pressure	0.0015	1	0.0015	13.89	0.0074	
AB	0.0011	1	0.0011	9.70	0.0170	
AC	0.0005	1	0.0005	4.65	0.0680	
BC	0.0008	1	0.0008	6.94	0.0337	
A²	1.645E-06	1	1.645E-06	0.0151	0.9057	
B²	0.0003	1	0.0003	2.55	0.1542	
C²	0.0012	1	0.0012	11.01	0.0128	
Residual	0.0008	7	0.0001			
Lack of Fit	0.0004	3	0.0001	1.57	0.3281	**not significant**
Pure Error	0.0004	4	0.0001			
Cor Total	0.0179	16				

The model is suggested to be significant by the model's F-value of 17.51. An F-value this large might happen as a result of noise only 0.05% of the time. Significant model terms are those with P-values less than 0.0500. In this case A, B, C, AB, BC, C² are significant model terms. The Lack of Fit F-value of 1.57 implies the Lack of Fit is not significant relative to the pure error. There is a 32.81% chance that a Lack of Fit F-value this large could occur due to noise.

Table 5- ANOVA for Kerf Taper

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0532	9	0.0059	16.28	0.0007	**significant**
A-Laser power	0.0016	1	0.0016	4.30	0.0767	
B-Cutting speed	0.0361	1	0.0361	99.38	< 0.0001	
C-Gas pressure	0.0092	1	0.0092	25.26	0.0015	
AB	0.0013	1	0.0013	3.45	0.1056	
AC	0.0007	1	0.0007	1.99	0.2009	
BC	0.0002	1	0.0002	0.4477	0.5249	
A²	0.0000	1	0.0000	0.0451	0.8378	
B²	0.0030	1	0.0030	8.23	0.0240	
C²	0.0010	1	0.0010	2.70	0.1446	
Residual	0.0025	7	0.0004			
Lack of Fit	0.0017	3	0.0006	2.77	0.1747	**not significant**
Pure Error	0.0008	4	0.0002			
Cor Total	0.0557	16				

The model is suggested to be significant by the model's F-value of 16.28.An F-value this large might happen owing to noise just 0.07% of the time.Model terms are considered significant when the P-value is less than 0.0500. In this case B, C, B² are significant model terms. The Lack of Fit F-value of 2.77 implies the Lack of Fit is not significant relative to the pure error. A large Lack of Fit F-value has a 17.47% likelihood of being caused by noise.

Equation in terms of actual factors is used to calculate the predicted values of kerf width and kerf taper angle and given in table 6 and 7 along with experimental values. From table 6 and table 7, it is observed that the minimum and maximum percentage deviation between experimental and predicted values of kerf width are 0 and 6.0 and for kerf taper angle 0.23 and 6.91 respectively.

The relationship between the actual and predicted values of experiment of Al 6061 for 12mm using laser machining process is shown in figure 4. It has observed that the developed model is adequate and predicted results are in good agreement with the experimental results.

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Table 6- Experimental and predicted values of Kerf Width

	Process Parameters			Kerf Width		
Run	**Laser Power**	**Cutting Speed**	**Gas pressure**	**Experimental**	**Predicted**	**Percentage Deviation (%)**
1	5500	1500	1.8	0.2400	0.2350	2.08
2	5750	1500	1.6	0.2650	0.2650	0.00
3	5750	1500	1.6	0.2700	0.2650	1.85
4	5500	1500	1.4	0.2300	0.2300	0.00
5	6000	1500	1.8	0.2900	0.2900	0.00
6	6000	1700	1.6	0.2350	0.2388	-1.62
7	6000	1300	1.6	0.3500	0.3413	2.49
8	5750	1500	1.6	0.2650	0.2650	0.00
9	5500	1700	1.6	0.2300	0.2388	-3.83
10	5750	1500	1.6	0.2500	0.2650	-6.00
11	5500	1300	1.6	0.2800	0.2763	1.32
12	5750	1700	1.8	0.2250	0.2213	1.64
13	5750	1500	1.6	0.2750	0.2650	3.64
14	5750	1300	1.8	0.3100	0.3188	-2.84
15	5750	1700	1.4	0.2300	0.2213	3.78
16	5750	1300	1.4	0.2600	0.2638	-1.46
17	6000	1500	1.4	0.2350	0.2400	-2.13

Table 7- Experimental and predicted values of Kerf Taper Angle

	Process Parameters			Kerf Taper Angle		
Run	**Laser Power**	**Cutting Speed**	**Gas pressure**	**Experimental**	**Predicted**	**Percentage Deviation (%)**
1	5500	1500	1.8	0.2476	0.2505	-1.17
2	5750	1500	1.6	0.2864	0.2666	6.91
3	5750	1500	1.6	0.2660	0.2666	-0.23
4	5500	1500	1.4	0.3647	0.3451	5.37
5	6000	1500	1.8	0.2298	0.2494	-8.53
6	6000	1700	1.6	0.3348	0.3307	1.22
7	6000	1300	1.6	0.2444	0.2318	5.16
8	5750	1500	1.6	0.2742	0.2666	2.77
9	5500	1700	1.6	0.3814	0.3940	-3.30
10	5750	1500	1.6	0.2506	0.2666	-6.38
11	5500	1300	1.6	0.2202	0.2243	-1.86
12	5750	1700	1.8	0.3509	0.3354	4.42
13	5750	1500	1.6	0.2557	0.2666	-4.26
14	5750	1300	1.8	0.2208	0.2138	3.17
15	5750	1700	1.4	0.4089	0.4159	-1.71
16	5750	1300	1.4	0.2533	0.2688	-6.12
17	6000	1500	1.4	0.2931	0.2902	0.99

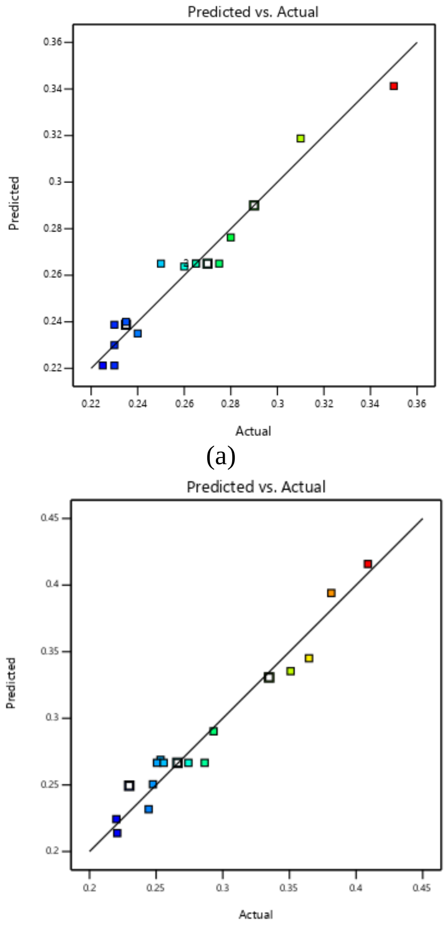
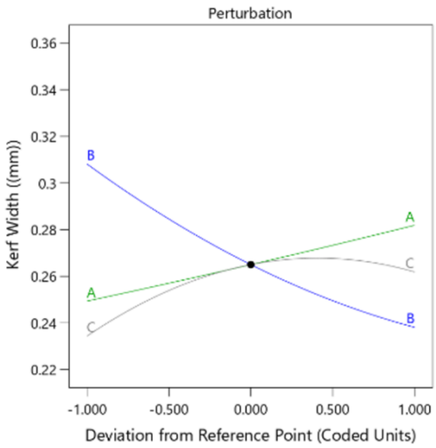


Fig. 4- Actual vs Predicted values for (a) Kerf Width (b) Kerf Taper Angle



(a)

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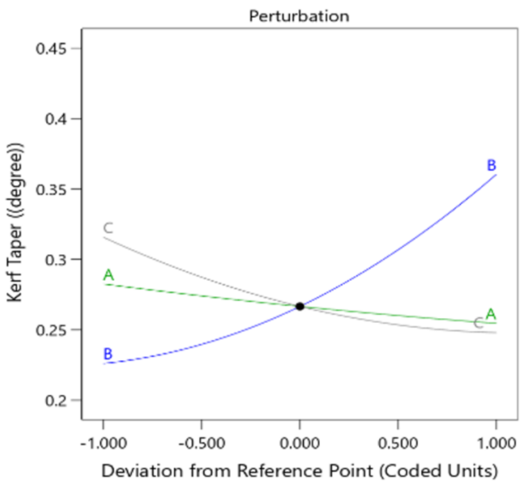

(b)

Fig. 5- Influence of process parameters for (a) Kerf Width (b) Kerf Taper Angle

VI- CONCLUSION

Analysis of the influence of process parameter on the laser cutting process has performed with fiber laser machine on 12 mm thickness of Al 6061. After DOE analysis total 17 run have identified for experiment with sheet operation. Experimental result shows that minimum kerf width of 0.225 mm is obtained at cutting speed 1700 mm/min, gas pressure 1.8 MPa, laser power of 5750 W, minimum kerf taper of 0.2202 degree is obtained at cutting speed 1300 mm/min, gas pressure 1.6 MPa & laser power of 5500 W. Kerf width decreases with increase in cutting speed remarkably. With increase in laser power and gas pressure causes little increase in kerf width. Kerf taper increases with increase in cutting speed. Increase in gas pressure and laser power causes slight decrease in kerf taper.

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