Optimization of surface roughness on stainless steel 316L using low power fiber laser beam machining

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Abstract

Laser has become an attractive tool and a popular mode for its good quality of cutting metal with low level of surface roughness. But it is always extremely difficult to achieve good quality cutting on sheet metal (1mm thickness) using low power fiber laser beam machining in the order of 50W. Among several process variables a relatively uncommon process variable i.e. sawing angle plays a very significant role in determining the surface roughness characteristics in low power solid state laser beam machining. In the present research study laser cutting in stainless steel 316L alloy is investigated through multi diode pulsed fiber laser beam machining. Experimental investigation based on Central Composite Design (CCD) of Response Surface Methodology (RSM) has been carried out to determine mathematical model and also an optimization analysis on surface roughness (Ra). Investigation of the effect of sawing angle with other process parameters such as cutting speed, power setting, duty cycle and pulse frequency on the surface roughness for a stainless steel has been conducted. Experimental validation of the proposed model shows that desired surface roughness can be obtained by optimization of controllable of proper process parameters. Also regression analysis is used to develop model to predict the effect of independent process parameters on laser cut quality.

Keywords: Sawing angle, RSM, Stainless steel 316 L, Surface roughness.

1. INTRODUCTION

Though invented in 1960s, high intensity laser cutting has attained a wide range of application in the field of precision cutting of sheet metals. Conductive and non-conductive advanced engineering materials like reflective metals, plastics, ceramics and composites which are difficult to cut, can be successfully cut with the help of laser beam cutting (LBC).[1] Besides cutting difficult to cut materials LBC can perform complex shapes or profiles with close tolerances for cutting steel sheets, for that it is extensively used in industries. Stainless steel 316 L alloy for its superior properties remains to be high demand in various industries. Poor thermal conductivity, low elastic modulus and high chemical affinity at elevated temperatures make this alloy difficult to process for the conventional cutting methods. Solid state Nd: YAG laser and fiber laser are used most extensively in industrial cutting of sheet metals. The qualities like high intensity, low spot diameter, good focusing characteristic, localized heating and narrow heat affected zone (HAZ) have made diode pumped fiber lasers to earn growing popularity in industrial precision cutting of thin sheet metals. The non conventional thermal machining process laser beam cutting helps to obtain material removal by focusing a highly intensive laser beam on the workpiece.[2] The thermal energy of the laser beam afterward helps to melt as well as vaporize the workpiece all through the thickness /depth of the material and ultimately creates a cutting front with the help of an uncommon process parameter i.e. sawing angle. Compressed air plays the role of assist medium which causes expulsion of the molten material from the cutting front along with same cooling effect on the machining zone.[3]
The relationship between surface roughness and input variables such as sawing angle, cutting speed, laser power, duty cycle, and pulse frequency has not been studied by many researchers. Chen [4] observed that a decrease in the value of the surface roughness is caused by an increase in the air pressure and cutting speed. Rajaram et al. [5] found that a significant effect on the surface roughness and striation is generated by the laser power and cutting speed. Almeida et al [6] used factorial design approach to evaluate the effects of pulse energy, overlapping rate and type of assist gas on the surface roughness and dross formation when Nd: YAG laser cutting of titanium alloy (Ti 6Al 4V) is performed. For the high melting point and low viscosity of the formed oxides it is difficult for oxy fuel methods to cut an important engineering material like stainless steel.
The aim of this study is proper evaluation of the optimum laser cutting parameters for 1 mm AISI 316L stainless steel sheets with the use of low power pulsed fiber laser beam and air, as assist gas. Response surface methodology (RSM) is used in the present research work to investigate the effect of the main parameters, i.e. sawing angle, cutting speed, laser power, duty cycle, and pulse frequency affecting the machining criteria like surface roughness. ANOVA test has been applied successfully to check the adequacy of the machining criteria.

2. IMPORTANCE OF SAWING ANGLE

It is very difficult to perform through cutting upto 2 mm thickness by 50 W of average pulsed laser beam cutting. But this through cutting operation is possible by an uncommon process variable i.e. sawing angle and altering the constant focal point distance. Basically sawing angle at first produces an opening/kerf on the metal surface and afterwards changes the focal point position along the thickness and becomes capable of removal of material through proper focusing on the cutting operation in a proper way. In this process compressed air helps to remove dross adherence on the bottom edge and protects it from oxidation. Besides this assist gas helps to remove and clean re-deposited material.

3. EXPERIMENTAL PLANNING

A diode pumped pulsed fiber laser machining system, manufactured by M/S Sahajanand Laser Technology; India is used for the experimental purpose. This CNC motion system,

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fiber laser beam, collimator and cutting head are integrated to the experimental cutting system. The cutting head consists of a focusing optic and an assist gas nozzle. The exit hole diameter in the nozzle remains to be 0.6mm. The single mode core of the double clad fiber helps to create the fiber laser beam. The present experiment shows the collimated laser of a 9mm diameter and then focus with 21 µm spot diameter. The machine specification of the details is listed in table 1.

Table 1

Machine specification

Specification	Description
Laser type	Multi diode fiber laser
Wave length	1064 nm
Mode of operation	Pulsed mode
Mode of laser Beam	Fundamental/ Gaussian mode (TEM_{00})
Beam diameter $1/e^2$	9mm (after collimator)
Laser beam spot diameter	21 µm
Average power	50 W

Stainless steel AISI 316L specimens having a mean thickness of 1 mm is used as workpiece material. The experimental figure is a square block of 5×5 mm. The stainless steel materials are machined by fiber laser emitting at different machine parameter settings selected as per experimental model. A central composite design half (CCD) and response surface method have been applied to analyze the effect of the five major laser micro cutting process parameters i.e. sawing angle, cutting speed, laser power, duty cycle, and pulse frequency. Total 32 experiments have been conducted and replicate with three times. Development of a regression model equation relating to surface roughness to the input variables has been made out of experimental data of surface roughness. Contact type stylus Mitutyo surface roughness tester (SURFTEST SJ-410) is used to measure the arithmetic mean surface roughness (centre line average) which is considered to be a controlling parameter in industries for machining process and product quality. A schematic representation of job holding fixture is shown in figure 1. After taking the measurements for three times average values are calculated and reported for analysis. Air serves the purpose of assist gas in the experiment. The compressed air pressure is maintained at 3 bar. The ranges of process parameters are selected from the trail experiments. The ranges of each controllable process parameters as per response surface methodology technique are listed in table 2.

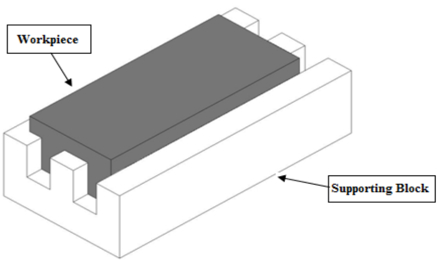

Fig.1. Schematic presentation of job holding fixture to measure surface roughness

Table 2

Controllable parameters and their limits

Controllable Parameters	Units	Levels				
		-2	-1	0	1	2
Sawing Angle (A)	ϴ	0.5	1	1.5	2	2.5
Cutting Speed (B)	mm/sec	0.5	0.75	1	1.25	1.5
Pulse Frequency (C)	Khz	50	55	60	65	70
Duty Cycle (D)	%	86	88	90	92	94
Working Power (E)	%	90	92	94	96	98

4. EXPERIMENTAL RESULTS AND DISCUSSION

Experimental details with coded values of process parameter settings and measured response are shown in table 3.

Table 3

DOE and experimental results

Experimental Information						Results
S.N	Machining Parameters (coded value)					Surface roughness (µm)
	A	B	C	D	E	
1.	-1	-1	-1	-1	1	4.148
2.	1	-1	-1	-1	-1	5.906
3.	-1	1	-1	-1	-1	4.655
4.	1	1	-1	-1	1	4.516
5.	-1	-1	1	-1	-1	2.480
6.	1	-1	1	-1	1	4.082
7.	-1	1	1	-1	1	3.601
8.	1	1	1	-1	-1	3.884
9.	-1	-1	-1	1	-1	4.222
10.	1	-1	-1	1	1	4.830
11.	-1	1	-1	1	1	5.180
12.	1	1	-1	1	-1	4.768
13.	-1	-1	1	1	1	4.180
14.	1	-1	1	1	-1	3.732
15.	-1	1	1	1	-1	4.127
16.	1	1	1	1	1	5.524
17.	-2	0	0	0	0	4.699
18.	2	0	0	0	0	6.094
19.	0	-2	0	0	0	5.546
20.	0	2	0	0	0	5.848
21.	0	0	-2	0	0	5.183
22	0	0	2	0	0	3.252
23.	0	0	0	-2	0	2.588
24.	0	0	0	2	0	2.787
25.	0	0	0	0	-2	2.287
26.	0	0	0	0	2	2.642
27.	0	0	0	0	0	2.772
28.	0	0	0	0	0	2.590
29.	0	0	0	0	0	2.843
30.	0	0	0	0	0	2.732
31.	0	0	0	0	0	2.626
32.	0	0	0	0	0	2.510

4.1 Developing of Mathematical Model

A second order rotable polynomial model has been developed to execute further analysis. Minitab 17 software is used for analyzing the response i.e. surface roughness and determination of the mathematical model with best fits is given below as equation no. 1.

Surface roughness (Ra) = 627 + 11.24 A - 64.2 B - 6.512 C - 5.92 D - 3.05 E + 2.659 A×A + 11.836 B×B + 0.01479 C×C - 0.00316 D×D - 0.01709 E×E - 1.195 A×B + 0.0255 A×C - 0.1474 A×D - 0.0602 A×E + 0.1324 B×C + 0.3244 B×D + 0.0609 B×E + 0.02338 C×D + 0.02526 C×E + 0.0538 D×E (1)

4.2 ANOVA analysis

In the present study the adequacy of the developed mathematical model for surface roughness, analysis of variance (ANOVA) and subsequent F and P value test have been conducted. Table 4 shows ANOVA of the quadratic model with other adequacy measures R^2, adjusted R^2 and predicted R^2. For understanding the effect of control factors on the responses, consideration of first order, second order and interactions between different control factors has been made. The associated p- value less than 0.05 for the model (i.e. α = 0.05 or 95% confidence level) as per table 4, shows statistical significance of the model terms. Importance of the second order regression models for these responses and linear and interactions of parameters is derived. F value (2.82) and P value (0.138) of the Lack of fit implies that it is not significant relative to the pure error, which is desired. From table it is observed that statistically: pulse frequency (55.31%) is most dominating factor followed by sawing angle (27.80%), duty cycle (6.85%), cutting speed (5.419%) and working power (4.52%).

Table 4

Analysis of Variance for surface roughness

Source	DF	Adj. SS	Adj.MS	F-Value	P-Value
Model	20	43.0521	2.1526	69.56	0.000
Linear	5	8.2687	1.6537	53.44	0.000
A	1	2.3058	2.3058	74.51	0.000
B	1	0.4480	0.4480	14.48	0.003
C	1	4.5736	4.5736	147.80	0.000
D	1	0.5670	0.5670	18.32	0.001
E	1	0.3743	0.3743	12.09	0.005
Square	5	30.4450	6.0890	196.77	0.000
2-Way interaction	10	4.3384	0.4338	14.02	0.000
Error	11	0.3404	0.0309	-	-
Lack of fit	6	0.2627	0.0438	2.82	0.138
Pure Error	5	0.0776	0.0155	-	-
Total	31	43.3925	-	-	-
S= 0.175910, R-sq = 99.22%, R-sq(adj) = 97.79%, R-sq (pred) = 83.77%					

From the surface plot in figure 2 shows the combined effect of significant process parameters pulse frequency and cutting speed on surface roughness. The sawing angle, Duty cycle and working power are kept constant at 1.5^0 , 90%, and 94% respectively. It is observed that increase in surface roughness causes an increase in the cutting speed at lower values of pulse frequency but when the values of pulse frequency become higher surface roughness lowers down after increasing the cutting speed. This is because of the fact that the extent of the spot overlaps in pulse mode laser cutting affects surface roughness mostly. The cut edge surface will be smoother when the spot overlap is more. The extent of spot overlap varries as per the combination of pulse frequency and cutting speed. High level of spot over lapping and continious power density per unit length are produced by low cutting speed due to comparative high interaction and it leads to complete cutting with uniform smooth surface. But with the increase in cutting speed at lower value of pulse frequencies, low spot overlapping, discontinuous power density along the cut front and less time for the melting of the materials, resulting in rough cutting i.e. an increase in surface roughness. For better surface roughness the pulse frequency and cutting speed is found within the range of 55-65 khz and 0.75-1.00 mm/sec respectively.

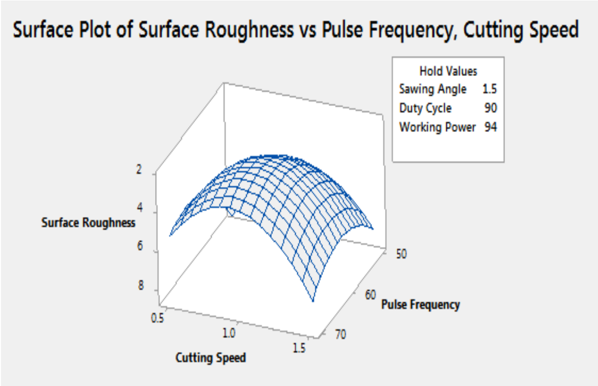

Fig.2. Surface plot of surafce roughness with pulse frequency and cutting speed

4.3 Conclusion of optimal process parameter

The optimization result for minimum corner inaccuracy based on the developed mathematical model i.e. equation 1 is shown in figure 3. The value count for linear desirability function (d) remains to be 1 i.e. all parameters are within their working limit. The parameter setting for minimum surface roughness value has been shown to be 2.0528 µm when sawing angle 1.3^0, cutting speed 0.80 mm/sec, pulse frequency 62 khz, duty cycle 87% and working power 98%.

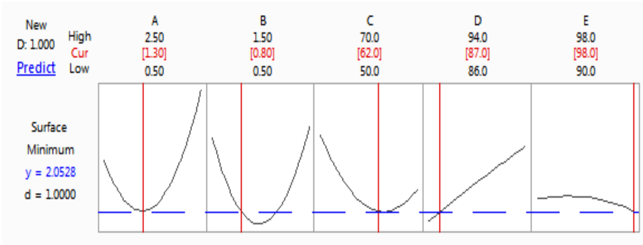

Fig. 3. Optimization result of surface roughness

Table 5

Confirmation testing

Responses	Actual Value	Predicted Value	Difference	% Error
Surface Roughness	2.0958	2.0528	0.043	2.05

After getting the optimal parameter settings for desired surface roughness characteristics, the next step is to verify the feasibility of the proposed response surface equations. The validation experiments show a small percentage error between the estimated and the experimental values suggesting the ability of the develop models to yield nearly exact results within the limits of cutting parameters being used.

5. CONCLUSION

In this present research Response Surface Methodology (RSM) is applied to investigate the effect of main parameters that affect the machining criteria such as surface roughness on stainless steel 316L. 50 W average laser system is successfully applied to through cut 1 mm thickness 316 L stainless steel with uncommon process parameter sawing angle. The effect of sawing angle illustrated in this paper in details. During the experiments focal distance changes after certain predefined depth achieved which is chosen from pilot experience to achieve desired cut quality. Simultaneous considerations of almost all the control factors have been made to establish the trends of variation. It can be concluded that surface roughness is controlled under certain critical machining condition sawing angle, pulse frequency, cutting speed, duty cycle and working power can be varied as per requirement to achieve low surface roughness in laser beam machining. From the present set of experimentation the following conclusion can be drawn:

a) This sawing angle is very important in case of low power laser beam cutting and also attractive to be an efficient input parameter, by which through cut is possible, along with alteration of focal point or constant movement of Z axis always remains within the tight focusibility.

b) Use of an assisting gas for protection of the cutting section from high temperature oxidation reaction and purging of the molten material from the cut section in laser cutting process. Also assist gas pressure has an effective quality of removal of melted material by decreasing amount of the re-solidified material in the sidewall attachment.

c) The most dominating factors for surface roughness are pulse frequency and cutting speed. The set of suggested optimal solutions may be utilized for cutting of stainless steel 316L alloy sheet.

d) The estimated experimental result under the optimal parameter setting matches very well with the predicted value.

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