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Optimization of CO_2 laser cutting parameters on Austenitic type Stainless steel sheet

A Parthiban [1], S Sathish [2], M Chandrasekaran[3] and R Ravikumar[4]
[1]Assistant professor, Department of Mechanical Engineering, School of Engineering, Vels university, Chennai-117.
[2]Assistant professor, Department of Automobile Engineering, School of Engineering, Vels university, Chennai-117.
[3]Professor, Department of Mechanical Engineering, School of Engineering, Vels university, Chennai-117.
[4]Professor, Department of Mechanical Engineering, Ariyalur Engineering College, Melakaruppur-621707.

E-mail: [1]parthibana@yahoo.co.in

Abstract. Thin AISI 316L stainless steel sheet widely used in sheet metal processing industries for specific applications. CO_2 laser cutting is one of the most popular sheet metal cutting processes for cutting of sheets in different profile. In present work various cutting parameters such as laser power (2000 watts-4000 watts), cutting speed (3500mm/min – 5500 mm/min) and assist gas pressure (0.7 Mpa- 0.9Mpa) for cutting of AISI 316L 2mm thickness stainless sheet. This experimentation was conducted based on Box- Behenken design. The aim of this work is to develop a mathematical model kerf width for straight and curved profile through response surface methodology. The developed mathematical models for straight and curved profile have been compared. The Quadratic models have the best agreement with experimental data, and also the shape of the profile a substantial role in achieving to minimize the kerf width. Finally the numerical optimization technique has been used to find out best optimum laser cutting parameter for both straight and curved profile cut.

1. Introduction

CO_2 Laser cutting is one of the advanced processes to achieve high precision and accurate assembly with minimum consumption of sheet metal. Austenitic stainless steel is playing vital role in modern industries. Now a day's AISI 316L stainless steel sheet has significant role in automobile industries. However AISI 316L is one of the important materials due to its inherent properties such as high strength, good corrosion resistance. Still machining of AISI 316L with laser cutting is a difficult task due to different profile cutting. Consequently kerf dimensions play the most significant role in determining the productivity and the quality of a product produced with AISI 316L. So this work takes AISI 316L stainless steel as a work piece material for CO_2 laser cutting. With regard, to the laser power, cutting speed and gas pressure are considered as a predominant principal parameter in laser cutting. Lot of researcher and investigations has been done in analyzing the cost and quality of laser cutting.

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However with regard to the reduction of wastage that is caused in kerf dimension has not been taken up for serious study. Hence this study considers the principal parameters on kerf width for straight and curved profile.

The Nd: YAG laser is a solid state laser, working at a wavelength of 1.06 μm. CO_2 laser is a gas type laser that radiates at wavelength of 10.6 μm [1]. Nd: YAG lasers have low beam power, but when operating in pulsed mode, and to obtain maximum peak power is able to cut still thicker sheet metals [2]. CO_2 laser is proper for well cutting of sheet metals at high speed because it delivers the maximum average beam power, superior efficiency and good quality of beam. Conversely, Due to maximum peak power at high speed of

CO_2 laser, it is reflected to a lesser extent by metallic surfaces and this high absorptive of the CO_2 laser enable to process even highly reflective materials with relatively high cutting speed [3]. Therefore, CO_2 laser is suitable for cutting of metals in general and reflective materials in particular.
Laser cutting of sheet metals has a most important research area for marking out the best quality of cut. [4]. the quality of cuts mainly depends upon the variety of process parameters such as laser power, gas pressure, cutting speed and sheet metal thickness. [5,6] have been investigating about the outcome of laser cutting parameters on kerf dimension and surface quality of cut. Most of the researchers to varying the only one parameter at a time approach to study the effect of process parameters on responses. However, this approach consumes more time and money in favor of a large number of experimental runs since only one parameter is varied in each experimental run, and then keeps other parameters as constant. As well as in this method the interaction effects process parameters are not considered. To beat such that problems, Design of experiments (DOE) commonly used in experimental approach [7,8]. From the litrature survey no more researcher not consentrate about laser cutting of different profiles. So that the present work consentrate about optimization of laser cutting of different profiles like straight and curved profile.

2. Methodology

The CO_2 Laser cutting process considered in this work AISI 316L Stainless steel sheet for straight and curved profile is discussed following section.

2.1. Experimental procedure

The experiments were carried out on AMADA make CO_2 Laser cutting machine as shown in figure.1 and the specification of machine as shown in table 1. The work piece considered for this work is stainless steel AISI 316L the sheet size was 500 X 500 X 2 mm each specimen to cut straight profile 20mm and curved profile radius of 20mm. Cutting operation carried out on work piece with straight and curved profile as shown figure.2 the work piece was carefully clamped on work table[9]. The input parameters considered are power, cutting speed and gas pressure. Box-Behnken Design was selected for the three levels and 17 run experiments were carried out both straight and curved profile cut. The considered parameters ranges are the laser power in between (2000watts, 3000watts and 4000watts), Cutting Speed levels are within (3500mm/min, 4500 mm/min and 5500mm/min) and Gas pressure was (0.7Mpa, 0.8 Mpa and 0.9Mpa**)** [10]. The 17 experimental runs were conducted based on Box-behnken approach. The collected experimental data were given in table 2.

2.2. Measurement of Responses

To measure the kerf width for straight and curved profile by indirect measurement using Tool makers microscope with 10X magnification factor, the work piece hold on the work table.

3. Result and Discussion

3.1. Response surface methodology

Response surface methodology is a collection of mathematical and statistical techniques, useful for the mathematical modelling and analysis of problems in which a response of interest is influenced by several parameters and the objective is to optimize this response [11-12]. RSM models were developed and evaluated with Design expert software. Second order polynomial equations were obtained for predict the data [13]. The generalized form of response surface model is shown in equation 1.
Table 3 shows the model summary of kerf width for stright profile. The table shows that the quadratic model is best for predict the kerf width value. The significant parameters are identified by using ANOVA table.The Model F-value of 14.17 implies the model is significant. There is only a 0.10% chance that a Model F-Value is large could occur due to noise.Values of "Prob > F" less than 0.0500 indicate model terms are significant.In this case power, cutting speed, $power^2$ and Gas $pressure^2$ are significant model terms.and the model summary of kerf width for curved profile. The table shows that the modified model is best for predict the kerf width value. The significant parameters are identified by using ANOVA table 3.The Model F-value of 11.32 implies the model is significant.There is only a 0.21% chance that a Model F-Value is large could occur due to noise.Values of "Prob > F" less than 0.05 indicate model terms are significant.In this case power, cutting speed, $power^2$ and Gas $pressure^2$ are significant model terms.

The figure 3(a) shows the effects of power and cutting speed on kerf width for straight profile. The Power and cutting speed are carried out on X and Y axis. The response for kerf width straight profile carried on Z axis. This graph is mainly plotted for make inference on kerf width responses against cutting speed and gas pressure. It is increasing Laser power increase the kerf width. The figure 3(b) is mainly plotted for kerf width for straight profile responses against power and gas pressure. The graph contains some interaction effects, because the graph does not lie in linear plane. But it is a curved plane due to the interaction effects of gas pressure from graph laser power increase kerf width for straight profile also increase and the figure 3(c) shows the effects of power and cutting speed on kerf width for curved profile. The Power and cutting speed are carried out on X and Y axis. The response of kerf width for curved profile considered on Z axis. These graphs are also same like and power response surface graphs it also contains some interaction effects, because the graph is not a linear one. Then it is an interaction plots. The power and cutting speed are not a linear one kerf width for curved profile. From graph power and cutting speed increases kerf width for curved profile also increase. The figure 3(d) is mainly plotted kerf width for curved profile responses against power and gas pressure. The graph contains some interaction effects, because the graph does not lie in linear plane. But it is a curved plane due to the interaction effects of power a from graph laser power and gas pressure increase kerf width also increases that the developed mathematical model should be a second order polynomial equation. The developed mathematical models are as shown in Equation 2 and 3.

3.2 Performance Evaluation of Developed Models

The Figure 4 shows that the kerf width for straight and curved profile response surface model values and Experimental values were compared on the basis of their prediction. The models were validated with 17 data sets of Box-behenken design used for the experimental data collection [14]. The plots represent the experimental value nearer to the Response Surface models.

$$Ra = b_0 + \sum_{i=1}^{4} b_i X_i + \sum_{i=1}^{4} b_{ii} X_{ii}^2 + \sum_{i=1}^{4}\sum_{j=1}^{4} b_{ij} X_i X_j + \varepsilon \quad (1)$$

$$\begin{aligned} Kerf\ width\ for\ straight\ \mathrm{Pr}ofile &= +0.2087 - 9.34e^{-5} \times P + 1.66e^{-5} \times v + 0.606 \times p \\ &+ 1.325e^{-9} \times P \times v + 7.5e^{-7} \times P \times p + 2.5e^{-6} \times v \times p + 1.528e^{-8} \times P^2 \\ &- 2.99e^{-9} \times v^2 - 0.3945 \times p^2 \end{aligned} \quad (2)$$

$$\begin{aligned} Kerf\ width\ for\ curved\ \mathrm{Pr}ofile &= +0.1362 - 8.22e^{-5} \times P + 2.02e^{-5} \times v + 0.6787 \times p \\ &+ 1.075e^{-9} \times P \times v - 7e^{-6} \times P \times p + 3e^{-6} \times v \times p + 1.4662e^{-8} \times P^2 \\ &- 3.287e^{-9} \times v^2 - 0.4262 \times p^2 \end{aligned} \quad (3)$$

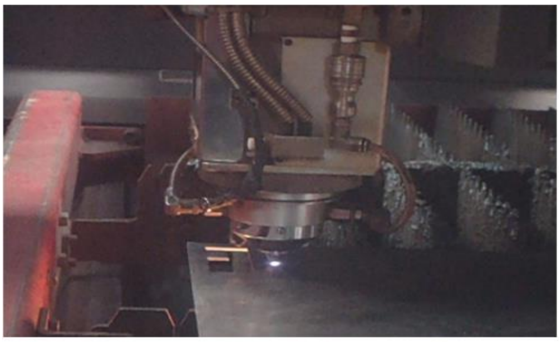

Figure 1. AMADA CO_2 laser cutting Machine

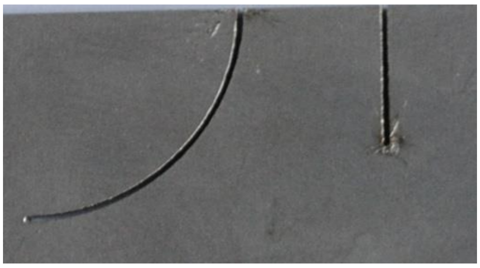

Figure 2. Photo image of straight and curved profile

Table 1. Specification of machine

Model	Amada FO-3015NT
Laser type	carbon di oxide (CO_2)
Mode	Continious Wave(CW)
Power	4000 Watts
Focal length	127.5mm
Assist gas	Nitrogen
Focal position	-0.5

Table 2. Experimental data

S.I No	Power (Watts)	Cutting Speed (mm/min)	Gas pressure (Mpa)	Straight Profile Kerf Width (mm)	Curved Profile Kerf Width (mm)
1	3000	5500	0.7	0.3282	0.3117
2	3000	3500	0.9	0.3393	0.3218
3	3000	4500	0.8	0.3448	0.3291
4	4000	4500	0.9	0.3552	0.3374
5	2000	4500	0.7	0.3495	0.3312
6	3000	4500	0.8	0.341	0.3255
7	3000	4500	0.8	0.339	0.3225
8	4000	3500	0.8	0.3594	0.3419
9	2000	5500	0.8	0.3444	0.3279
10	2000	4500	0.9	0.3472	0.3307
11	3000	5500	0.9	0.3262	0.3099
12	3000	4500	0.8	0.3387	0.3222
13	3000	3500	0.7	0.3423	0.3248
14	4000	5500	0.8	0.3582	0.3417
15	2000	3500	0.8	0.3509	0.3324
16	3000	4500	0.8	0.3412	0.3237
17	4000	4500	0.7	0.3572	0.3407

Table 3 . ANOVA table for kerf width for straight profile

Source	Sum of Squares	DF	Mean Square	F Value	p-value Prob>F
Model	0.0013993	9	0.0001555	14.172779	0.0010
A	0.0001805	1	0.0001805	16.454072	0.0048
B	0.0001523	1	0.0001523	13.878965	0.0074
C	1.081E-05	1	1.081E-05	0.9855351	0.3539
AB	7.023E-06	1	7.023E-06	0.6401591	0.4499
AC	2.25E-08	1	2.25E-08	0.0020511	0.9651
BC	2.5E-07	1	2.5E-07	0.0227896	0.8843
A^2	0.0009831	1	0.0009831	89.614708	< 0.0001
B^2	3.777E-05	1	3.777E-05	3.4429145	0.1059
C^2	6.553E-05	1	6.553E-05	5.9734688	0.0445
Residual	7.679E-05	7	1.097E-05		
Lack of Fit	5.304E-05	3	1.768E-05	2.9772931	0.1597
Pure Error	2.375E-05	4	5.938E-06		
Cor Total	0.0014761	16			

Table 4 . ANOVA table for kerf width for curved profile

Source	Sum of Squares	DF	Mean Square	F Value	p-value Prob>F
Model	0.0013092	9	0.0001455	11.317291	0.0021
A	0.000195	1	0.000195	15.17289	0.0059
B	0.0001103	1	0.0001103	8.5780195	0.0221
C	9.245E-06	1	9.245E-06	0.7192354	0.4244
AB	4.622E-06	1	4.622E-06	0.3596177	0.5676
AC	1.96E-06	1	1.96E-06	0.1524826	0.7078
BC	3.6E-07	1	3.6E-07	0.028007	0.8718
A^2	0.0009052	1	0.0009052	70.42333	< 0.0001
B^2	4.551E-05	1	4.551E-05	3.5402345	0.1019
C^2	7.65E-05	1	7.65E-05	5.9515391	0.0448
Residual	8.998E-05	7	1.285E-05		
Lack of Fit	5.794E-05	3	1.931E-05	2.4110487	0.2073
Pure Error	3.204E-05	4	8.01E-06		
Cor Total	0.0013992	16			

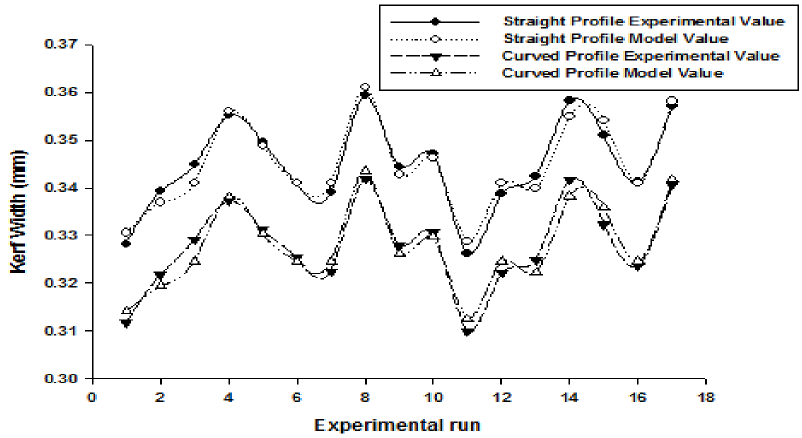

Figure 3. kerf width for straight and curved profile (Experimental data Vs Model data)

Table 5 . Criteria for Numerical optimization

Name	Goal	Lower Limit	Upper Limit	Importance
Laser power (watts)	is in range	2000	4000	3
Cutting speed (mm/min)	is in range	3500	5500	3
Gas pressure (Mpa)	is in range	0.7	0.9	3
Kerf Width in straight profile(mm)	minimize	0.3262	0.3594	5
Kerf Width in curved profile (mm)	minimize	0.3099	0.3419	5

Table 6 . Optimization result for cutting conditions

Si. No	Laser Power (watts)	Cutting speed (mm/min)	Gas pressure (Mpa)	Kef width in straight Profile (mm)	Kef width in curved Profile (mm)
1	2595.59	5500	0.9	0.3287	0.3128
2	2587.66	5500	0.9	0.3287	0.3128
3	2603.12	5499.89	0.9	0.3286	0.3127
4	2577.47	5500	0.9	0.3288	0.3129
5	2684.49	5500	0.9	0.3283	0.3123
6	2503.08	5500	0.9	0.3294	0.3135
7	2589.96	5500	0.9	0.3290	0.3131
8	2598.72	5500	0.9	0.3291	0.3132
9	2590.4	5500	0.89	0.3292	0.3133
10	2586.65	5500	0.7	0.3306	0.3138

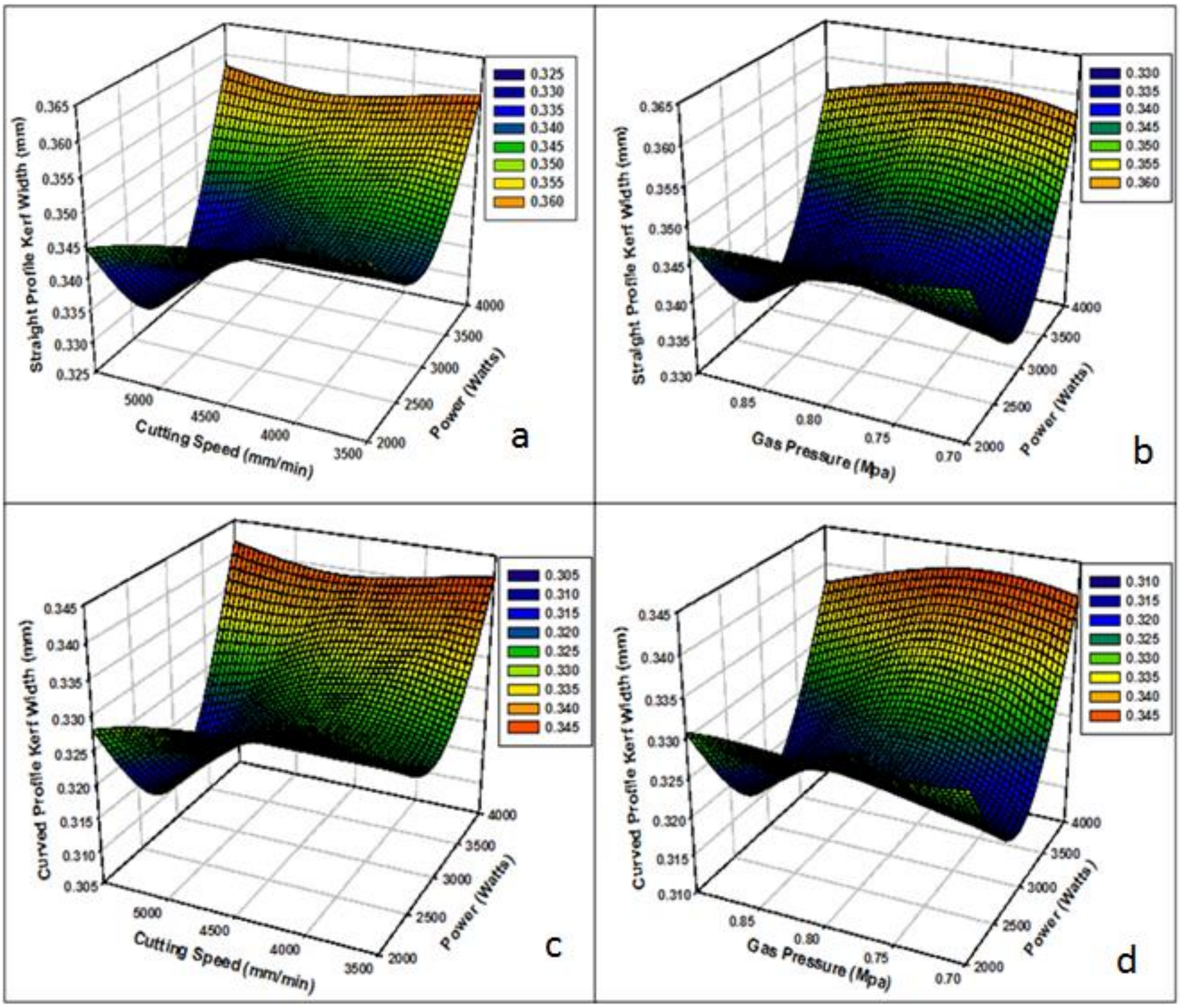

Figure 4. Surface model of interaction effect for CO_2 Laser cutting parameter

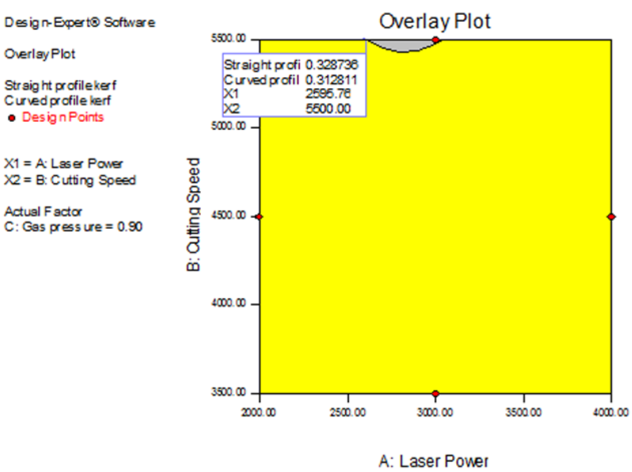

Figure 5. Over lay plot shows the region of optimal cutting condition

4. Optimization

Optimization can be defined as the process of finding the situations that give the maximum or minimum value of a function. Optimization, in its broadest sense, can be applied to solve any engineering problem [15].

In this work optimization of straight profile and curved profile cut. The kerf width is a quality, the cutting parameter as Laser power, Cutting speed and gas pressure are required different cutting geometry. But this work is tried to achieve same cutting parameter at cut all type of geometry. The numerical optimization was used; the multi response optimization is solved desirability approach by using design expert software. The numerical optimization is set the goal as shown in Table 5 to minimize the response to achieve high quality. Table 6 shows the optimized value for AISI 316 L 2mm thickness sheet of input parameters to the corresponding response value. the finally to predicted the response value kerf width for straight profile 0.3287 mm and kerf width for curved profile 0.3128 mm has been achieved. And the figure 9 shows overlay plot drawn between the laser power and cutting speed the Assist gas pressure at 0.9 Mpa. These ranges of graphical optimization result shows on the figure 9.the shaded area on the overlay plot regions are to be achieved for proposed criteria and select the optimal laser cutting parameters.

5. Conclusion

The stainless steel 316 L as work piece material for straight and curved profile and CO_2 laser processes were carried out in this work. Based on experimental work the following conclusions were made

- The developed second-order response surface models for Kerf width for straight profile and Kerf width for curved profile using the Box-behenken design have been found adequate.
- The developed empirical models can be used to predict the response values within the range of experimental values. From the response plot it has been observed laser power, gas pressure has been less effect of kerf dimensions as compared to cutting speed.
- For achieving smaller value of kerf width a moderate value of cutting speed is required for straight profile cut. Similar to curved profile cut.
- These models may be used satisfactorily for the prediction of Kerf width for straight and curved profile cut rate in laser cutting of thin steel sheet.
- This second-order response surface models model can reduce the experimental cost and time in manufacturing industries. This proposed methodology can be used to predict the other response values in CO_2laser cutting operation and other non tradition machining operations
- The minimum of kerf width for straight profile and kerf width curved profile is obtained from the study were 0.3281 mm and 0.3120 mm, when the process parameters such as Laser power, cutting speed and gas pressure were maintained at 2807.45 watts, 5500 mm/min, and 0.9 Mpa. It is possible to obtain the minimum kerf width using the above values of process parameters to achieve both straight and curved cut profile geometry.

Acknowledgments

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