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Parametric analysis of laser machining with response surface method on SS-304

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Abstract

Stainless steel is an important engineering material that is difficult to be cut by oxy-fuel methods because of the high melting point and low viscosity of the formed oxides. However, it is suitable to be cut by laser. The objective of this work is to do parametric analysis of process parameters of CO_2 laser cutting system on surface characteristics of the cut section in the cutting of 5mm Stainless Steel (SS) sheet (ASTM 304). In this study, the laser cutting parameters such as laser power, cutting speed and gas pressure are analyzed and optimized with consideration of workpiece surface roughness. Design of experiments (DOE), ANOVA and Response Surface Methodology (RSM) approaches are used to analyze the laser cutting variables and find out the optimum value for surface roughness. By analyzing, it is observed that the laser power has more effect on responses rather than cutting speed and gas pressure. It is clearly shown that the above performance characteristics in laser cutting process can be optimized effectively through this approach.

Keywords: Laser cutting, surface roughness, DOE, ANOVA, RSM;

1. Introduction

LASER is an acronym for Light Amplification by Stimulated Emission of Radiation which describes the theory of laser operation. One of the applications of laser is laser machining. The cost of cutting hard-to-machine materials by conventional mechanical machining processes is high due to the low material removal rate and short tool life, and some materials are not possible to cut by the conventional machining process at all. Laser beam machining is the machining processes involving a laser beam as a heat source. Laser cutting is a popular process, which finds wide applications in various manufacturing industries due to its precision of operation and low cost.

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Laser cutting, being a non-contact process, does not involve any mechanical cutting forces and tool wear. In this process, the workpiece material is locally melted by the focused laser light. The melt is then blown out of the kerf with an assist gas that flows coaxial with the laser beam [1-2]. In metal cutting operations, in general, oxygen or nitrogen is used while argon or helium is used for wood or plastic cutting. It was shown that the laser cutting quality depends on the laser power, cutting speed, gas pressure, beam diameter, beam incident angle, stand-off distance, pulse frequency and focus positions.

From papers [3-5], it was found that the most significant cutting parameters are cutting speed, gas pressure and laser power which has more effect on cutting quality. A few of experimental investigations has been undertaken with the aim of analyzing the effect of these three process parameters on cut surface quality. Different researchers used different optimizing techniques for optimizing cutting parameters [6-11]. In this paper, the cutting parameters such as laser power, cutting speed and gas pressure were analyzed and optimized with consideration of workpiece surface roughness with help of DOE, ANOVA and RSM.

2. Experimental setup

The experiments were conducted on CNC laser cutting machine hyper gear 510, MAZAK at Martiaen Engineering Company. This machine used a 10.6 µm wavelength CO_2 laser with a nominal power output of 2500W at pulsed mode. Focal length of lens used was 127 mm, nozzle diameter (2.0 mm), stand-off distance (4 mm), and material thickness (5 mm) were kept constant throughout the experimentation. A 5 mm thick Stainless steel-304 was used as workpiece material. Technical Specification of laser cutting machine hyper gear 510 is given in Table 1. SS-304 has selected as workpiece material due to lower carbon which minimize carbide precipitation. SS-304 has used in high-temperature applications and widely utilized material for sheet metal operation for various industrial and household applications like screws, machinery parts, car headers, and fabrication of electronics components. The chemical composition of the SS-304 is provided in Table 2. In this study, the cutting parameters such as laser power, cutting speed and gas pressure were analyzed and optimized with consideration of workpiece surface roughness.

Table 1 Technical Specification of laser cutting machine

Model	Specification
Laser continuous rated output	2.5 Kw
Maximum cutting size	1525×3050 mm
Travel (X/Y/Z)	3070/1545/100 mm
Positioning accuracy (x, y axes)	± 0.01 / 500 mm
Positioning accuracy (z axes)	± 0.01 / 100 mm
Wave length	10.6 µm
Beam diameter	22.5 mm (max.)

Table 2 Chemical composition of the SS-304

C	Cr	Ni	Mn	Si	P	S	Fe
0.08	18-20	8-10.5	2.0	1.0	0.045	0.030	Balance

Design of experiment approach (DOE), ANOVA and Response Surface Methodology were used to analyze cutting parameters with consideration of workpiece surface roughness and identify the optimized parameter regions. RSM also gives the relation between interaction of two cutting variable and surface roughness. The values of the parameters that have varied during the execution of experiments are shown in Table 3.

Table 3 Laser cutting variables and their levels

Symbol	Cutting Parameters	Level 1	Level 2	Level 3
A	Laser power(kW)	1.3	1.5	1.7
B	Gas pressure(bar)	0.5	0.6	0.7
C	Cutting speed(mm/min)	2000	2100	2200

3. Analysis and discussion of experimental result

A series of experiments were performed under the experimental plan to analyze the influence of the process parameters upon processed surface roughness and to obtain a complex relationship to show roughness variation according to these parameters. Statistical software Design-Experts [12] was used to code the variables and to establish the design matrix in Table 4.

Table 4 Experimental Data

Std	Run	Block	Factor 1 A: Power kW	Factor 2 B: Gas Pressure Bar	Factor 3 A: Cutting Speed m/min	Response 1 Surface Roughness micron
1	13	Block 1	1.30	0.50	2.10	3.42
2	9	Block 1	1.70	0.50	2.10	4.11
3	3	Block 1	1.30	0.70	2.10	2.95
4	1	Block 1	1.70	0.70	2.10	4.11
5	5	Block 1	1.30	0.60	2.00	3.74
6	12	Block 1	1.70	0.60	2.00	3.54
7	6	Block 1	1.30	0.60	2.20	3.99
8	16	Block 1	1.70	0.60	2.20	3.85
9	10	Block 1	1.50	0.50	2.00	2.41
10	2	Block 1	1.50	0.70	2.00	2.18
11	17	Block 1	1.50	0.50	2.20	2.81
12	8	Block 1	1.50	0.70	2.20	2.35
13	7	Block 1	1.50	0.60	2.10	3.42
14	14	Block 1	1.50	0.60	2.10	3.42
15	15	Block 1	1.50	0.60	2.10	3.44
16	4	Block 1	1.50	0.60	2.10	3.40
17	11	Block 1	1.50	0.60	2.10	3.42

Table 5 ANOVA for response surface quadratic model

| Source	Sum of Square	Df	Mean Square	F value	p-value Prob>F	
Model	5.12	9	0.57	6.57	0.0107	Significant
A-Power	0.29	1	0.29	3.29	0.1126	
B-Gas Pressure	0.17	1	0.17	1.94	0.2061	
C-Cutting Speed	0.16	1	0.16	1.84	0.2168	
AB	0.055	1	0.055	0.64	0.4508	
AC	9.000E-004	1	9.000E-004	0.010	0.9217	
BC	0.013	1	0.013	0.15	0.7076	
A^2	2.59	1	2.59	29.95	0.0009	
B^2	1.31	1	1.31	15.11	0.0060	
C^2	0.76	1	0.76	8.78	0.0210	
Residual	0.61	7	0.087			
Lack of Fit	0.61	3	0.20	1009.29	< 0.0001	Significant
Pure Error	8.000E-004	4	2.000E-004			
Cor Total	5.73	16				

Applying the ANOVA on the experimental data, we obtained the influence of each parameter and the adequacy of the data. The summary of the analysis is shown in Table 5. A low P-value (≤ 0.05) indicates statistical significance for the source on the corresponding response (i.e., $\alpha = 0.05$, or 95% confidence level), this indicates that the

obtained models are considered to be statistically significant, which is desirable; as it demonstrates that the terms in the model have a significant effect on the response. This table shows the degrees of freedom (DF), sum of squares (SS), mean squares (MS), F-values (F-VAL.) and probability (P-VAL.) in addition to the percentage contribution (Contr. %) of each factor and different interactions.

The Model F-value of 6.57 implies the model is significant. There is only a 1.07% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. Values greater than 0.1000 indicate the model terms are not significant. "Lack of Fit F-value" of 1009.29 implies the Lack of Fit is significant. There is only a 0.01% chance that a "Lack of Fit F-value" this large could occur due to noise. Significant lack of fit is bad- we want the model to fit.

Table 6 Values of signal to noise ratio

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	3.42	1	0.13	3.11	3.73	1.00
A-Power	0.19	1	0.10	-0.057	0.43	1.00
B-Gas Pressure	-0.14	1	0.10	-0.39	0.10	1.00
C-Cutting Speed	0.14	1	0.10	-0.10	0.39	1.00
AB	0.12	1	0.15	-0.23	0.47	1.00
AC	0.015	1	0.15	-0.33	0.36	1.00
BC	-0.057	1	0.15	-0.41	0.29	1.00
A^2	0.79	1	0.14	0.45	1.12	1.01
B^2	-0.56	1	0.14	-0.90	-0.22	1.01
C^2	-0.42	1	0.14	-0.76	-0.086	1.01
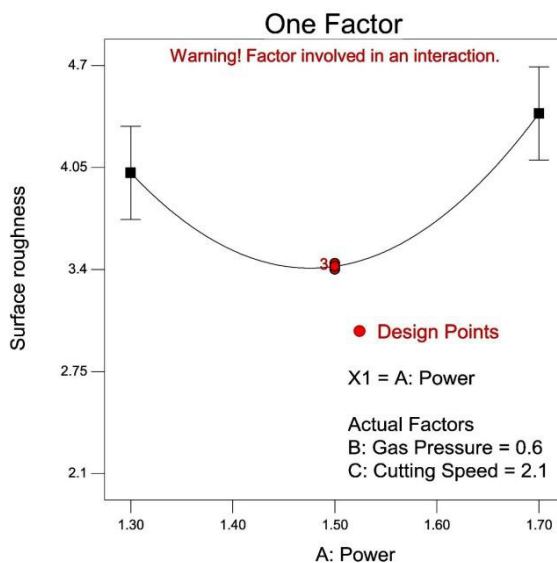
(a) Power vs. Surface roughness
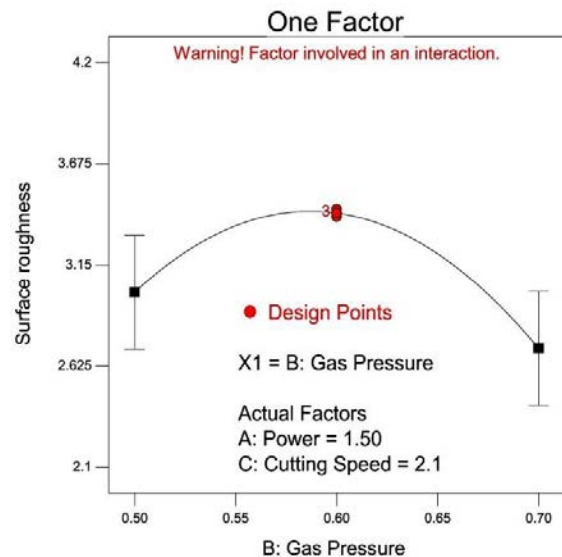
(b) Gas pressure vs. surface roughness
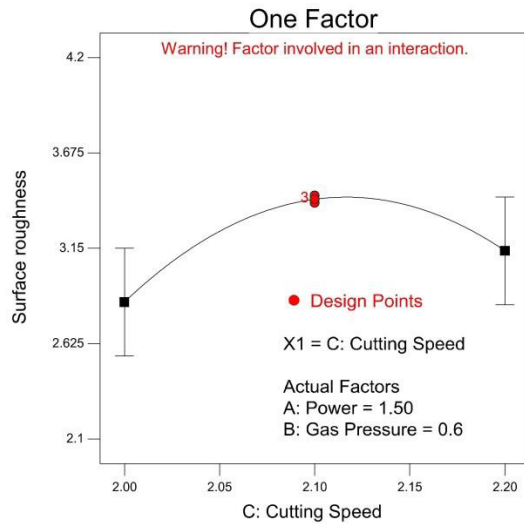
(c) Cutting speed vs. surface roughness

Figure 1. One factor effect on surface roughness

Std. Dev. 0.29, R-Squared 0.8941, Mean 3.33, Adj R-Squared 0.7580, C.V. 8.85(%), Pred R-Squared -0.6917, PRESS 9.69, Adeq Precision 8.489. A negative "Pred R-Squared" implies that the overall mean is a better predictor of data response than the current model. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable, which is given in Table 6. The ratio of 8.489 indicates an adequate signal. This model can be used to navigate the design space.
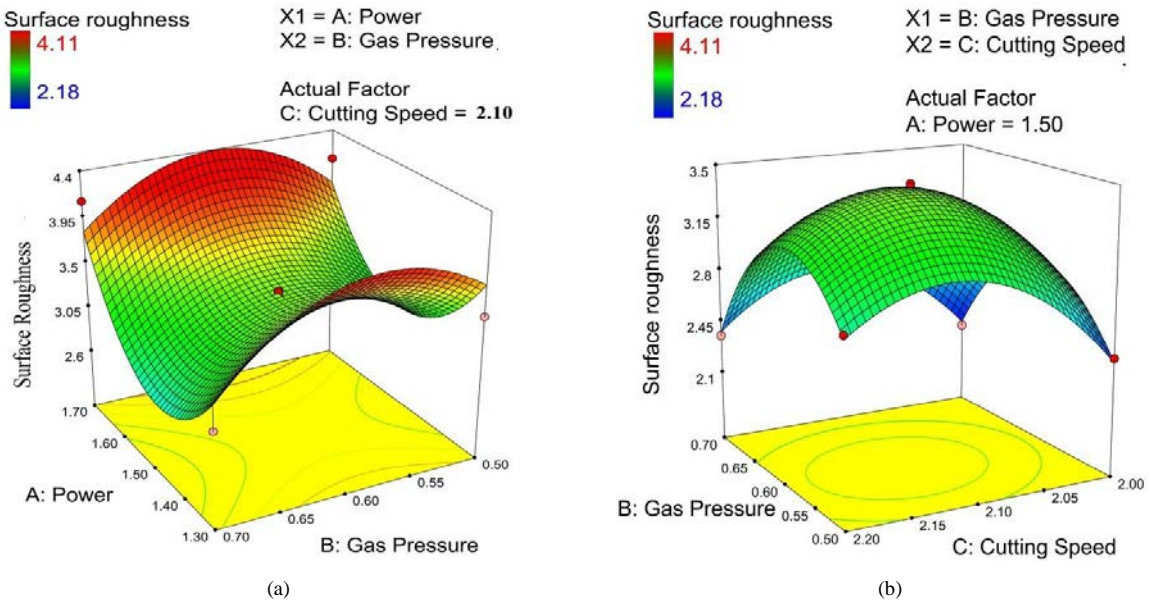

Figure 2. Interaction effect of cutting parameters on surface roughness

- Final Equation in Terms of Coded Factors:
  Surface roughness = $3.42 + 0.19*A - 0.14*B + 0.14*C + 0.12*A*B + 0.015*A*C - 0.057*B*C + 0.79*A^2 - 0.56*B^2 - 0.42*C^2$

- Final Equation in Terms of Actual Factors
  Surface roughness = -163.02563 - 63.03125 * Power + 68.71250 * Gas Pressure + 182.23750 *Cutting Speed + 5.87500 * Power * Gas Pressure + 0.75000 * Power * Cutting Speed - 5.75000 * Gas Pressure * Cutting Speed + 19.62500 * $Power^2$–55.75000 * Gas $Pressure^2$ - 42.50000 *Cutting $Speed^2$

Figure 1 shows the individual effect of all three parameters, laser power, gas pressure and cutting speed on surface roughness. Figure 2(a) shows a contour surface of the response (i.e. surface roughness) versus laser power and gas pressure, while keeping cutting speed fixed at 2.1 m/min. Figure 2(b) shows a contour surface of the response versus gas pressure and cutting speed, while keeping power fixed at 1.50 kW.

Figure 3 shows the relationship between the actual and predicted values of experiment. It has observed that the developed model is adequate and predicted results are in good agreement with experimental results. From the desirability contour graph we get the better desirability for the model at maximum gas pressure and medium laser power.
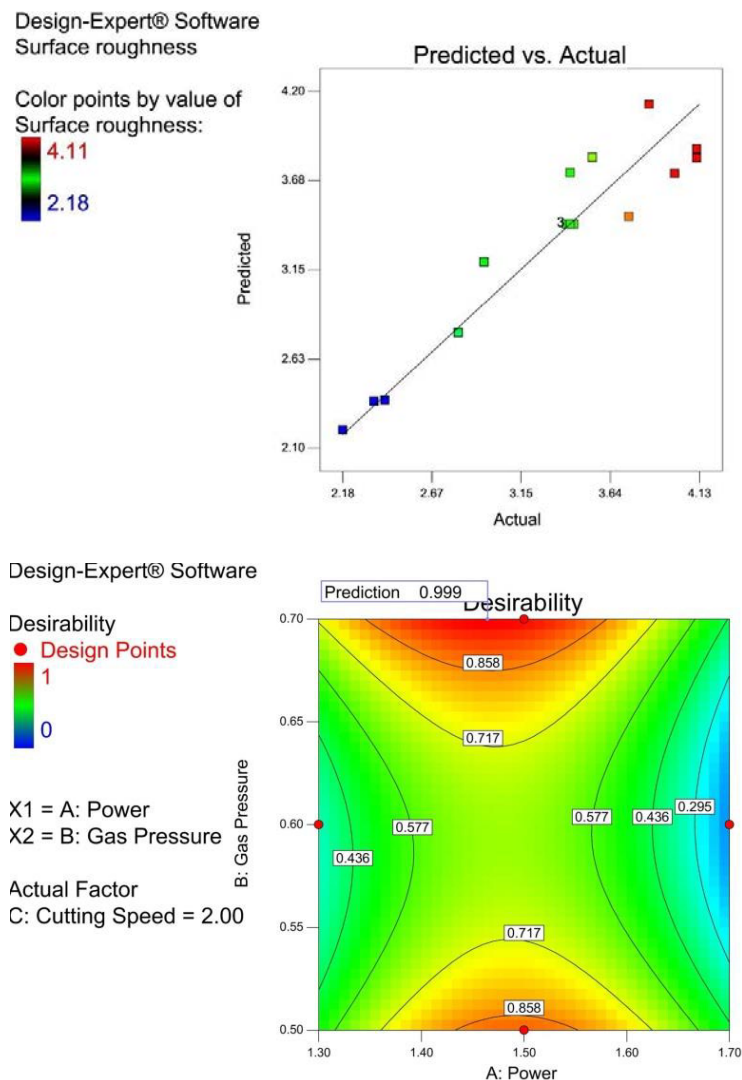

Figure 3. Graph of predicted vs actual roughness values and desirability

4. Conclusion

In this paper, the complete analysis of the influence process parameters on the laser cutting process has performed with CNC laser cutting machine hyper gear 510, MAZAK make. After DOE analysis total 17 run have identified for experiment with sheet metal operation (5 mm thick) SS 304 as workpiece material. The optimal values of these parameters have defined with the aim of achieving the required surface roughness. It has found that the laser power is most significant compare to cutting speed and gas pressure. Laser power and gas pressure has identified most significant interactive parameter with highest F value of 0.64. By using regression analysis method, the optimized value of parameters found as power 1.46 kW, gas pressure 0.70 bar and cutting speed 2.00 m/min for the minimum value of surface roughness 2.18179 µm.

Based on these results, the optimal cutting condition, at which the surface roughness is minimized and both the delayed cutting phenomenon is estimated to improve both the quality of the cut section and the cutting efficiency

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