Multi-objective optimization and analysis for laser beam cutting of stainless steel (SS304) using hybrid statistical tools GA-RSM

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Abstract. A laser beam machine is a non-traditional manufacturing technique that uses thermal energy to cut nearly all types of materials. The quality of laser cutting is significantly affected by process parameters. The purpose of this study is to use a genetic algorithm (GA) in conjunction with response surface approaches to improve surface roughness in laser beam cutting CO2 with a continuous wave of SS 304 stainless steel. The effects of the machining parameters, such as cutting speed, nitrogen gas pressure, and focal point location, were investigated quantitatively and optimized. The tests were carried out using the Taguchi L9 orthogonal mesh approach. Analysis of variance, main effect plots, and 3D surface plots were used to evaluate the impact of cutting settings on surface roughness. A multi-objective genetic algorithm in MATLAB was used to achieve a minimum surface roughness of 0.93746 µm, with the input parameters being 2028.712 mm/m cutting speed, 11.389 bar nitrogen pressure, and a focal point position of -2.499 mm. The optimum results of each method were compared, as the results the response surface approach is less promising than the genetic algorithm method.

Keywords: Laser beam machine; Genetic algorithm; Response surface method; Surface roughness; parametric optimization

1. Introduction

Laser cutting is an unconventional manufacturing process in which the material is removed by melting, evaporation, and chemical decomposition when the laser beam is focused on the workpiece. When a high-intensity laser beam is focused on the work surface, the heat energy is absorbed and the work volume is transformed into a molten, vaporized, or chemically altered state that can be easily removed by an auxiliary gas stream having high pressure. This process does not include mechanical cutting resistance or tool wear. The laser beam machine can perform a variety of material processing operations such as laser precision punching, cutting, engraving, flipping, and writing [1–6].

The lasers are used to treat advanced materials with properties such as thermal conductivity, specific heat, melting point, and boiling point. LBM is widely used to meet today's demands such as high flexibility and throughput, lack of connection mechanism, elimination of finishing work, automatic adjustment, reducing processing cost, improving product quality, and increasing material utilization [7–13]. LBM process parameters can be grouped into the following categories: beam-related, material/workpiece-related, application-related, machine configuration, and lasing materials that affect a variety of processing quality characteristics, such as surface roughness, heat affected zone (HAZ), cut width, recast layer, etc. The quality of laser cutting is significantly affected by process parameters.
Therefore, it is important to check the influence of the cutting parameters on the cut edge quality to improve the performance of the machine [14–18].

Researchers are interested in developing LBM techniques because of the rising demand for sophisticated difficult-to-machine materials and the availability of high-power lasers. Despite these advancements, there is still a lack of understanding regarding the relationships between manufacturing process parameters and the final mechanical performance of these components, preventing future advancement and use of this technology.

The effects of laser cutting speed (4 m/min to 14 m/min) on kerf width and penetration depth by varying amounts of silica sand in the cement mortar. The influence of the silica sand (percentage) in the cement mortar was evaluated [19]. The liquid medium helps in controlling heat affected zone and the taper angle of the cavity drilled utilizing improving the machining quality, and the sizes of the cavity and heat affected zone are significantly affected by laser power [20]. The Taguchi method is applicable for the multiple performance characteristics of cutting operations that can be used for analysis of experimental result. It was observed that Ra has greatly affected by assistance gas pressure while laser power and cutting speed have little effect [21].

Laser beam cutting process parameters such as scan speed, spot diameter, and laser power on cut quality characteristics (kerf depth, kerf width and material removal rate) of solar cells were investigated and optimized [22]. While cutting stainless steel (SS 307) using a laser beam machine, surface roughness was considerably impacted by cutting speed and laser power but was less affected by assisting gas pressure [23]. The grey relation analysis approach was used to investigate the influence of laser power, cutting speed, assistance gas pressure, and stand-off distance on cutting quality while cutting nonferrous metal sheets, such as aluminum alloy BS 1100 2mm thick sheet, using a CO\textsubscript{2} laser [24]. The top kerf width increases with increasing laser power, gas pressure, and injection diameter, and decreases with increasing cutting speed and focal position. Cutting speed, on the other hand, is the most important element determining the top kerf [25]. At the same setting and materials, Cutting with a fiber laser has the same surface roughness as cutting with a CO\textsubscript{2} laser, but the cutting speed is more than twice as fast while cutting with a CO\textsubscript{2} laser has a more stable surface roughness and slower [26].

Furthermore, as revealed by the previous research, several optimization approaches were used for multi-objective optimization of laser beam cutting, but the combined genetic algorithm and response surface methods are a new approach to enhance surface roughness. As a result, the primary goal of this research is to combine GA with RSM to improve the laser beam cutting quality of SS304 material. The impact of machining factors including; cutting speed, nitrogen gas pressure, and focus point position is studied. Genetic algorithm and response surface methods are used to search for optimum parameters. Simultaneously, the optimum results of each method are compared.

2. Materials and methods

2.1. Material used
The material used during experiment is stainless steel (SS 304) due to its wide range of application in automotive, aerospace, and food industry. The dimensions of the sample were 600 mm x 600 mm and a thickness of 5 mm. The sample shape is designed for easy and accurate measurement of all cut quality characteristics. Table 1 shows the percentage of the composition of the working material.

2.2. Experimental setup and procedure
The experiment was performed with CO\textsubscript{2} LBM running in continuous wave mode and providing a maximum output power of 2.2 kW at a wavelength of 10.6 \textmu m. The cross-section was generated in a Gaussian beam mode (TEM00) with a focal length of 127 mm, pure nitrogen with the help of gas (99.95\%), a HK20 nozzle (2 mm) (conical), and a time intervals of 1 minute. Table 2 illustrates the fixed parameters used during the experiment.
2.3. Experimental design
The CO₂ LBM parameters applicable for cutting of SS 304 stainless steel, namely Cutting speed, Nitrogen gas pressure, and Focal point position were considered for experimental purpose. Other parameters were kept constant for the scope of this research. Different settings of input process parameters with their levels used in the experiment are summarized in Table 3. The operating level was chosen as recommended by manufacturer.

Taguchi's design of experiments was chosen to perform laser cutting experiments to provide efficient design of experiments with minimal testing. An experiment design matrix was created using the Taguchi L₉ (3 ^ 3) orthogonal matrix based on the selected cutting process parameters and levels. Table 4 shows the experimental design using the Taguchi L₉ and the experimental results of surface roughness. Figure 1 (a) shows CO₂ laser machine used for experiment and (b) shows work specimens produced for experiments.

Table 1 Chemical composition of AISI 304 stainless steel

| Workpiece       | Chemical composition |
|-----------------|----------------------|
| SS 304 Stainless steel | C 0.08, Si 1.00, Mn 2.00, P 0.045, S 0.030, Ni 8.00–10.50, Cr 18.00–20.00, Fe Balance |

Table 2 Constant parameters used during experiments

| S. No. | Parameters                     | Value/Types |
|--------|--------------------------------|-------------|
| 1      | The thickness of the workpiece | 5 mm        |
| 2      | Wave length                    | 10.6 µm     |
| 3      | Wave mode                      | Continuous  |
| 4      | Focal length                   | 127 mm      |
| 5      | Assist gas                     | Nitrogen    |
| 6      | Nozzle shape                   | Conical     |
| 7      | Nozzle radius                  | 4 mm        |
| 8      | Standoff distance              | 1 mm        |
| 9      | Laser power                    | 2.2 kW      |
| 10     | Work piece                     | AISI 304 stainless steel |

Table 3 Controllable input process parameters with levels

| Process Parameter     | Unit   | Levels  |
|-----------------------|--------|---------|
|                       |        | 1       | 2       | 3       |
| Cutting speed         | mm/min | 2000    | 2500    | 3000    |
| Nitrogen pressure     | Bar    | 9       | 10.5    | 12      |
| Focal point position  | mm     | -2.5    | -1.5    | -0.5    |

Table 4 Experimental design and experimental results of surface roughness

| Exp. trial | Input Parameters | Response | S/N ratio |
|------------|------------------|----------|-----------|
|            | Cutting speed    |          |           |
|            | mm/m             |          |           |
| 1          | 2000             |          |           |
| 2          | 2000             |          |           |
| 3          | 2000             |          |           |
| 4          | 2500             |          |           |
| 5          | 2500             |          |           |
| 6          | 2500             |          |           |
|            | Nitrogen pressure|          |           |
|            | Bar              |          |           |
| 1          | 9                |          |           |
| 2          | 10.5             |          |           |
| 3          | 12               |          |           |
| 4          | 9                |          |           |
| 5          | 10.5             |          |           |
| 6          | 12               |          |           |
|            | Focal point position |      |           |
|            | mm               |          |           |
| 1          | -2.5             |          |           |
| 2          | -1.5             |          |           |
| 3          | -0.5             |          |           |
| 4          | -1.5             |          |           |
| 5          | -0.5             |          |           |
| 6          | -2.5             |          |           |
|            | Mean Ra µm       |          |           |
| 1          | 1.840            |          |           |
| 2          | 1.982            |          |           |
| 3          | 2.168            |          |           |
| 4          | 2.344            |          |           |
| 5          | 2.084            |          |           |
| 6          | 1.667            |          |           |
|            | S/N ratio        |          |           |
| 1          | -5.29636         |          |           |
| 2          | -5.94207         |          |           |
| 3          | -6.72119         |          |           |
| 4          | -7.39915         |          |           |
| 5          | -6.37795         |          |           |
| 6          | -4.43871         |          |           |
3. Results and discussion

3.1. Effect of different input process parameters on surface roughness

The input process parameters for surface roughness analysis are cutting speed, nitrogen gas pressure, and focal point position, and the selected response parameters are mean surface roughness and signal-to-noise ratio. From Table 4, we observed the minimum surface roughness is 1.667 μm at a cutting speed of 2500 mm/min, a nitrogen pressure of 12 bars, and a focal position of -2.5 mm. To examine the effect of process parameters on surface roughness, the graph plotted between mean of Ra, signal-to-noise ratio to cutting speed, nitrogen gas pressure, and focal point position. From the Main effect diagram, the surface roughness increases with increasing cutting speed and decreases with increasing nitrogen gas pressure, but as of 10.5 bars it starts to decreases. Moreover, Ra increases significantly with increasing focal point position but begins to decrease after -1.5 mm, as shown in Figure 2.

The surface roughness was analyzed using ANOVA for identifying the significant factors affecting the performance measures. The mean Ra at 95% confidence interval and the percentage contribution was calculated using Adj SS from ANOVA as shown in Table 5. Figure 3 shows the influence of each process parameters on surface roughness in percentage. Percentage contribution of cutting speed is
5.24%, contribution of focal point position is 85.77% and contribution of nitrogen gas pressure is 8.99%. This shows that focal point position has significant effect on surface roughness.

### Table 5 Analysis of variance

| Source                | DF | Adj SS  | Adj MS  | F-value | P-value |
|-----------------------|----|---------|---------|---------|---------|
| Cutting speed         | 2  | 0.3810  | 0.1905  | 0.45    | 0.690   |
| Nitrogen gas pressure | 2  | 0.6542  | 0.3271  | 0.77    | 0.564   |
| Focal point position  | 2  | 6.2417  | 3.1208  | 7.37    | 0.119   |
| Error                 | 2  | 0.8466  | 0.4233  |         |         |
| Total                 | 8  | 8.1235  |         |         |         |

**Figure 3.** percentage contribution of process parameters based on ANOVA

The 3D surface graphs are plotted for surface roughness against cutting speed, nitrogen pressure, and focal point position as shown in Figure 4 (a-c). From analysis of 3D surface plot of the interaction, we can predict that at cutting speed (2400 – 2600) mm/min, nitrogen gas pressure (11.5 – 12) bar, and focal point position (-2.2 – -2.5) mm could yield optimum surface roughness (lower surface roughness). To summarize, it is advised to utilize a medium cutting speed, higher nitrogen pressure, and a low focus point location to achieve good surface roughness.
3.2. Regression mathematical modeling

The regression mathematical models have been developed for interaction between process parameter and surface roughness using Minitab 18 software. The equation below is used as objective function to get optimized solution using Genetic algorithm. Figure 5 shows a normal probability map of the residuals for surface roughness.

\[
\text{Mean } Ra = 18.69 - 0.002591 X_1 - 2.394 X_2 + 0.5263 X_3 + 0.09030 X_2^2 - 0.1812 X_3^2 + 0.000166 X_1 X_2 - 0.000329 X_1 X_3
\]

Where is X1 - Cutting speed, X2 – Nitrogen gas pressure, and X3 – Focal point position

3.3. GA-RSM hybrid approach for process parameters training and optimization

The Genetic Algorithm is a strong evolutionary approach inspired by natural selection. It works by performing bio-inspired operations such as population initialization, selection, mutation and crossover to achieve the notion of survival of the fittest individuals. The fitness function for GA is loaded with the RSM equation to construct the GA-RSM model. In MATLAB, the multi-objective genetic algorithm is chosen as the optimization technique. The ideal fitness value is obtained by varying the GA parameter functions through sequential trials.

Figure 4 (a – c) 3D Surface plots of Ra against process parameters

Figure 5 Normal probability plot of residuals
Table 6  Selected parameter functions and parameter value in GA

| Parameter                              | Value                          |
|----------------------------------------|-------------------------------|
| Population type                        | Double vectors                |
| Population size                        | 110                           |
| Creation function                      | Feasible population           |
| Fitness scaling function               | Rank                          |
| Selection function                     | Tournament                     |
| Tournament size                        | 4                             |
| Reproduction                           | Default values                |
| Elite count                            | 1.5 (0.05* Population size)   |
| Crossover fraction                     | 0.8                           |
| Mutation function                      | Adaptive feasible             |
| Crossover function                     | Constraint dependent          |
| Number of generations                  | 300 (100*No. of input parameters) |
| Function tolerance                     | 1e-6                          |
| Constraint tolerance                   | 1e-3                          |

Figure 6 (a) Average spread as a function of iteration number; (b) histogram of the scores at each generation and (c) histogram of the ranks of the individuals
From the genetic algorithm the best optimum result obtained on 102 iterations which is quite fast. The graph in Figure 6 displays the average spread as a function of iteration number, the histogram of scores at each generation, and the histogram of individual ranks. The input settings are optimized for the lowest possible surface roughness. The minimal surface roughness measured was 1.667 µm, using input parameters of 2500 mm/m cutting speed, 12 bar nitrogen pressure, and a focal point location of -2.5 mm. Minimum surface roughness 0.93746 µm was attained using a multi-objective genetic algorithm in MATLAB, with the best input parameters being 2028.712 mm/m cutting speed, 11.389 bar nitrogen pressure, and a focal point location of -2.499 mm. Table 7 show the optimal values for mean surface roughness using the GA and the RSM method. A GA based methodology has been effectively developed to model, simulate, and optimize the surface roughness process parameters for minimal surface roughness compared to the RSM.

### Table 7 Optimization of response parameters using GA and RSM

| Method | Optimized parameter setting | Predicted optimum value for surface roughness |
|--------|----------------------------|-----------------------------------------------|
| GA     | 2028.712 mm/m Cutting speed, 11.389 Bar Nitrogen pressure and -2.499 mm Focal point position | 0.93746 µm |
| RSM    | 2000 mm/m Cutting speed, 11.2424 Bar Nitrogen pressure and -2.5 mm Focal point position | 1.3045 µm |

#### 3.4. Response surface methods for optimization

The mean surface roughness individual desirability and optimal outcomes are 1.000 and 1.3045 µm, respectively, according to the optimization plot Figure 7. The optimum setting parameters are 2000 mm/m cutting speed, 11.4242 bar nitrogen pressure, and a focal point location of -2.5 mm. Table 7 show the optimal values for mean surface roughness using the GA and the RSM method.

![Figure 7 Optimization of response parameters using RSM](image)

#### 4. Conclusions

In this research, genetic algorithm hybrid with response surface approaches was used to improve surface roughness in laser beam cutting CO2 with a continuous wave of SS 304 stainless steel. The experiments were conducted using the Taguchi L9 orthogonal mesh method, and the impacts of process variables such as cutting speed, nitrogen gas pressure, and focal point position were examined. ANOVA, main effect plots, and 3D surface plots were used to evaluate the impact of printing parameters on surface roughness. The following are the findings of the investigation:
Cutting speed (2400 – 2600) mm/min, nitrogen gas pressure (11.5 – 12) bar, and focal point location (-2.2 – -2.5) mm were found to give the best surface roughness.

The ANOVA results reveal that the focus point position has the significant impact on surface roughness.

Cutting speed contributes 5.24 %, focus point location contributes 85.77 %, and nitrogen gas pressure contributes 8.99 % of the total contribution surface roughness. This demonstrates that the location of the focus point has a significant impact on surface roughness.

A multi-objective genetic algorithm in MATLAB was used to achieve a minimum surface roughness of 0.93746 µm, with the optimal input parameters being 2028.712 mm/m cutting speed, 11.389 bar nitrogen pressure, and a focus point position of -2.499 mm.

The RSM method yielded the best mean surface roughness response values of 1.3045 µm and 1.000 desirability.

RSM optimization reveals that the optimum surface quality is achieved with a cutting speed of 2000 mm/m, nitrogen pressure of 11.4242 bar, and focus point location of -2.5 mm.

According to the findings, the response surface technique is less promising than the genetic algorithm.

References

[1] Anghel C, Gupta K and Jen T C 2020 Analysis and optimization of surface quality of stainless steel miniature gears manufactured by CO2 laser cutting, Optik. 203, 164049.
[2] Ding H, Wang Z and Guo Y 2020 Multi-objective optimization of fiber laser cutting based on generalized regression neural network and non-dominated sorting genetic algorithm, Infrared Phys. Technol. 108, 103337.
[3] Mishra D R, Bajaj A and Bisht R 2020 Optimization of multiple kerf quality characteristics for cutting operation on carbon–basalt–Kevlar29 hybrid composite material using pulsed Nd:YAG laser using GRA, CIRP J. Manuf. Sci. Technol. 30, 174-183.
[4] Pramanik D, Kuar A, Sarkar S and Mitra S 2020 Optimisation of edge quality on stainless steel 316L using low power fibre laser beam machining, Adv. Mater. Process. Technol. 7(1), 42-53.
[5] Muthuramalingam T, Moiduddin K, Akash R, Krishnan S, Hammad Mian S, Ameen W and Alkhalefah H 2020 Influence of process parameters on dimensional accuracy of machined Titanium (Ti-6Al-4V) alloy in laser beam machining process, Opt. Laser Technol. 132, 106494.
[6] Kwon W, Kim T and Song K Y 2020 Experimental investigation on CO2 laser assisted micro-grinding characteristics of Al2O3, Int. J. Precis. Eng. Manuf. 22(1), 51-62.
[7] Amaral I, Silva F J G, Pinto G F L, Campilho R D S G and Gouveia R M 2019 Improving the cut surface quality by optimizing parameters in the fibre laser cutting process, Procedia Manuf. 38, 1111-1120.
[8] Jozef M, Andrej Z, Rastislav N and Ružica R N 2018 The effect of selected technological parameters of laser cutting on the cut surface roughness, Tehnicki vjesnik 25(4), 997-1003.
[9] El-Hofy M H and El-Hofy H. 2018 Laser beam machining of carbon fiber reinforced composites: a review, Int. J. Adv. Manuf. Technol. 101(9-12), 2965-2975.
[10] Elsheikh A H, Deng W and Showaib E A 2020 Improving laser cutting quality of polyethylene terephthalate sheet: experimental investigation and optimization, J. Mater. Res. Technol. 9(2), 1325-1339.
[11] Moradi M, Moghadam M K, Shamsborhan M, Beiranvand Z M, Rasouli A, Vahdati M and Bodaghi M 2021 Simulation, statistical modeling, and optimization of CO2 laser cutting process of polycarbonate sheets, Optik. 225, 164932.
[12] Chaki S, Bose D and Bathe R N 2020 Multi-objective optimization of Pulsed Nd: YAG laser cutting process using entropy based ANN-PSO model, Lasers Manuf. Mater. Process. 7(1), 88-110.
[13] Chaki S, Bathe R N, Ghosal S and Padmanabham G 2015 Multi-objective optimisation of pulsed
Nd:YAG laser cutting process using integrated ANN–NSGAII model, *J. Intell. Manuf.* **29**(1), 175-190.

[14] Rana R S, chouksey R, Dhakad K and Paliwal D 2018 Optimization of process parameter of Laser beam machining of high strength steels: a review, *Mater. Today: Proc.* **5**(9), 19191-19199.

[15] Patidar D and Rana R S 2018 The effect of CO\textsubscript{2} laser cutting parameter on mechanical and microstructural characteristics of high strength steel: a review, *Mater. Today: Proc.* **5**(9), 17753-17762.

[16] Kumar S P, Norkey G and Kumar P A 2019 Optimization of process parameters during the laser cutting of Inconel-718 sheet using regression based Genetic algorithm, *Mater. Today:. Proc.* **18**, A17-A25.

[17] Canel T, Zeren M and Sinmaçelik T 2019 Laser parameters optimization of surface treating of Al 6082-T6 with Taguchi method, *Opt. Laser Technol.* **120**, 105714.

[18] Molnár L, Csiszér T, Borbás L and Bognár L L 2019 Optimization of laser beam cutting parameters of high density composite fibre cement flat board, *Mater. Today:. Proc.* **12**, 388-394.

[19] Lee D and Pyo S 2018 Experimental investigation of multi-mode fiber laser cutting of cement mortar, *Mater.* **11**(2), 278.

[20] Parmar M and James S 2018 Experimental and modeling study of liquid assisted laser beam micromachining of smart ceramic materials, *JMMP.* **2**(2), 28.

[21] Lokesh S, Niresh J, Neelakrishnan S and Deepak R S P 2018 Optimization of cutting parameters of composite material laser cutting process by Taguchi method, *IOP Conf. Ser.: Mater. Sci. Eng.* **324**, 012054.

[22] Mbithia B K, Byiringiro J B and Niyibizi A 2018 Experimental investigation and optimization of laser cutting parameters for solar cells based on Taguchi method cutting, *IOSR J. Mech. Civ. Eng.* **14**(5), 41-51.

[23] Nassar A, Nassar E and Younis M A 2016 Effect of laser cutting parameters on surface roughness of stainless steel 307, *Leonardo Electronic J. Pract. Technol.* **15**(29), 127–136.

[24] Prabhakaran M, Patil A N, Raikar N and Sidharth K 2016 Experimental investigation on gas laser, *Int. J. Adv. research Sci. Eng.* **5**(08), 27–38.

[25] Eltawahni H A, Hagino M, Benyounis K Y, Inoue T, and Olabi A G 2012 Effect of CO\textsubscript{2} laser cutting process parameters on edge quality and operating cost of AISI316L, *Opt. Laser Technol.* **4**(4), 1068–82.

[26] Hudeček P and Dostál P 2016 Melt flow and energy limitation of laser cutting, *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, **64**(5), 1555–1559.