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Research Article

Analysis of correlations of multiple-performance characteristics for optimization of CO_2 laser nitrogen cutting of AISI 304 stainless steel

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Abstract

The identification of laser cutting conditions for satisfying different requirements such as improving cut quality characteristics and material removal rate is of great importance. In this paper, an attempt has been made to develop mathematical models in order to relate laser cutting parameters such as the laser power, cutting speed, assist gas pressure and focus position, and cut quality characteristics such as the surface roughness, kerf width and width of heat affected zone (HAZ). A laser cutting experiment was planned as per Taguchi's L27 orthogonal array with three levels for each of laser cutting parameters considered. 3 mm thick AISI 304 stainless steel was used as workpiece material. Mathematical models were developed using a single hidden layer artificial neural network (ANN) trained with the Levenberg–Marquardt algorithm. On the basis of the developed ANN models the effects of the laser cutting parameters on the cut quality characteristics were presented. It was observed that laser cutting parameters variously affect cut quality characteristics. Also, for the range of operating conditions considered in the experiment, laser cut quality operating diagrams were shown. From these operating diagrams one can see the values of cut quality characteristics that can be achieved and subsequently select laser cutting parameter values. Furthermore, the analysis includes correlations between cut quality characteristics and material removal rate. To this aim, six trade-off operating diagrams for improving multiple responses at the same time were given.

Keywords: CO_2 laser nitrogen cutting, cut quality characteristics, material removal rate, operating diagrams, correlations

1. Introduction

Laser cutting is one of the most significant applications for industrial lasers. Compared with other conventional machining processes, laser cutting removes less material, involves highly localized heat input to the workpiece, minimizes distortion, and offers no tool wear [1]. Laser cutting is the process of melting or vaporization of material in a very small, well-defined area. The processes of heating, melting, and evaporation are produced by the laser beam affecting the workpiece surface [2]. Once the beam has been generated, a lens system focuses the beam on a point with diameters of around 0.2 mm. The focusing of the beam allows for high energy densities to be reached, a typical value is about 1.4×10^{10} W/m^2 [3]. The high power density of the focused laser beam in the spot melts or evaporates material in a fraction of a second, and coaxial jet of an assist gas removes the evaporated and molten material from the affected zone.

Different types of lasers are available in the market such as solid lasers, liquid lasers and gaseous lasers. Nd:YAG and CO_2 are the two most widely used industrial lasers [3]. Numerous advantages and possibilities of laser cutting technology have motivated considerable theoretical and experimental research aimed at better understanding of the laser cutting process. Studies that focused on the development and applications of laser beam cutting techniques were reviewed in [4]. When the cut quality is considered, in most reported studies, kerf width, surface roughness and width of the heat affected zone (HAZ), were commonly used as cut quality characteristics [5].

Laser cut quality cannot be easily predicted due to the dynamic nature of the laser cutting process [6]. In laser cutting, the process performance changes drastically with the laser cutting parameters [7]. Via appropriate selection and optimization of laser cutting parameters, cut quality characteristics can be improved considerably. However, the optimum parameter settings for one cut quality characteristic may deteriorate other cut quality characteristics. With a limited theoretical and practical background to assist in systematic selection, these parameters are usually set by previous experience, manufacturer recommendations, or in a trial and error procedure. But, this trial-and-error approach is costly in time and labor [8]. Above all, optimal cutting parameter settings for achieving good cut quality are not guaranteed.

Consequently, it is of great importance to exactly quantify the relationships between the laser cutting parameters and cutting performance through mathematical modeling and subsequently determine (near) optimal cutting conditions through the use of optimization algorithms. The application of Taguchi method without formulating any kind of model is also an attractive alternative, particularly when dealing with multiple responses. In the case of laser cutting, process models are often developed empirically using the

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multiple regression analysis (MRA) [6], response surface method (RSM) [9, 10] and in recent years by means of artificial neural networks (ANNs) [7, 8, 11-15] and fuzzy expert system [16]. The aforementioned methods are powerful tools for systematic modeling and analysis of laser cutting processes. These approaches integrate experimental, mathematical (statistical), and artificial intelligence methods, thus providing sufficient accuracy of predictions for the real conditions in which the laser cutting process takes place. It has been reported that ANNs, which are based on matrix-vector multiplications combined with nonlinear (activation) functions, offer powerful modeling ability for complex processes with many non-linearities and interactions such as laser cutting, and can readily outperform MRA [7].

In this paper an attempt has been made to develop mathematical models for the prediction of cut quality characteristics such as surface roughness, kerf width and width of HAZ in CO_2 laser nitrogen cutting of AISI 304 stainless steel. Three ANN models were developed to relate each of the cut quality characteristic with different laser cutting parameters such as the laser power, cutting speed, assist gas pressure and focus position. All ANN models were of the same architecture and the Levenberg–Marquardt algorithm was applied for the ANN training purpose. To obtain data for ANN models development, the laser cutting experiment was planned and conducted according to Taguchi's L_{27} orthogonal array (OA) experimental layout plan.

On the basis of developed ANN models, main and some interaction effects of laser cutting parameters on cut quality characteristics were presented by generating 2-D and 3-D plots. The obtained findings about effects of laser cutting parameters on cut quality characteristics were in accordance with similar findings in literature which confirmed the validity of developed mathematical models. Furthermore, through simulation of the developed models, operating diagrams showing achievable surface roughness, kerf width, width of HAZ and material removal rate (MRR) values for the range of laser cutting parameters considered in the study were provided. Finally, correlations between cut quality characteristics were presented and discussed.

2 Experimental details

2.1 Workpiece material

Stainless steel is an important material having wide application in industry. In this study, AISI 304 (EN X5CrNi18.10) stainless steel was used as the workpiece material. The chemical composition is given in Tab. 1. The sheet dimensions were 500 x 500 mm with thickness of 3 mm.

Table 1. Nominal chemical composition of AISI 304 stainless steel

Cr	Ni	C	Mn	Si	S	Fe
%						
18.9	9.22	0.07	1.64	0.5	0.006	Balance

2.2 Experimental plan

The accuracy of experimentation can be increased by using the scientific experimental design techniques. Taguchi experimental design provides an efficient plan to study the entire experimental region of interest for the experimenter, with the minimum number of trials as compared with the classical design of experiment, therefore it was chosen for performing the laser cutting experiment. Furthermore, since it was assumed that the effects of the laser cutting parameters on the cut quality characteristics were complex and nonlinear, the experiment was set up with parameters with more levels. To this aim, a standard L_{27} (3^{13}) Taguchi's OA with 4 input parameters and 3 levels was used. The L_{27} consists of 27 rows (experimental trials) and may be used for the analysis of 13 parameters at 3 levels. Laser cutting parameters, i.e. laser power, cutting speed, assist gas pressure and focus position were assigned to columns 1, 2, 5 and 9, respectively. The numerical values of selected parameters at different levels are shown in Tab. 2.

Table 2 Laser cutting parameters and their levels

Cutting parameter	Unit	Level		
		1	2	3
laser power, P	kW	1.6	1.8	2
cutting speed, v	m/min	2	2.5	3
assist gas pressure, p	MPa	0.9	1.05	1.2
focus position, f	mm	−2.5	−1.5	−0.5

The values range for each parameter was chosen such that full cut for each parameter combination is achieved and by considering manufacturer's recommendation for parameter settings.

2.3 Experimental procedure

The experiment trials as per Taguchi's L_{27} OA experimental design were performed using ByVention 3015 CO_2 laser cutting machine with a nominal power of 2.2 kW at a wavelength of 10.6 µm, operating in continuous wave mode. The cuts were performed with a Gaussian distribution beam mode (TEM_{00}) using a focusing lens of focal length of 127 mm. Nitrogen with purity of 99.95% was used as assist gas in all experimental trials. Conical shape nozzle (HK20) with the nozzle diameter of 2 mm was used. In all experimental trials the distance between the workpiece and nozzle was controlled at 1 mm.

2.4 Cut quality characteristics

Laser cut quality characteristics considered in the study included the measurement of the surface roughness, kerf width, and width of HAZ. Surface roughness on the cut edge was measured in terms of the average roughness, R_a, using a Surftest SJ-301 (Mitutoyo) profilometer. Each measurement was taken along the cut at approximately the middle of the thickness. Kerf width, which represents the top kerf width, was measured at three different places at equal distances along the length of cut using the optical microscope (Leitz, Germany). A 20 mm long segment of the cut edge taken at the middle of the cut was examined using the optical microscope for measurement of the width of HAZ. Surface roughness, kerf width and width of HAZ measurements were repeated to obtain averaged values.

3 Results and Discussions

3.1 ANN models for performance characteristics

For the development of the ANN models for predicting cut quality characteristics, the MATLAB Neural Network Toolbox was used. Three ANN models were developed:

- Model 1 which relates laser cutting parameters and surface roughness,
- Model 2 which relates laser cutting parameters and kerf width,
- Model 3 which relates laser cutting parameters and HAZ.

All ANN models were of the same architecture, that is, four neurons in input layer for representing laser power, cutting speed, assist gas pressure and focus position, three hidden neurons and one output neuron. The hyperbolic tangent sigmoid transfer function was used in the hidden layer, and linear transfer function was used in the output layer. According to the selected transfer functions the input and output data was normalized in [−1, 1] range. ANN models were trained using the Levenberg–Marquardt algorithm by using 19 out of 27 sets of input/output experimental data and the rest was used for testing the ANNs performance. The Levenberg-Marquardt algorithm was selected for ANNs training because it provides the best convergence in the cases of approximation of an unknown function (function prediction) [17]. In the ANN training process the well-known bias-variance trade-off was considered. The prediction performance of the ANN models was evaluated by calculating the mean absolute percentage error (MAPE):

$$MAPE(\%) = \frac{1}{n}\sum_{n}\left|\frac{\text{Experimental value - Predicted value}}{\text{Experimental value}}\right| \times 100 \quad (1)$$

where n is the number of data.

The results from Tab. 3 suggest that the ANN models' predictions are in good agreement with experimental values within the scope of laser cutting conditions investigated in the study. Thus, the developed mathematical models can be used for the analysis of the CO_2 laser nitrogen cutting process.

Table 3 ANN models performance

	Model 1	Model 2	Model 3
Number of training epochs	21	3	40
MSE achieved after training	0.0492	0.0007	0.12052
MAPE (%) on training data	8.71	5.51	1.26
MAPE (%) on testing data	9.66	6.50	7.30

3.2 Effects of laser cutting parameters on cut quality characteristics

The first part of the analysis is concerned with the effects of the laser cutting parameters on the cut quality characteristics. To this aim, simulation of the ANN quality characteristics models was performed by changing one parameter at a time, while keeping all the other parameters constant at center level (Fig. 1).

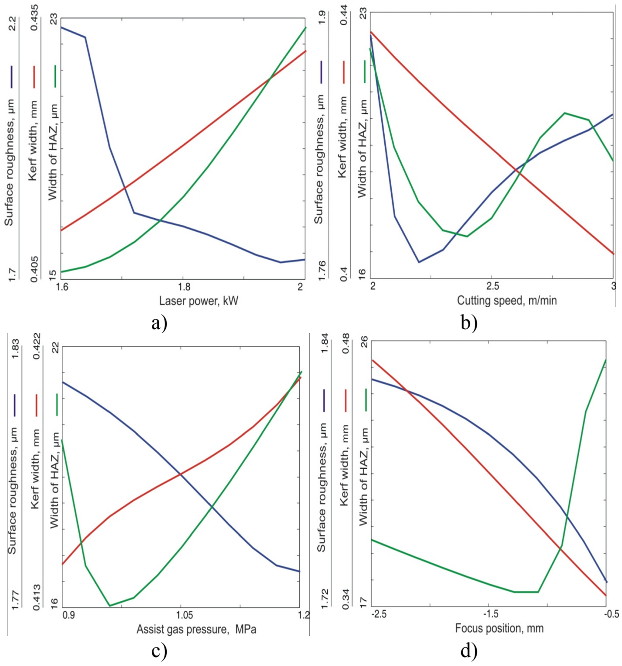

Figure 1 Effect of laser cutting parameters on cut quality characteristics: a) effect of laser power, b) effect of cutting speed, c) effect of assist gas pressure, d) effect of focus position.

As clearly seen from Fig. 1, changing laser cutting parameters, in the range investigated in the study, variously affects cut quality characteristics.

For improving the surface finish it is beneficial to use high laser power, high assist gas pressure, an intermediate level of cutting speed, and focus the laser beam nearer to the workpiece surface. In the relevant literature the similar observations were made [2, 6, 9]. In the case of kerf width, an increase in the laser power and assist gas pressure increases the kerf width, whereas the cutting speed and focus position have the opposite effect. In literature [18-20] it was found that the kerf width increases as the laser power and assist gas pressure are increased. Yilbas [18, 19] observed that the kerf width decreases as the cutting speed increases. Further, Eltawahni et al. [9] observed that lowering the focus position is beneficial for the kerf width minimization. Similar conclusions from the above studies further confirm the validity of developed ANN models. Finally, when the width of HAZ is considered, it is seen that width of HAZ increases with an increase in the laser power. From Fig. 1 (b, c and d) it is seen that the minimal width of HAZ is obtained at an intermediate level of the cutting speed, assist gas pressure and focus position. As shown in Fig. 1b, initially with an increase in the cutting speed, the width of HAZ is decreased since the time for heat conduction is lowered and the spread of heat damage is reduced. However, the width of HAZ increases with further increase in the cutting speed, and then decreases with further increase in the cutting speed. The similar observation was made by Rajaram et al. [6].

Not intending to go into a deeper analysis, it should be noted that the analysis of the effect of the laser cutting parameters on cut quality characteristics is more complex considering interaction effects of the laser cutting parameters (Fig. 2). It is clearly observed that the effect of a given parameter can change drastically when the value of some other parameter changes.

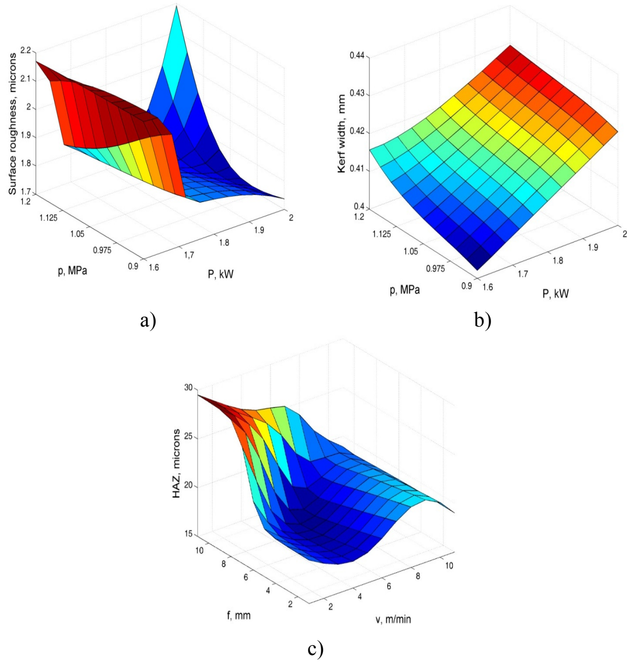

Figure 2 Some interaction effect on the cut quality characteristics: a) interaction effect of laser power and assist gas pressure on surface roughness, b) interaction effect of laser power and assist gas pressure on kerf width, c) interaction effect of cutting speed and focus position on HAZ

Finally, the analysis is further complicated considering the interaction effects of all laser cutting parameters. Although the effects of the laser cutting parameters on the cut quality characteristics are complex and vary with nonlinear functional dependency, using an optimization method one can obtain near optimal laser cutting parameter settings. However, in the case of multi-objective optimization, determining near optimal laser cutting parameters is further complicated and some trade-offs have to be made.

3.3 Laser cut quality operating diagrams

The developed ANN models can predict the laser cut quality characteristics within the entire experimental space for a given set of input laser cutting parameters. However, for practical application of the developed ANN models in real manufacturing environment, the technological limitations of the laser cutting system should be considered. In other words, it is of prime importance to predict the laser cut quality characteristics under the laser cutting conditions that could be achieved in production. For example, it is well known that the variation of the laser cutting parameters can be made at certain discrete values. In that sense, the entire experimental space considered in the present study, was discretized into the laser cutting conditions which correspond to a combination of laser cutting parameters that can be achieved on laser cutting machine used. This was accomplished by varying laser power at 9 levels, cutting speed at 11 levels, assist gas pressure at 7 levels and focus position at 5 levels (Tab. 4). Hence, all possible combinations of the laser cutting parameters represent 3465 different laser cutting conditions, i.e. 693 for each of the focus position settings.

Table 4. Laser cutting parameters considered

Laser power (*P*), kW	1.6	1.65	1.7	1.75	1.8	1.85	1.9	1.95	2		
Cutting speed (*v*), m/min	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
Assist gas pressure (*p*), MPa	0.9	0.95	1	1.05	1.1	1.15	1.2				
Focus position (*f*), mm	–2.5	–2	–1.5	–1	–0.5						

Figs. 3, 4, and 5 show the range of surface roughness, kerf width and width of HAZ values for particular laser cutting parameter settings. Also, considering that the MRR is very important for manufacturers, the MRR operating diagram was also plotted (Fig. 6). MRR is one of the most important criteria determining the laser cutting operation, with a higher rate always preferred in large batch production. The MRR was calculated as [21]:

$$MRR = v \cdot d \cdot K_w \qquad (2)$$

where *d* is the workpiece thickness.

Each point in diagrams corresponds to a particular combination of laser cutting parameters, i.e. represents particular laser cutting condition. For example, the red colored point in the Fig. 3 corresponds to the laser cutting condition when using the following laser cutting parameter settings: laser power = 2 kW, cutting speed = 2 m/min, assist gas pressure = 1 MPa and focus position = –2.5 mm.

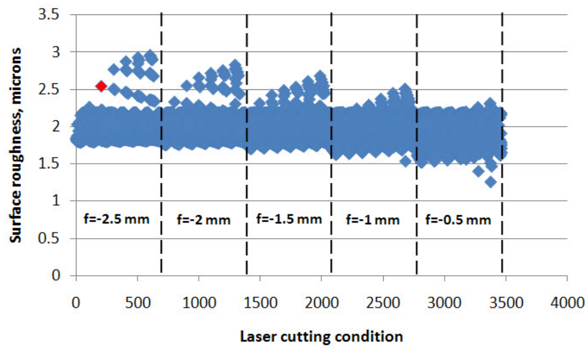

Figure 3 Achievable surface roughness values

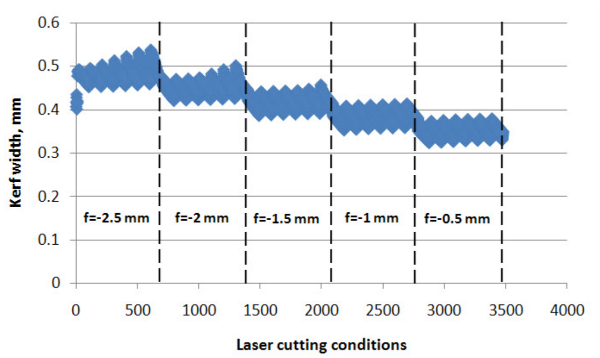

Figure 4 Achievable kerf width values

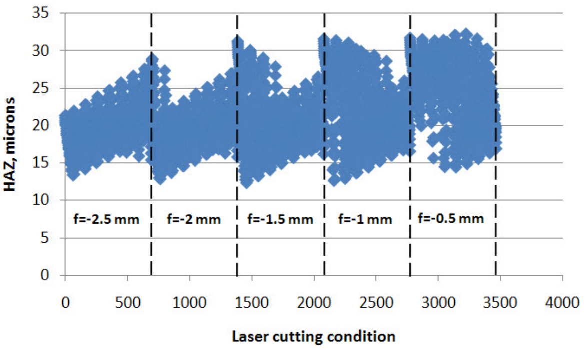

Figure 5 Achievable width of HAZ values

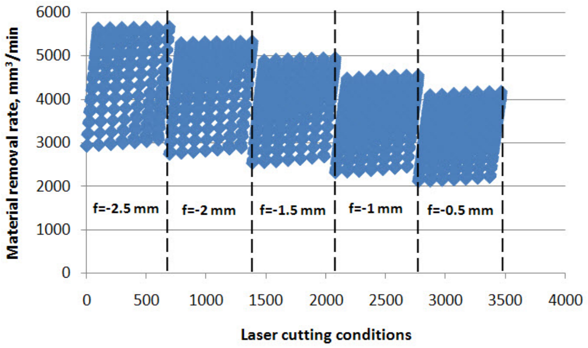

Figure 6 Achievable MRR values

Within the given parametric range of the laser cutting parameters used in the experiment and achievable laser cutting parameter combination on the laser cutting machine, from Figs. 3, 4, 5 and 6 the following can be observed: surface roughness varies between 1.254 μm and 2.959 μm, kerf width varies between 0.323 mm and 0.538 mm, width of HAZ varies between 12.3 μm and 32.19 μm, and MRR varies between 2101 mm^3/min and 5678 mm^3/min. Minimal surface roughness of 1.254 μm can be obtained using laser power of 2 kW, cutting speed of 2 m/min, assist gas pressure of 1.2 MPa and focus position of –0.5 mm. Minimal kerf width of 0.323 can be obtained using laser power of 1.6 kW, cutting speed of 3 m/min, assist gas pressure of 0.9 MPa and focus position of –0.5 mm. Minimal width of HAZ can be obtained using laser power of 1.6 kW, cutting speed of 2.8 m/min, assist gas pressure of 0.9 MPa and focus position of –1.5 mm. Finally, maximal MRR can be obtained using laser power of 2 kW, cutting speed of 3 m/min, assist gas pressure of 1.2 MPa and focus position of –2.5 mm.

3.4 Correlations between performance characteristics

In laser cutting, improving multiple quality characteristics at the same time is of particular interest to manufacturers. Therefore, an attempt has been made to consider two performance characteristics at a time. To this aim, the developed ANN models were used to predict the response parameters for all combinations of laser cutting parameters given in Tab. 4. Since there were 4 output performance characteristics (surface roughness, kerf width, width of HAZ and MRR), all combinations were considered, i.e. six 2-D plots were generated as shown in Fig. 7.

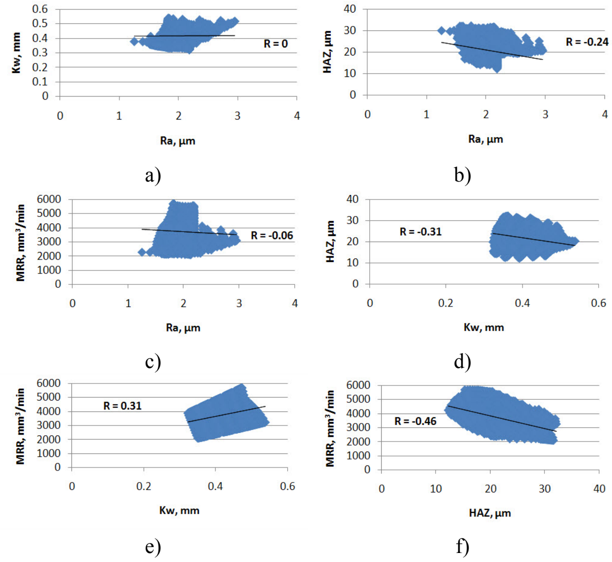

Figure 7 Trade-off operating diagrams for performance characteristics

From Fig. 7 (a, c) it is seen that there is very low or no correlation between the surface roughness and kerf width, and surface roughness and MRR. Although uncorrelated, these performance characteristics are not necessarily independent. Actually, a correlation around zero may disguise a strong non-linear relationship. From Fig. 7 (b, d and f) it is evident that there exist a certain level of negative correlation between the performance characteristics, i.e. as the values of one performance characteristic increases, the values of the second performance characteristic decreases and vice versa. Finally from Fig. 7e a direct relationship between the kerf width and MRR as expected since the MRR is a function of kerf width.

From the obtained results and Fig. 7 the following can be summarized:

- Minimal surface roughness of 1.254 μm comes with kerf width of 0.379 mm, width of HAZ of 29.98 μm and MRR of 2274 mm^3/min,
- Minimal kerf width of 0.323 mm comes with surface roughness of 2.188 μm, width of HAZ of 19.87 μm and MRR of 3875 mm^3/min,
- Minimal width of HAZ of 12.29 μm comes with surface roughness of 2.19 μm, kerf width of 0.392 mm and MRR of 4235 mm^3/min,
- Maximal MRR of 5678 mm^3/min comes with surface roughness of 1.814 μm, kerf width of 0.473 mm and width of HAZ of 15.34 μm.

In situations when there is a need to simultaneously consider different performance characteristics, which are often in real manufacturing conditions, the practical application of the above given operating diagrams in Fig. 7 is evident. For example, with a requirement of a high MRR with surface roughness less than 2 μm, a process engineer can select many possible solutions from Fig. 7c and subsequently determine the combinations of laser cutting parameters. In this case, surface roughness of 1.872 μm and MRR of 5509 mm^3/min can be obtained using the following laser cutting parameters: laser power = 1.75 kW, cutting speed = 3 m/min, assist gas pressure = 1.2 MPa and focus position = –2.5 mm. Under these conditions, kerf width of 0.46 mm and width of HAZ of 18 μm would be obtained. Furthermore, if some of the performance characteristics do not satisfy the pre-determined limitations one may seek the next solution. The operating diagrams from Fig. 7 can serve for simultaneous minimization, maximization or minimization and maximization of the performance characteristics.

4 Conclusions

In this paper, empirical models based on artificial neural networks for the prediction of the cut quality characteristics in CO_2 laser inert cutting of stainless steels were developed. Laser cutting experimental results from the Taguchi's experimental design, where four laser cutting parameters i.e. laser power, cutting speed, assist gas pressure and focus position were arranged, were used to train ANN models using the Levenberg-Marquardt algorithm. Within the range of operating conditions, the following conclusions can be drawn:

- Laser cutting parameters variously affect cut quality characteristics,
- For decreasing the surface roughness it is beneficial to use high laser power, low cutting speed, high assist gas pressure and focus the laser beam nearer to the workpiece surface,
- For obtaining narrower kerf width it is beneficial to use low laser power, high cutting speed, low assist gas pressure and focus the laser beam nearer to the workpiece surface,
- Using low laser power, intermediate cutting speed, low assist gas pressure and focusing the laser beam in the middle of the material thickness produces minimal width of HAZ,
- Maximal material removal rate is obtained by focusing the laser beam deep into the bulk of materials and by using high laser power, cutting speed and assist gas pressure,
- Low correlation between performance characteristics rate indicate that there might exists a strong nonlinear relationship.

For laser cutting conditions (3465) that can be achieved within the experimental region on the laser cutting machine used, operating diagrams for each performance characteristics and six trade-off operating diagrams for improving multiple performance characteristics at the same time were given. The optimal laser cutting conditions for each performance characteristics can be easily identified from these diagrams which will lead to efficient utilization of CO_2 laser inert cutting of stainless steel. By providing multiple solutions, these operating diagrams can assist in the selection of laser cutting conditions for obtaining desired cutting performance. It is concluded that the presented approach is of practical importance that can be effectively used for the prediction of performance characteristics. The approach is extendable and has the potential to be used in other machining processes.

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