

ANALYSIS OF THE HEAT AFFECTED ZONE IN CO₂ LASER CUTTING OF STAINLESS STEEL

by

Miloš J. MADIĆ* and Miroslav R. RADOVANOVIĆ

Faculty of Mechanical Engineering, University of Niš, Niš, Serbia

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This paper presents an investigation into the effect of the laser cutting parameters on the heat affected zone in CO₂ laser cutting of AISI 304 stainless steel. The mathematical model for the heat affected zone was expressed as a function of the laser cutting parameters such as the laser power, cutting speed, assist gas pressure, and focus position using the artificial neural network. To obtain experimental database for the artificial neural network training, laser cutting experiment was planned as per Taguchi's L₂₇ orthogonal array with three levels for each of the cutting parameter. Using the 27 experimental data sets, the artificial neural network was trained with gradient descent with momentum algorithm and the average absolute percentage error was 2.33%. The testing accuracy was then verified with 6 extra experimental data sets and the average predicting error was 6.46%. Statistically assessed as adequate, the artificial neural network model was then used to investigate the effect of the laser cutting parameters on the heat affected zone. To analyze the main and interaction effect of the laser cutting parameters on the heat affected zone, 2-D and 3-D plots were generated. The analysis revealed that the cutting speed had maximum influence on the heat affected zone followed by the laser power, focus position and assist gas pressure. Finally, using the Monte Carlo method the optimal laser cutting parameter values that minimize the heat affected zone were identified.

Key words: CO₂ laser cutting, heat affected zone, modelling, stainless steel, artificial neural network

Introduction

Among various advanced machining processes, laser cutting is one of the most widely used thermal-based processes applied for processing a wide variety of materials. In laser cutting the material is melted or evaporated by focusing the laser beam on the workpiece surface. It is a high energy-density process that works quickly on complex shapes, is applicable to any type of material, generates no mechanical stress on the workpiece, reduces waste, provides ecologically clean technology, and has the ability to do work in the micro range [1]. Numerous additional advantages such as convenience of operation, high precision, small heat affected zone (HAZ), minimum deformity, low level of noise, flexibility, ease of automation, etc., along with technological improvements in laser cutting machines, have made laser cutting technology more prevalent in today's production systems. For the above reasons, laser

* Corresponding author; e-mail: madic@masfak.ni.ac.rs

cutting has become an area of great interest for research. Considerable research studies have been carried out to examine the laser cutting process, with some of the findings summarized in recent comprehensive review papers [2-4]. Of particular interest to manufacturers using laser cutting technology are the maximization of productivity and quality and minimization of cost. Each of these goals often requires "optimal" selection of the laser cutting parameter settings. When the cut quality is considered, in most reported studies, kerf width, surface roughness, and size of the HAZ, were commonly used as cut quality characteristics [5]. The efficiency of cutting a material by laser depends on the physical properties of the material including heat conduction, phase change, plasma formation, surface absorption, and molten-layer flow [6]. The heat conduction into the workpiece, in turn, influences bulk phenomena such as grain refinement, carbide formation and other sulfide and phosphide impurities that might exist due to the alloying elements in stainless steel [7]. These phenomena result in the formation of small HAZ within the depth range of 10-50 μm [6]. HAZ is often associated with undesirable effects such as distortion, surface cracking, embrittlement, decrease in weldability, decrease in corrosion, fatigue resistance, *etc.* [8]. Hence, it is of great importance to exactly quantify the relationship between the HAZ and cutting conditions so as to minimize the HAZ. Considerable research studies were undertaken regarding the analysis of HAZ in laser cutting. Sheng *et al.* [7] showed that the HAZ increases with increasing laser power. On the other hand, it was found that the HAZ decreases with increasing cutting speed. Mathew *et al.* [9] conducted parametric studies on pulsed Nd:YAG laser cutting of carbon fiber reinforced plastic composites. The HAZ predictive model was developed using response surface methodology (RSM) in terms of the cutting speed, pulse energy, pulse duration, pulse repetition rate, and assist gas pressure. Paulo Davim *et al.* [10] conducted an experimental study for CO₂ laser cutting of polymeric materials. It was observed that the HAZ increases with the laser power and decreases with the cutting speed. Rajaram *et al.* [11] investigated the combined effects of the laser power and cutting speed on the size of HAZ in CO₂ laser cutting of 4130 steel. It was found that an increase in the cutting speed and a decrease in the laser power resulted in a decrease in the width of HAZ for the power range from 700 to 1100 W. However, it was observed that when using laser power of 1300 W, width of HAZ increases with an increase in the cutting speed of up to 2.8 m/min. and decreases with further increase in the cutting speed.

The objective of this paper is to analyze the effect of the laser cutting parameters on the HAZ obtained in CO₂ laser nitrogen cutting of stainless steel. Four main laser cutting parameters such as the laser power, cutting speed, assist gas pressure and focus position were considered. A mathematical model for the analysis of the width of HAZ was developed using the artificial neural network (ANN) on the basis of experimental results. The laser cutting experiment was planned and conducted according to the Taguchi's L₂₇ orthogonal array. In addition, optimal laser cutting parameter values that minimize the width of HAZ were identified. The optimization problem was formulated and solved by the Monte Carlo method.

Experimental procedure

The CO₂ laser cutting parameters considered in the present study were laser power (P), cutting speed (v), assist gas pressure (p), and focus position (f). The parameters were varied in the following range: laser power 1.6-2 kW, cutting speed 2-3 m/min., assist gas pressure 12 bar and focus position -2.5 mm to -0.5 mm. The values range for each parameter was chosen such that wider experimental range was covered, full cut for each parameter combination was achieved and by considering manufacturer's recommendation for parameter settings.

Since it was assumed that the effects of the laser cutting parameters on the HAZ were complex and non-linear, the experiment was set up with parameters with more levels (tab. 1). Focusing lens with focal length of 127 mm, a conical shape nozzle HK20 with nozzle diameter of 2 mm, and a nozzle stand-off distance of 1 mm were kept constant throughout the experimentation.

Table 1. Laser cutting parameter values

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	bar	9	10.5	12
Focus position, f	mm	-2.5	-1.5	-0.5

Table 2. Experimental plan and HAZ results

Exp. trial	Natural factor				Experimental results
	P [kW]	v [m min. ⁻¹]	p [bar]	f [mm]	
1	1.6	2	9	-2.5	21.00
2	1.6	2	10.5	-1.5	23.67
3	1.6	2	12	-0.5	23.33
4	1.6	2.5	9	-1.5	15.33
5	1.6	2.5	10.5	-0.5	20.67
6	1.6	2.5	12	-2.5	18.67
7	1.6	3	9	-0.5	19.67
8	1.6	3	10.5	-2.5	17.67
9	1.6	3	12	-1.5	20.00
10	1.8	2	9	-1.5	30.33
11	1.8	2	10.5	-0.5	25.67
12	1.8	2	12	-2.5	20.33
13	1.8	2.5	9	-0.5	26.00
14	1.8	2.5	10.5	-2.5	19.67
15	1.8	2.5	12	-1.5	20.33
16	1.8	3	9	-2.5	18.33
17	1.8	3	10.5	-1.5	17.00
18	1.8	3	12	-0.5	19.33
19	2	2	9	-0.5	28.33
20	2	2	10.5	-2.5	19.33
21	2	2	12	-1.5	20.33
22	2	2.5	9	-2.5	19.67
23	2	2.5	10.5	-1.5	22.67
24	2	2.5	12	-0.5	26.33
25	2	3	9	-1.5	18.33
26	2	3	10.5	-0.5	20.67
27	2	3	12	-2.5	15.00

Based on the selected laser cutting parameters and their levels, a design matrix was constructed (tab. 2) in accordance with the standard L₂₇ Taguchi orthogonal array (OA). The selected design matrix consisted of 27 rows corresponding to the total number of experiment trials. All of the experiment trials were conducted on a 2.2 kW CO₂ byVenton 3015 laser cutting machine provided by Bystronic Inc. Experiment trials were conducted in random order to avoid any systematic error. The cuts were performed with a continuous wave and Gaussian distribution beam mode (TEM₀₀) on 3 mm thick AISI 304 stainless steel sheet using nitrogen as assist gas with purity of 99.95%. The schematic of the CO₂ laser cutting process and of laser cut specimen profile is shown in fig. 1.

Two straight cuts, each of 60 mm in length, were made in each experimental trial and the cut quality was evaluated in terms of the width of HAZ. An optical microscope (Leitz, Germany) was used to measure the width of HAZ along the 10 mm segment of the cut edge.

The measurements were repeated three times to obtain averaged values. All experimental data were used to generate an experimental database for the ANN model development.

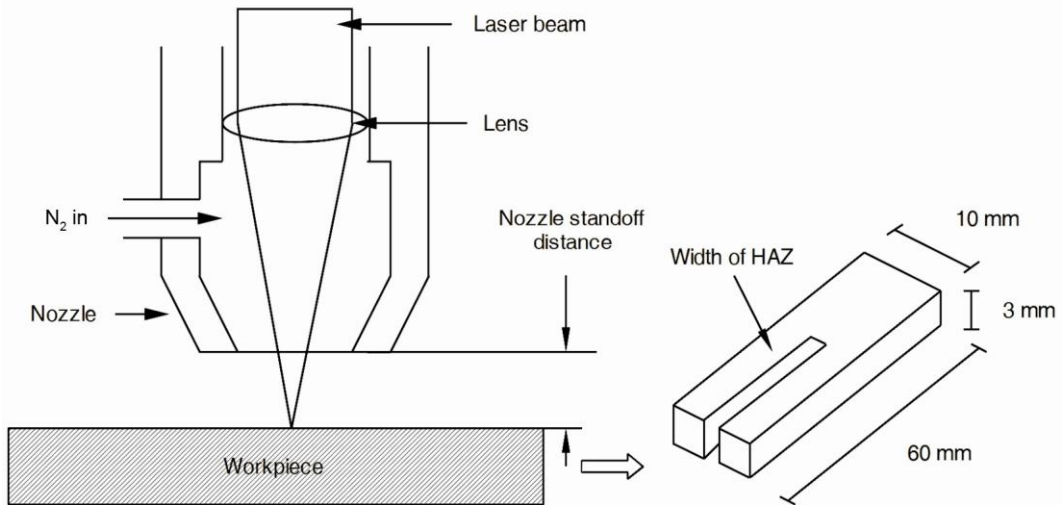


Figure 1. Schematic of laser beam cutting and laser cut specimen profile

Mathematical modeling

To perform the analysis of the effect of the laser cutting parameters on the width of HAZ, an accurate mathematical model is needed. Through the mathematical model, any experimental result of the width of HAZ with any combination of laser cutting parameters can be estimated. Although the regression models are very promising for practical applications, they are of limited applicability and reliability in laser cutting modeling. It was shown that artificial neural networks (ANN), which are based on matrix-vector multiplications combined with non-linear (activation) functions, offer better data fitting capability than regression models for complex processes with many non-linearities and interactions such as CO₂ laser cutting [12]. ANN are able to learn the key information patterns within multidimensional information domain and can be used in modeling of complex physical phenomena [13]. Therefore, the width of HAZ predictive model was developed using ANN on the basis of experimental results.

ANN model design

To establish a mathematical relationship between the width of HAZ and the laser cutting parameters a multilayer feed forward type ANN was selected [14]. Four neurons at the input layer (for each of the laser cutting parameter), one neuron at the output layer for calculating the width HAZ and only one hidden layer were used to define ANN architecture. Single hidden layer ANN model was chosen, because it is widely reported that this architecture can be trained to approximate most functions arbitrarily well [15, 16]. Considering the total number of connection weights in the ANN architecture and biases of the hidden and output neurons, as well as the available number of data for training, it was decided that the number of hidden neurons should be four (fig. 2).

Hyperbolic tangent sigmoid and linear transfer functions were used in the hidden layer and output layer, respectively. In order to facilitate the ANN training process, the experimental data was normalized in the range $[-1, 1]$. To determine the connection weights and biases in the ANN, the training process was carried out using gradient descent with momentum training procedure “traingdm” of Matlab. Gradient descent with momentum method updates weights so as to minimize the mean square error (MSE) between the ANN predicted and desired (target) values. In each iteration, weights are updated by the partial derivative of the total error with respect to given weight through a learning rate η and the variation of the same weight during the previous iteration by momentum μ . Learning rate and momentum control the speed and stability of the training process, and usually take values between 0 and 1 [17]. It was found that the selected ANN architecture provides the best data fitting capability when learning rate (η) and momentum (μ) were kept at 0.1 and 0.9, respectively. The ANN training was stopped after 10000 iterations since no further improvement in performance was achieved, considering the well known bias-variance trade-off in model development [18].

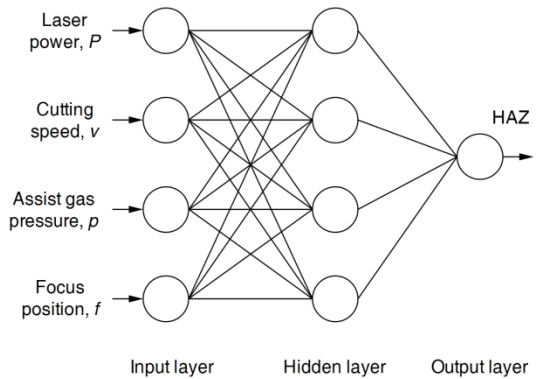


Figure 2. ANN model used in the study

ANN model validation

There is a variety of statistical performance measures for evaluating the ANN performance. To test the prediction capability of the developed model, the trained ANN was initially tested by presenting 27 input data patterns, which were employed for the training purpose. For each input pattern, the predicted value of the width of HAZ was compared with the respective experimentally measured value, and the statistical method of absolute percentage error (APE), as one of the most stringent criteria, was used. It is defined as:

$$APE = \left| \frac{\text{Experimental value} - \text{Predicted value}}{\text{Experimental value}} \right| \times 100 [\%] \tag{1}$$

The average APE for the training data was found to be 2.33%. In order to test the generalization ability of the ANN model, 6 new experiment trials were conducted with laser cutting parameter levels which did not belong to the training data set (tab. 3).

Table 3. Experiment trials for testing the ANN model

Test no.	P [kW]	v [m min ⁻¹]	p [bar]	f [mm]	Experimentally measured HAZ [μm]	ANN predicted HAZ [μm]
1	1.8	2.5	9	-2.5	20.33	20.23
2	2	2.5	10.5	-0.5	23.67	25.65
3	1.8	3	12	-1.5	17.33	17.50
4	2	2	10.5	-1.5	24	21.16
5	1.8	3	10.5	-2.5	18	17.75
6	2	2.5	9	-1.5	20.67	23.92

From tab. 3 it can be seen that experimentally measured and ANN predicted values of the width of HAZ are in good agreement. It was found that the average APE was 6.46%.

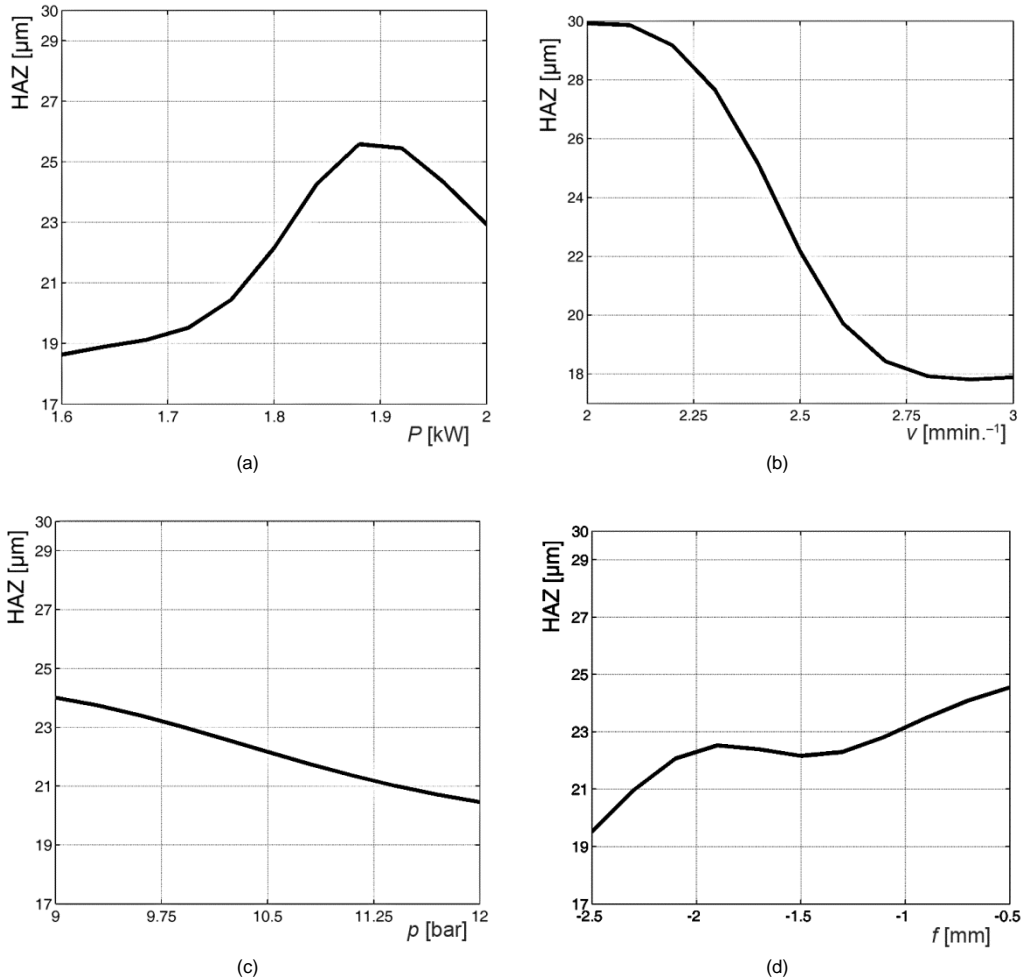


Figure 3. Effect of the laser cutting parameters on the width of HAZ

The results indicate that ANN predictions are in good agreement with experimental results and the ANN model has good generalization capability.

Results and discussion

The developed ANN model to predict the width of HAZ based on the selected laser cutting parameters showed good prediction accuracy within the scope of cutting conditions investigated in the study. Thus, the developed ANN model can be used to analyze the effect of the laser cutting parameters on the width of HAZ.

Main effect plots

Initially, the effect of the laser cutting parameters on the width of HAZ was analyzed by changing one parameter at a time, while keeping all other parameters constant at center level – level 2 (fig. 3). From fig. 3(a) it can be seen that the increase in the laser power results in an increase in the width of HAZ for the laser power range from 1.6 to 1.9 kW. This is due to the increase of thermal energy that is absorbed in material as the laser power increases. These findings are in agreement with the previously reported results [7, 11].

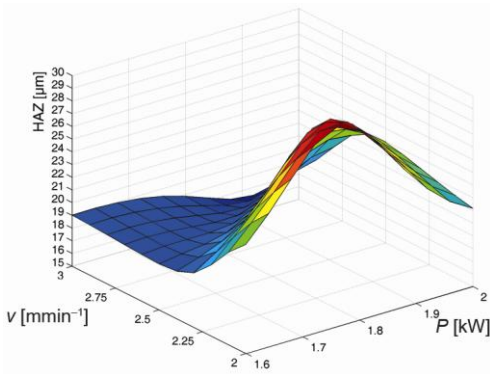
However, using the laser power above 1.9 kW, the effect of the laser power on the width of HAZ is opposite, *i. e.* with an increase in the laser power the width of HAZ tends to decrease. This trend could be confirmed by similar findings in the literature [11]. These opposite effects of the laser power could be explained by considering the interaction effect of the laser power with other parameters. For example, as explained by Mathew *et al.* [9], there exists an optimum region of the laser power to cutting speed ratio where the width of HAZ is minimal. As shown in fig. 3(b) with an increase in the cutting speed the width of HAZ decreases non-linearly. As the cutting speed is increased, the interaction time between laser beam and material is reduced and hence the width of HAZ is reduced. Similar conclusions were made in the earlier studies [7, 9, 11]. From fig. 3(c) it can be seen that the width of HAZ decreases linearly with increasing assist gas pressure. This positive influence on the width of HAZ can be attributed to the efficient cooling effects of the assist gas. In the case of the focus position, fig. 3(d), suggests that focusing the laser beam deep into the bulk of material is beneficial for minimizing the width of HAZ. When the focus position is close to the back surface of the sheet, the kerf width becomes wider so that nitrogen more effectively ejects the molten material, minimizing heat penetration into the material *i. e.* minimizing the the HAZ.

Interaction effect plots

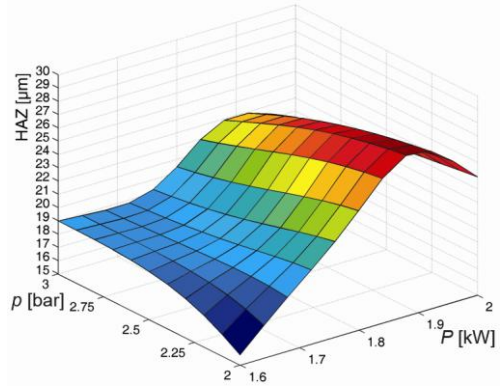
In order to determine the interaction effects of the laser cutting parameters on the width of HAZ, 3-D surface plots were generated considering two parameters at a time, while the third and fourth parameter were kept constant at center level. Since there are six possible two-way interactions (P and v , P and p , P and f , v and p , v and f , and p and f), six 3-D plots were generated (fig. 4) using the ANN model.

Figure 4(a) shows the width of HAZ as a function of the laser power and the cutting speed. The interaction is expressed by the difference between the relatively smaller influence of the laser power when using high cutting speed, and the big influence of the laser power when using low cutting speed. As shown in fig. 4(b), the effect of the assist gas pressure on the width of HAZ is variable and depends on the laser power level.

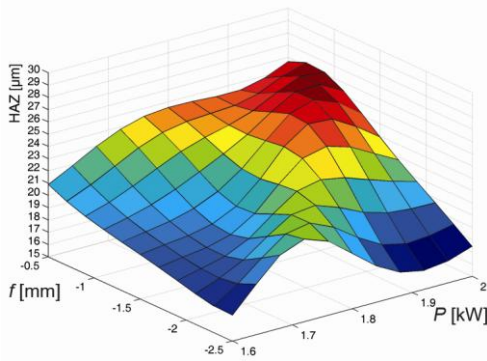
Generally, an increase in the assist gas pressure reduces the width of HAZ. However, at low power level, high assist gas pressure increases the width of HAZ. This effect may be attributed to the role the assist gas plays in heat transport through the thickness of the workpiece and to the rise in flow turbulence and less effective cooling at high pressure [19]. Focusing the laser beam up to the half of material thickness (-1.5 mm) and using high laser power results in high width of HAZ, fig. 4(c). On the other hand, focusing the laser beam deep into the bulk of material (-2.5 mm) and using high laser power (in the range from 1.9 to 2 kW) decreases the width of HAZ. This effect is also noticeable when using laser power of 1.6 kW and by shifting the focus position in positive direction towards the workpiece surface (about -2 mm).



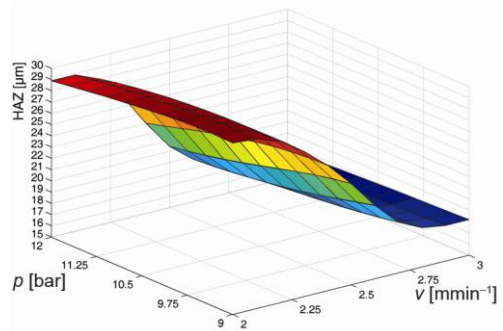
(a) Max. width of HAZ = 30.7 μm , min. width of HAZ = 16.37 μm



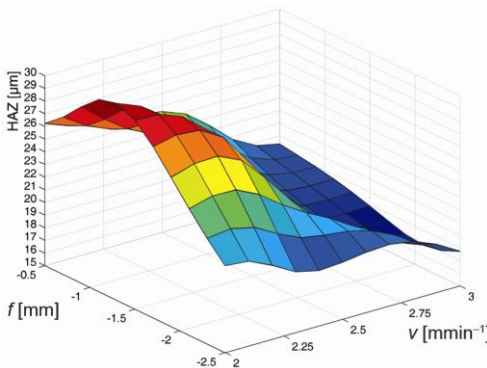
(b) Max. width of HAZ = 27.11 μm , min. width of HAZ = 15.79 μm



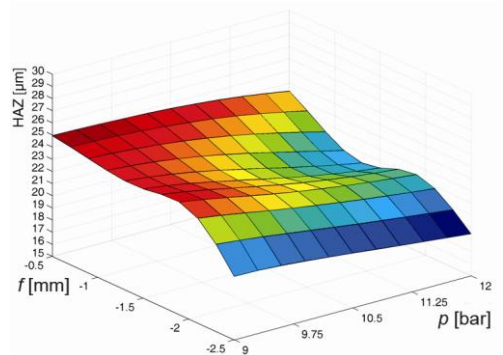
(c) Max. width of HAZ = 26.38 μm , min. width of HAZ = 16.55 μm



(d) Max. width of HAZ = 30.31 μm , min. width of HAZ = 17.39 μm



(e) Max. width of HAZ = 30.57 μm , min. width of HAZ = 18.46 μm



(f) Max. width of HAZ = 24.95 μm , min. width of HAZ = 17.39 μm

Figure 4. Interaction effects of the laser cutting parameters on the width of HAZ

In the focus position and the assist gas pressure interaction plot, fig. 4(d), it can be seen that increase in the cutting speed decreases the width of HAZ, whereas the effect of the assist gas pressure on the width of HAZ is negligible. From fig. 4(e) it can be seen that the in-

teraction effect of focus position and cutting speed produces highly non-linear change in the width of HAZ. Using low cutting speed of up to 2.5 m/min, while focusing the laser beam approximately at the half of the material thickness, produces high width of HAZ.

However, using the cutting speed of above 2.5 m/min, while focusing the laser beam deep into the bulk of material (around -2 mm), is beneficial for reducing the width of HAZ. Figure 4(f) shows that low focus position in conjunction with high assist gas pressure is beneficial for minimizing the width of HAZ. On the other hand, focusing the laser beam near the top surface and using low assist gas pressure results in increased width of HAZ. It is also noticeable that the effect of the assist gas on the width of HAZ is nearly linear.

Finally, from fig. 4 one can summarize the order of magnitude of the interaction effects in descending order as follows: P and v , v and p , v and f , P and p , P and f , and p and f .

Additionally, from the analysis of figs. 3 and 4 it can be concluded that the cutting speed has maximum influence on the width of HAZ followed by the laser power, focus position and assist gas pressure.

Optimization of the HAZ

The optimal selection of cutting parameters should increase the product quality to some extent by minimizing the width of HAZ value. Minimization of the width of HAZ is particularly desirable in micromachining, marking, and other high-performance laser applications. To determine the optimal laser cutting conditions, the optimization problem was formulated as follows:

$$\begin{aligned} \text{Find: } & P_{\text{opt}}, v_{\text{opt}}, p_{\text{opt}}, f_{\text{opt}}, \text{ to minimize: } HAZ = f(P, v, p, f), \text{ subject to:} \\ & 1.6 \leq P \leq 2 \text{ [kW]}, \quad 2 \leq v \leq 3 \text{ [mmin.}^{-1}\text{]}, \quad 9 \leq p \leq 12 \text{ [bar]}, \quad -2.5 \leq f \leq -0.5 \text{ [mm]} \end{aligned} \quad (2)$$

For calculating the width of HAZ, the mathematical function based on ANN was used. To find the optimum laser cutting parameter settings formulated in eq. (3) one may apply a large number of optimization techniques. Despite numerous optimization methods, every method has certain advantages and disadvantages for implementation. In recent years, among the traditional optimization methods, there has been increasing application of metaheuristic optimization algorithms such as genetic algorithm (GA), simulated annealing (SA), particle swarm optimization (PSO), *etc.* However, effective utilization of these methods in solving the optimization problems requires that the number of algorithm's parameters is adequately set.

In this study the Monte Carlo optimization algorithm was selected because of its simplicity and efficiency. The first step in the Monte Carlo optimization procedure is the generation of random numbers $r_{i,j}$ uniformly distributed in the range [0, 1] using the function *rand*. To satisfy the limitations of the laser cutting parameters values, random numbers $r_{i,j}$ were used to generate random numbers $q_{i,j}$ uniformly distributed into the range of interest for each of the laser cutting parameters $[q_i^{\min}, q_i^{\max}]$. Therefore, for each of the laser cutting parameters, the randomized values were generated and subsequently the width of HAZ was calculated using the mathematical function based on ANN. After 1000 Monte Carlo simulations were performed, the acceptable near optimal solution was identified.

As a result of optimization, the minimum value of width of HAZ = 14.20 μm was obtained with the following laser cutting parameter values: $P_{\text{opt}} = 2 \text{ kW}$, $v_{\text{opt}} = 2.74 \text{ m/min}$, $p_{\text{opt}} = 12 \text{ bar}$, and $f_{\text{opt}} = -2.5 \text{ mm}$. The optimization result can be confirmed from fig. 5, where the width of HAZ is given as a function of the cutting speed and assist gas

pressure at $P = 2$ kW and $f = -2.5$ mm. Considering small change in the width of HAZ when changing cutting speed from 2.75 m/min to 3 m/min. and assist gas pressure from 9 bar to 12 bar, and by considering laser cutting economics (productivity and cost), the optimal cutting conditions are as follows: $P = 2$ kW, $v = 3$ m/min., $p = 9$ bar, and $f = -2.5$ mm.

Conclusions

The present paper analyzed the effect of the laser cutting parameters on the width of HAZ during CO₂ laser nitrogen cutting of AISI 304 stainless steel. The analysis was performed by developing ANN mathematical model with laser power, cutting speed, assist gas pressure, and focus position as the input parameters. The developed ANN model was trained from 27 sets of experimental data using the gradient descent with momentum algorithm and tested by 6 extra experimental data sets. The average predicting errors were found to be 2.33% and 6.46% in the training and testing processes, respectively. From the analysis of the effect of the laser cutting parameters on the width of HAZ the following conclusions can be drawn:

- the width of HAZ is highly sensitive to the selected laser cutting parameters and their interactions,
- the functional dependence between the width of HAZ and the laser power, cutting speed and focus position is highly non-linear, whereas in the case of the assist gas pressure this dependence is nearly linear,
- the effect of a given laser cutting parameter on the width of HAZ must be considered through the interaction with other parameters, and
- cutting speed has maximum influence on the width of HAZ followed by the laser power, focus position and assist gas pressure.

The combination of experimental results with powerful modeling abilities of ANN represents an appropriate approach for mathematical modeling and analysis of CO₂ laser cutting process with practical applications in real manufacturing environment for determining laser cutting parameter settings to achieve the desired performance. In addition to modeling, using the Monte Carlo method, the optimal laser cutting parameter values that minimize the width of HAZ were identified. The optimal cutting conditions, which are beneficial for both productivity and costs are: $P = 2$ kW, $v = 3$ m/min., $p = 9$ bar, and $f = -2.5$ mm.

Nomenclature

f_{opt} – optimal focus position, [mm]
 P_{opt} – optimal laser power, [kW]
 p_{opt} – optimal assist gas pressure, [bar]
 $q_{i,j}$ – random numbers
 $r_{i,j}$ – random numbers

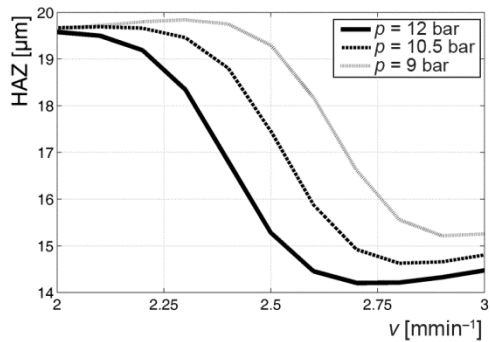


Figure 5. Optimal cutting region for reducing width of HAZ

v_{opt} – optimal cutting speed, [mmin⁻¹]

Greek symbols

η – learning rate
 μ – momentum

References

- [1] Biswas, R., *et al.*, Artificial Neural Network Modelling of Nd:YAG Laser Microdrilling on Titanium Nitride-Alumina Composite, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 224 (2010), 3, pp. 473-482
- [2] Dubey, A. K., Yadava, V., Laser Beam Machining - A Review, *International Journal of Machine Tools and Manufacture*, 48 (2008), 6, pp. 609-628
- [3] Dutta Majumdar, J., Manna, I., Laser Processing of Materials, *Sadhana*, 28 (2003), 3-4, pp. 495-562
- [4] Meijer, J., Laser Beam Machining (LBM), State of the Art and New Opportunities, *Journal of Materials Processing Technology*, 149 (2004), 1-3, pp. 2-17
- [5] Radovanović, M., Madić, M., Experimental Investigations of CO₂ Laser Cut Quality: A Review, *Non-conventional Technologies Review*, 15 (2011), 4, pp. 35-42
- [6] Abdel Ghany, K., Newishy, M., Cutting of 1.2 mm Thick Austenitic Stainless Steel Sheet Using Pulsed and CW Nd:YAG Laser, *Journal of Materials Processing Technology*, 168 (2005), 3, pp. 438-447
- [7] Sheng, P. S., Joshi, V. S., Analysis of Heat-Affected Zone Formation for Laser Cutting of Stainless Steel, *Journal of Materials Processing Technology*, 53 (1995), 3-4, pp. 879-892
- [8] Dahotre, N. B., Harimkar, S. P., *Laser Fabrication and Machining of Materials*, Springer, Berlin, 2008
- [9] Mathew, G. L., *et al.*, Parametric Studies on Pulsed Nd:YAG Laser Cutting of Carbon Fibre Reinforced Plastic Composites, *Journal of Materials Processing Technology*, 89-90 (1995), 3-4, pp. 198-203
- [10] Paulo Davim, J., *et al.*, Some Experimental Studies on CO₂ Laser Cutting Quality of Polymeric Materials, *Journal of Materials Processing Technology*, 198 (2008), 1-3, pp. 99-104
- [11] Rajaram, N., Sheikh-Ahmad, J., Cheraghi, S. H., CO₂ Laser Cut Quality of 4130 Steel, *International Journal of Machine Tools and Manufacture*, 43 (2003), 4, pp. 351-358
- [12] Madić, M., Radovanović, M., Comparative Modeling of CO₂ Laser Cutting using Multiple Regression Analysis and Artificial Neural Network, *International Journal of Physical Sciences*, 7 (2012), 16, pp. 2422-2430
- [13] Fazeli, S. A., Rezvantalab, H., Kowsary, F., Thermodynamic Analysis and Simulation of a New Combined Power and Refrigeration Cycle using Artificial Neural Network, *Thermal Science*, 15 (2011), 1, pp. 29-31
- [14] Ganapathy, T., Gakkhar, R. P., Murugesan, K., Artificial Neural Network Modeling of Jatropha Oil Fueled Diesel Engine for Emission Predictions, *Thermal Science*, 13 (2009), 3, pp. 91-102
- [15] Hornik, K., Stinchcombe, M., White, H., Multilayer Feedforward Networks are Universal Approximators, *Neural Networks*, 2 (1989), 5, pp. 359-366
- [16] Cybenko, G., Approximation by Superpositions of a Sigmoidal Function, *Mathematics of Control, Signals and Systems*, 2 (1989), 4, pp. 303-314
- [17] Sumathi, S., Surekha, P., *Computational Intelligence Paradigms: Theory and Applications Using MATLAB*, CRC Press, Taylor & Francis Group., Boca Raton, Fla., USA, 2010
- [18] Feng, C. X., Yu, Z. G., Kusiak, A., Selection and Validation of Predictive Regression and Neural Network Models Based on Designed Experiments, *IIE Transactions*, 38 (2006), 1, pp. 13-23
- [19] Sheikh-Ahmad, J. Y., *Machining of Polymer Composites*, Springer, Berlin, 2009