Analysis of the Heat Affected Zone in CO2 Laser Cutting of Stainless Steel

Rajesh.V.Chaudhari[1] M. D. Patel[2] J. B. Patel[3] H.C. Patel[4] A.G. Barad[5]
[1,2,3,4,5]Assistant Professor
[1,2,3,4,5]Department of Mechanical Engineering
[1,2,3,4,5]S R Patel Unjha

Abstract— This paper presents an investigation into the effect of the laser cutting parame-ters 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 pres-sure, and focus position using the artificial neural network. To obtain experimen-tal 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 av-erage absolute percentage error was 2.33%. The testing accuracy was then veri-fied 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 pa-rameters on the heat affected zone, 2-D and 3-D plots were generated. The anal-ysis 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

I. INTRODUCTION

LBM is one of the AMPs which is used for shaping almost whole range of engineering materials. The laser beams are widely used for cutting, drilling, marking, welding, sintering and heat treatment. The laser is also used to perform turning as well as milling operations but major application of laser beam is mainly in cutting of metallic and non-metallic sheets [1].

Among different types of lasers, CO2 lasers have low beam power, better efficiency and good beam quality. Because of material versatility, no change of tool or wear, high material utilization with production flexibility, high accuracy and edge quality ,laser beam cutting appears to be superior to any cutting process whether traditional or non-traditional [2]. LBM has wide applications in the field of automobile sectors, aircraft industry, electronic industry, civil structures, nuclear sector and house appliances. Stainless steel, a distinguishable engineering material used in automobiles and house appliances, is ideally suitable for laser beam cutting [3, 4].

II. MATERIALS AND METHODOLOGY

A number of experiments were conducted to study the effects of various machining parameters on Laser Machining. These studies were undertaken to investigate the effects of various machining parameters on Kerf width and Surface roughness. The selected workpiece material for the research work is AISI 304 steel was selected due to its emergent range of applications in the field of mould industries.

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 la-ser 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 applica-ble 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- 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 la-ser 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 set-tings. When the cut quality is considered, in most reported studies, kerf width, surface rough-ness, and size of the HAZ, were commonly used as cut quality characteristics [5]. The effi-ciency of cutting a material by laser depends on the physical properties of the material includ-ing 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 ex-ist 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 undesira-ble effects such as distortion, surface cracking, embrittlement, decrease in weldability, de-crease 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 plas-tic composites.

The HAZ predictive model was developed using response surface methodolo-gy (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 la-ser cutting of polymeric materials. It was observed that the HAZ increases with the laser pow-er 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 ob-served 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 pa-rameters 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 ex-periment was planned and conducted according to the Taguchi's L27 orthogonal array. In ad-dition, 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.

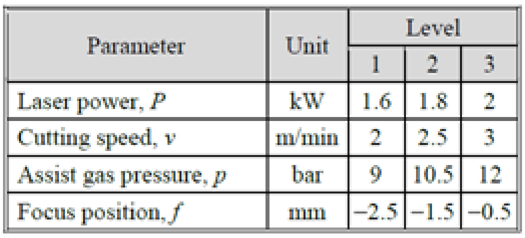
Experimental procedure

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 var-ied in the following range: laser power 1.6-2 kW, cutting speed 2-3 m/min., assist gas pres-sure 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 combina-tion was achieved and by considering manufacturer's recommendation for parameter settings.

Madić, M. J., et al.: Analysis of the Heat Affected Zone in CO2 Laser Cutting …

Since it was assumed that the effects of the la-ser cutting parameters on the HAZ were com-plex 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 2. Experimental plan and HAZ results



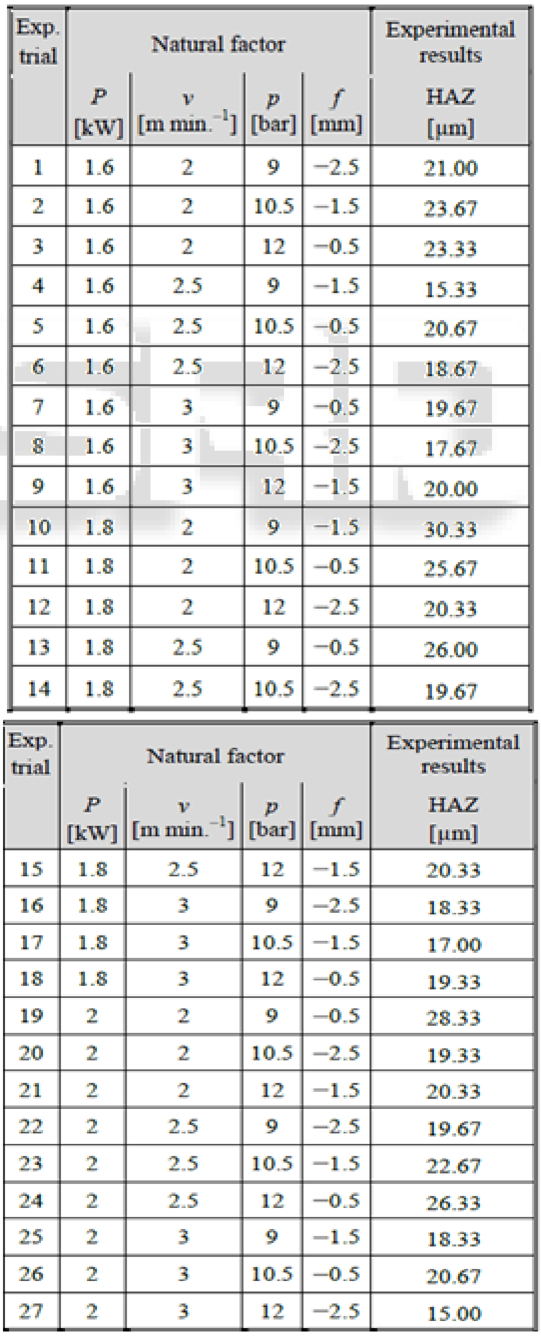
Parameter	Unit	Level		
		1	2	3
Laser power, *P*	kW	1.6	1.8	2
Cutting speed, *v*	m/min	2	2.5	3
Assist gas pressure, *p*	bar	9	10.5	12
Focus position, *f*	mm	−2.5	−1.5	−0.5

Table 1: Laser cutting Parameter values

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 byVention 3015 laser cut-ting 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 la-ser 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.

Table 1. Laser cutting parameter values Parameter Unit Level 1 2 3



Exp. trial	Natural factor				Experimental results
	P [kW]	v [m min.$^{-1}$]	p [bar]	f [mm]	HAZ [μm]
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

Table 2: Experimental plan and HAZ results

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 byVention 3015 laser cut-ting 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 la-ser 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, Table III: Estimated Regression Coefficients for Ra:

Term	**Coef**	**SE Coef**	**T**	**P**
Constant	59.4302	16.3270	3.640	0.002
Laser Power	-5.1353	8.3003	-0.619	0.545
Cutting Speed	-0.1737	1.4941	-0.116	0.909
Gas Pressure	-7.7797	1.9048	-4.084	0.001
Frequency	6.5935	2.9367	2.245	0.039
Laser Power* Laser Power	4.0107	1.7550	2.285	0.036
Cutting Speed* Cutting Speed	-0.0320	0.0702	-0.455	0.655
Gas Pressure* Gas Pressure	0.3356	0.0702	4.781	0.000
Frequency* Frequency	0.6150	0.2808	2.190	0.044
Laser Power* Cutting Speed	0.4642	0.4692	0.989	0.337
Laser Power* Gas Pressure	-0.4635	0.4692	-0.988	0.338
Laser Power* Frequency	-0.4547	0.9385	-0.485	0.635
Cutting Speed* Gas Pressure	-0.0303	0.0938	-0.323	0.751
Cutting Speed* Frequency	-0.1067	0.1877	-0.569	0.577
Gas Pressure* Frequency	-0.3296	0.1877	-1.756	0.098
S = 0.375387 R-Sq = 92.37%				

The Regression equation is:

$$R_a = 59.4302 - 5.1353 \times P - 0.1737 \times v - 7.7797 \times \mathrm{Pr} + 6.5935 \times f + 4.0107 \times P^2$$
$$- 0.032 \times v^2 + 0.3356 \times \mathrm{Pr}^2 + 0.615 \times f^2 + 0.4642 \times P \times v - 0.4635 \times P \times \mathrm{Pr}$$
$$- 0.4547 \times P \times f - 0.0303 \times v \times \mathrm{Pr} - 0.1067 \times v \times f - 0.3296 \times \mathrm{Pr} \times f$$

It is important to check the adequacy of the fitted model, because an incorrect or under-specified model can lead to misleading conclusions. By checking the fit of the model one can check whether the model is under specified. The model adequacy checking includes the test for significance of the regression model, model coefficients, and lack of fit, which is carried out subsequently using ANOVA on the curtailed model (Table-4).

Table 4: Analysis of variance for Ra:

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	27.3074	27.3074	1.95053	13.84	0.000
Linear	4	22.2719	22.2719	0.73008	5.18	0.007
Square	4	4.2324	4.2324	1.05809	7.51	0.001
Interaction	6	0.8032	0.8032	0.13386	0.95	0.488
Residual Error	16	2.2546	2.2546	0.14092		
Lack-of-Fit	10	2.2260	2.2260	0.22260	46.69	0.000
Pure Error	6	0.0286	0.0286	0.00477		
Total	30	29.5620				

III. RESULT AND DISCUSSIONS

The response of the Surface roughness (Ra) based on Laser Power and Cutting speed shown in Figure 1 while the Frequency and Gas Pressure holds to their middle value. The Surface roughness increases with increase in Laser Power linearly for any value of Cutting Speed. The Surface roughness also increases with cutting speed. That is due to Laser Power have dominant effect on heat generation and improper melting of materials. The good Surface finish achieved at low power (up to 1.3 KW for SR <6μm) and low cutting speed.

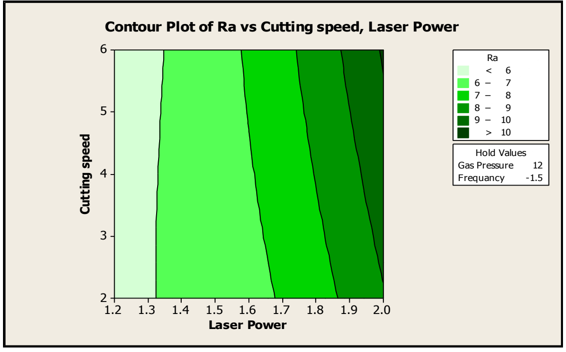


Fig. 1: Combined Effect of Laser Power and Cutting Speed on Ra

Figure 2 Shows that Gas Pressure has significant role in Surface Roughness. In Particular zone of Gas Pressure laser machining achieved the good surface finish. (i.e. for laser power up to 1.3 KW the good surface finish is achieved at nearer to 12 bar Gas pressure.

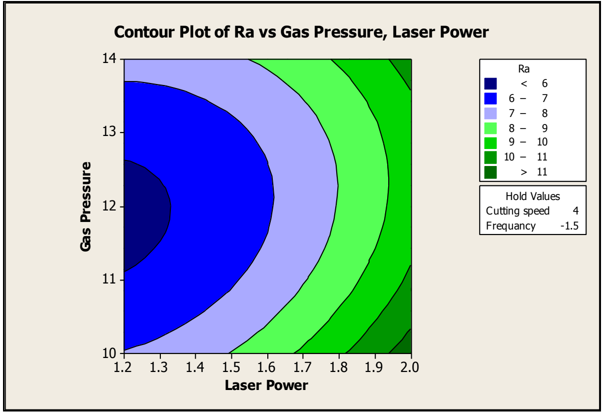


Fig. 2: Combined Effect of Laser Power and Gas Pressure on Ra

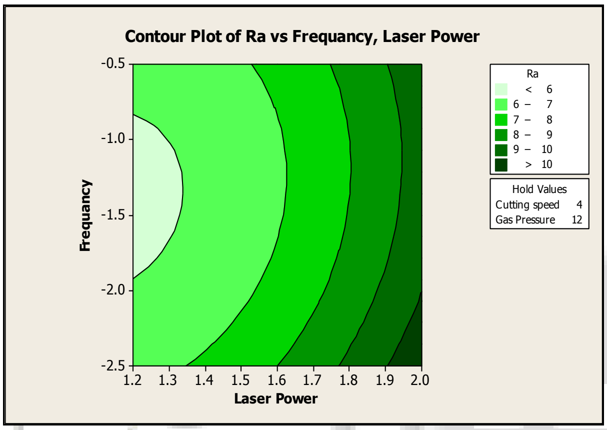


Fig. 3: Combined Effect of Laser Power and Frequency on Ra

Frequency also have significant role like Gas Pressure in Surface Roughness. In Particular zone of Frequency laser machining achieved the good surface finish as clearly identified from contour plot shown in figure 3.

The Surface roughness is high at low pressure (10 bar) and High Pressure (14 bar). In middle span the Surface roughness is low with increase in cutting speed. So we can increase the machining by increasing cutting speed with proper selection of Gas pressure and Laser power without affecting surface finish as shown in Figure 4.

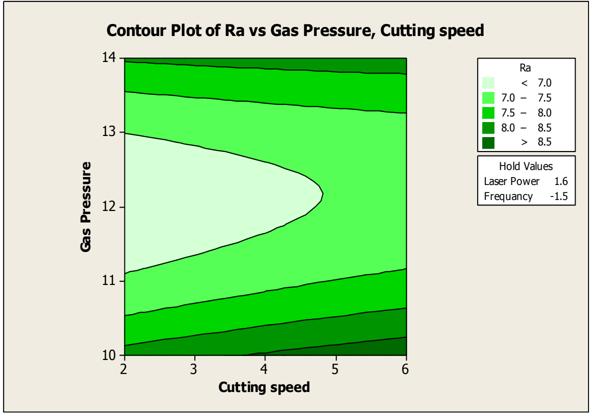


Fig. 4: Combined Effect of Cutting Speed and Gas Pressure on Ra

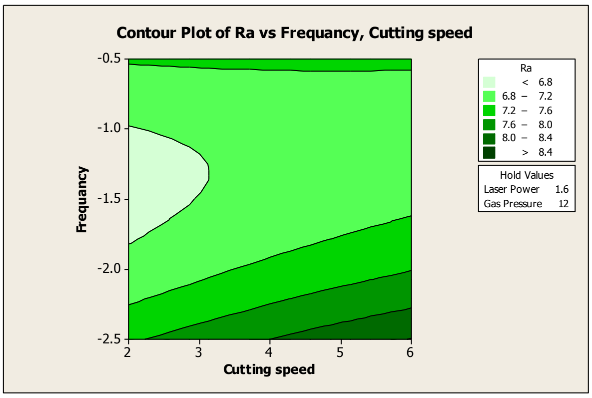


Fig. 5: Combined Effect of Cutting Speed and Frequency on Ra

The response of the Surface roughness (Ra) based on frequency and Cutting Speed shown in Figure 5 while the Laser Power and Gas Pressure holds to their middle value. The high surface roughness produced at low frequency for any value of the cutting speed.

IV. CONCLUSION

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 addi-tion to modeling, using the Monte Carlo method, the optimal laser cutting parameter val-ues that minimize the width of HAZ were identified. This study highlights the development of a comprehensive mathematical model for correlating the interactive and higher order influences of various Laser cutting parameters through response surface methodology (RSM), utilizing relevant experimental data as obtained through experimentation. The following conclusions have been drawn.

- The Surface roughness increases with increase in Laser Power linearly for any value of Cutting Speed. The Surface roughness also increases with cutting speed. That is due to Laser Power have dominant effect on heat generation and improper melting of materials. The good Surface finish achieved at low power (up to 1.3 KW for SR <6µm) and low cutting speed.
- In Particular zone of Gas Pressure laser machining achieved the good surface finish. (i.e. for laser power up to 1.3 KW the good surface finish is achieved at nearer to 12 bar Gas pressure.
- The high surface roughness produced at low frequency for any value of the cutting speed.

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] B.S. Yilbas, R. Devies, Z. Yilbas (1992), Study into penetration speed during CO2 laser cutting of stainless steel, Optics and Lasers in Engineering 17 p.p 69–82..

[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 Mate-rials, 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 Com-bined 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 Fu-eled 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 Approxima-tors, Neural Networks, 2 (1989), 5, pp. 359-366

[16] Cybenko, G., Approximation by Superpositions of a Sigmoidal Function, Mathematics of Control, Sig-nals and Systems, 2 (1989), 4, pp. 303-314

[17] Sumathi, S., Surekha, P., Computational Intelligence Paradigms: Theory and Applications Using MAT-LAB, 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