Vol. 34, No. 4 (2012) 232-238

Tribology in Industry

www.tribology.fink.rs

RESEARCH

Correlation between Surface Roughness Characteristics in CO_2 Laser Cutting of Mild Steel

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Keywords:

Surface Roughness
CO_2 Laser Cutting
Artificial Neural Networks
Modeling
Correlation

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ABSTRACT

CO_2 laser oxygen cutting of mild steel is widely used industrial application. Cut surface quality is a very important characteristic of laser cutting that ensures an advantage over other contour cutting processes. In this paper mathematical models for estimating characteristics of surface quality such as average surface roughness and ten-point mean roughness in CO_2 laser cutting of mild steel based on laser cutting parameters were developed. Empirical models were developed using artificial neural networks and experimental data collected. Taguchi's orthogonal array was implemented for experimental plan. From the analysis of the developed mathematical models it was observed that functional dependence between laser cutting parameters, their interactions and surface roughness characteristics is complex and non-linear. It was also observed that there exist region of minimal average surface roughness to ten-point mean roughness ratio. The relationship between average surface roughness and ten-point mean roughness was found to be nonlinear and can be expressed with a second degree polynomial.

1. INTRODUCTION

Laser cutting has become a highly developed industry technology. Compared with other conventional mechanical processes, laser cutting removes little material, involves highly localized heat input to the workpiece, minimizes distortion, and offers no tool wear [1]. Laser cutting is a thermal, non-contact, and highly automated process well suited for various manufacturing industries where a variety of components in large numbers are required to be machined with high dimensional accuracy and surface finish. Almost any material can be cut. 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.

Numerous advantages and possibilities of laser cutting technology motivated considerable theoretical and experimental research aimed at better understanding of the laser cutting process. The laser cutting process is characterized by a number of controllable and uncontrollable process parameters and their interactions, which in turn determine efficiency of the whole process in terms of productivity, quality and costs. Maximization of productivity and quality along with costs minimization are of particular interest to manufacturers. Each of these goals often requires "optimal" selection of the cutting parameter settings.

Laser cut quality cannot be easily predicted. This is due to the dynamic nature of the laser cutting process, and it is particularly obvious when cutting steels using oxygen as an assisting gas. The oxidation reactions with iron and other alloying elements add another source of heat and material removal occurs at two moving and often interacting fronts, the oxidation front and the laser beam front [2]. Determination of cut surface quality of produced parts can be best done by measurements of surface roughness [3]. Hence, it is of great importance to exactly quantify the relationship between surface roughness and cutting parameters so as to predict its value for any cutting condition through development of mathematical models. The literature reveals that different methodologies were employed for predicting the surface roughness in CO_2 laser cutting, such as: multiple regression analysis [2,4,5], response surface method [6,7], artificial neural networks [8] and fuzzy expert system [9].

Although many researchers have investigated the relationship between surface roughness and its relevant factors such as laser power, cutting speed, assist gas pressure and workpiece thickness, only few investigated the CO_2 laser oxygen cutting of mild steel. Moreover, the aim of this study is to model the correlations between the surface roughness characteristics [18].

2. SURFACE ROUGHNESS IN LASER CUTTING

Surface roughness affects fatigue life, corrosion, thermal conductivity, friction and wear and tear of parts [3,6]. The factors leading to surface roughness formation in laser cutting are complex. Great practical importance of surface roughness and its complex nature have attracted attention of a great number of researchers. The work of researchers considering surface roughness analysis in CO_2 laser cutting is indicated below.

Caiazzo et al. [10] conducted an experimental study for cutting of three thermoplastics, polyethylene (PE), polypropylene (PP), and polycarbonate (PC), with different thicknesses to obtain the minimum surface roughness. It was observed that for all three materials, surface roughness decreases as cutting speed increases. Moreover, the measurements of surface roughness (for PP, PE, PC) highlighted very low values (0.5 - 2 μm) compared with those observed on similar thicknesses of a typical construction steel. In an experimental study of cutting of polymethyl methacrylate (PMMA), Davim et al. [11] founded that the surface roughness increases with a decrease in laser power and an increase in cutting speed. Kurt et al. [3] investigated the effect of cutting parameters such as the assist gas pressure, cutting speed, and laser power on the dimensional accuracy and surface roughness in cutting engineering plastic (PTFE and POM) materials. It was observed that surface roughness decreases at higher cutting speeds and assist gas pressure. However, as the cutting speed increases together with the assist gas pressure, the increase of surface roughness is insignificant. Choudhury and Shirley [6] developed a model equation for relating surface roughness to the cutting parameters (laser power, cutting speed and assist gas pressure) for cutting of PP, PC and PMMA. Based on the model, surface roughness decreases with an increase in the cutting speed, laser power and assist gas pressure. Also it was observed that the effect of cutting speed and assist gas pressure were more pronounced than the effect of laser power. Eltawahny et al. [7] investigated the effects of cutting parameters on the cut edge quality features of medium density fibreboard (MDF) wood composite material. The results showed that the surface roughness decreases as the focal point position and laser power are increased while surface roughness increases as the cutting speed and assist gas pressure are increased. Additionally, it was observed that the effect of the laser power on the surface roughness reduces with the increase in sheet thickness. Rajaram et al. [2] indicated that the low cutting speed results in good surface roughness when cutting 4130 steel. As noted by the authors, this apparent contrast was due to the place of the range of cutting speeds used in the study with respect to the optimum cutting speed. When the order of magnitude is considered, the cutting speed had a major effect on the surface roughness while the laser power had a small effect. Additionally, it was found that the effect of the laser power on the surface roughness appears to be more significant at low power levels. Stournaras et al. [4] investigated the cut quality for the aluminum alloy AA5083 with the use of a pulsed laser cutting system using nitrogen as assist gas. The results showed that the laser power, cutting speed and pulsing frequency were the major influencing parameters whereas the influence of the assist gas pressure on the surface roughness was negligible. However, combined effect of high cutting speed with high-pressure assist gas removed the molten material more effectively and faster which resulted in smoother surface. Also, it was observed that increase in laser power decreases surface roughness. Riveiro et al. [12] examined the effects of cutting parameters in cutting of an aluminium–copper alloy (2024-T3). Regarding the surface roughness, the most influencing parameters were those related to the assist gas such as pressure, nozzle diameter and stand-off distance. Surface roughness was found to be reduced by an increase in assist gas pressure. It was observed that in both continuous wave (CW) and pulse mode the influence of a given cutting parameter on surface roughness must be considered through the interaction with other parameters and their levels. In further investigation, it was founded that the minimum surface roughness was obtained by means of the utilization of argon as assist gas [13]. Syn et al. [9] presented an approach for prediction of cut quality in cutting Incoloy(R) alloy 800 by employing fuzzy expert system. Based on the results of prediction runs of the model, it was shown that there are high interaction effects between assist gas pressure, cutting speed and laser power on surface roughness. Black et al. [14,15] observed that the surface roughness in cutting of thick ceramic tiles was mainly affected by the ratio of laser power to cutting speed, material composition, thickness, assist gas type and its pressure. From the analysis of the effects of cutting parameters on the cut quality in lasox cutting of mild steel, Sundar et al. [5] concluded the following: decrease in assist gas pressure shows a good decrease in surface roughness; higher cutting speed produces low surface roughness; there is a direct relation between the laser power and the surface roughness and the effect of laser power was more significant at low levels of laser power; and the effect on stand-off distance on surface roughness was very less significant.

From the above, it was seen that numerous parameters and their complex influences have an essential role on the surface roughness obtained in CO_2 laser cutting of a given material and thickness. The mechanism behind surface roughness formation is further complicated considering interaction effects between laser beam, process parameters, and workpiece properties. Also, the order of magnitude of a given parameter on surface roughness is dependent on the values of other parameters and their interactions.

There are several ways to describe surface roughness among which the average surface roughness, which is often represented with the R_a symbol, and ten-point mean roughness R_z are one of the most used. R_a is defined as the arithmetic value of the departure of the profile from the centerline along sampling length. R_a and R_z can be expressed by the following mathematical relationships [16]:

$$R_a = \frac{1}{L}\int_0^L \left|Y(x)\right| dx \tag{1a}$$

$$R_z = \frac{\sum_{i=1}^{5}\left|y_{pi}\right| + \sum_{j=1}^{5}\left|y_{vj}\right|}{5} \tag{1b}$$

where Y is the ordinate of the profile curve; L is the sampling length, y_{pi} and y_{vj} are highest and lowest 5 peaks within sampling length.

3. EXPERIMENTAL DETAILS AND MATHEMATICAL MODELS

The laser cutting experiment was performed on the 2.2 kW CO_2 ByVention 3015 laser cutting machine provided by Bystronic Inc. The technical characteristics of the CO_2 laser are: radiation wavelength 10.6 μm, mode TEM_{00}, circular polarization of laser beam, focusing lens with a focal length of 5 in. (127 mm). An oxygen gas (purity of 99.95 %) was supplied through the conical shape nozzle (HK10) with nozzle diameter of 1 mm and at stand-off distance of 0.7 mm. In the experiment the laser beam was focused on the sheet surface. The cuts were performed on specimens of 2 mm thick mild steel.

Table 1. Taguchi's L_{25} orthogonal array, experimental data and predicted values of surface roughness

Exp. trial	Laser cutting parameters			Experimental data		ANN model predictions		% Error	
	v (m/min)	P (kW)	p (bar)	R_a (μm)	R_z (μm)	R_a (μm)	R_z (μm)	R_a	R_z
1	3	0.7	3	1.487	6.577	1.496	6.571	0.155	0.090
2	3	0.9	4	1.290	4.820	1.290	4.835	0.035	0.311
4	3	1.1	5	2.477	9.030	2.467	9.001	0.409	0.319
5	3	1.3	6	2.937	11.070	2.945	11.109	0.285	0.349
6	3	1.5	7	1.780	8.073	1.777	8.084	0.182	0.126
8	4	0.7	4	2.337	9.483	2.343	9.493	0.282	0.105
9	4	0.9	5	3.307	11.823	3.302	11.789	0.145	0.288
10	4	1.1	6	1.190	4.210	1.189	4.207	0.053	0.067
11	4	1.3	7	2.013	7.807	2.018	7.806	0.256	0.012
13	4	1.5	3	2.603	9.600	2.602	9.602	0.036	0.021
14	5	0.7	5	1.173	4.287	1.147	4.304	2.242	0.395
15	5	0.9	6	1.380	5.443	1.406	5.454	1.918	0.188
17	5	1.1	7	1.710	6.417	1.710	6.418	0.004	0.016
18	5	1.3	3	0.963	3.633	0.897	3.008	6.919	17.212
19	5	1.5	4	1.007	3.603	1.000	3.603	0.584	0.004
21	6	0.7	6	1.587	5.977	1.582	5.975	0.270	0.034
22	6	0.9	7	0.880	2.757	0.880	3.028	0.020	9.857
24	6	1.1	3	0.780	2.700	0.907	3.029	16.254	12.178
25	6	1.3	4	1.073	4.267	1.018	4.265	5.179	0.049
3*	3	1.1	5	2.073	8.657	1.848	7.367	10.845	14.907
7*	3	1.3	6	1.707	7.647	1.376	8.767	19.391	14.647
12*	3	1.5	7	2.017	8.223	2.019	9.296	0.150	13.040
16*	4	0.7	4	1.660	6.277	1.767	5.836	6.538	7.019
20*	4	0.9	5	1.143	4.530	1.173	5.241	2.600	15.692
23*	4	1.1	6	0.903	3.220	0.841	3.029	6.880	5.940
* data for model testing									

The main cutting parameters such as cutting speed (v), laser power (P) and assist gas pressure (p) were taken as variable input parameters. Taguchi's standard L_{25} orthogonal array was chosen for experimental design (Table 1) [17].

Two straight cuts each of 60 mm in length were made in each experimental trial to ascertain surface finish. Surface roughness on the cut edge was measured approximately in the middle of the cut surface in terms of the average surface roughness (R_a) and ten-point mean roughness (R_z) using Surftest SJ-301 (Mitutoyo) profilometer. The sampling length of each measurement was set to 4 mm. The measurements were repeated three times to obtain averaged values.

To develop mathematical models for estimating surface roughness values experimental data was divided into two data sets: 19 data for mathematical model development and 6 data for model testing. The selection of data for training and testing was made by random method. To establish a mathematical relationship between laser cutting parameters (v, P, p) and surface roughness values (R_a, R_z) experimental data from Table 1 was used to develop two ANN models. First ANN model is to represent the function R_a=f(v, P, p), and the second R_z=g(v, P, p). Both ANN models were of the same architecture that is a single hidden layer feed-forward ANN with 4 hidden neurons. The number of hidden neurons was selected according to equation given in [8] which considers the number of experimental data points. Linear transfer function and hyperbolic tangent transfer function were used in the output and hidden layer, respectively. In order to stabilize and enhance ANN training the data was normalized to (-1,1) range. Prior to ANN training, the initial values of weights were set according to Nguyen-Widrow method. The MATLAB's Neural Network Toolbox software package was used for ANN model development and ANN training. Gradient descent algorithm with momentum was used for ANN training. After some preliminary investigations, learning rate 0.01 and momentum constant of 0.9 were chosen for ANN training. ANN models were developed considering the well-known bias-variance trade off. Once the ANN training process was finished and the near optimum weights and biases of the ANN were determined, the next step consists of comparing the ANN predicted values with experimental values for surface roughness. To test the prediction capability of the developed ANN surface roughness models the absolute percentage errors were calculated for each of the experimental point (Table 1). In the case of ANN model for R_a the average errors for training and testing data are 1.85 % and 7.73 %, respectively. In the case of ANN model for R_z the average errors for training and testing data are 2.19 % and 11.87 %, respectively. These results indicate that ANN predictions are in good agreement with the experimental results.

4. RESULTS AND DISCUSSION

Regarding the data normalization, activation functions used in hidden and output layer and by using the weights and biases obtained after ANN training, one can predict the surface roughness values for any given condition inside the experimental region. Thus, the effect of laser cutting parameters on the R_a and R_z can be studied using developed ANN models. The main effects of laser cutting parameters on surface roughness values can be analyzed by using 2-D response graphs (Fig. 1). These graphs were drawn by changing one parameter at a time, while keeping the all other parameters constant at center level.

As seen from Fig. 1a, there is an optimal laser power level (between 0.75 and 0.95 kW) which results in minimal R_a and R_z. Because laser cutting is less stable at low power levels low laser power increases surface roughness. From the other side, high laser power levels increase heat input, kerf width and melt layer thickness. Higher heat input may cause side burning and burr formation. While increasing cutting speed, the interaction time between laser beam and workpiece materials decreases i.e. there is less time for heat diffusion which leads to minimum side burning Fig. 1b. An increase in assist gas pressure increases surface roughness because heat generated by exothermic reaction increases Fig. 1c. The functional relationship between R_a and R_z and laser cutting parameters is nonlinear and follow same trend except that change in R_z is more pronounced when using high assist gas pressure. Excess energy from the exothermic reaction at the cutting front results in enhanced material removal rates but also in deeper grooves.

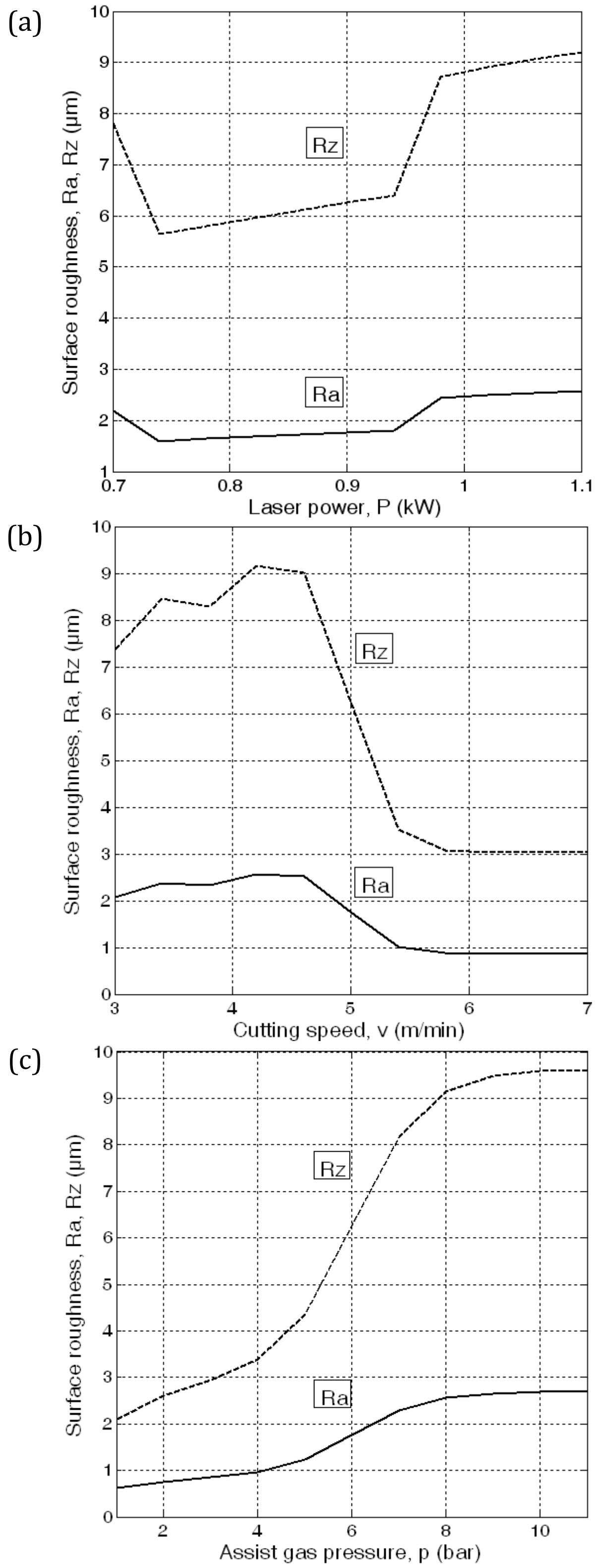

Fig. 1. Effect of laser cutting parameters on R_a and R_z.

In Fig. 2 3-D response surfaces of the R_z/R_a ratio can be seen with different combination of laser cutting parameters.

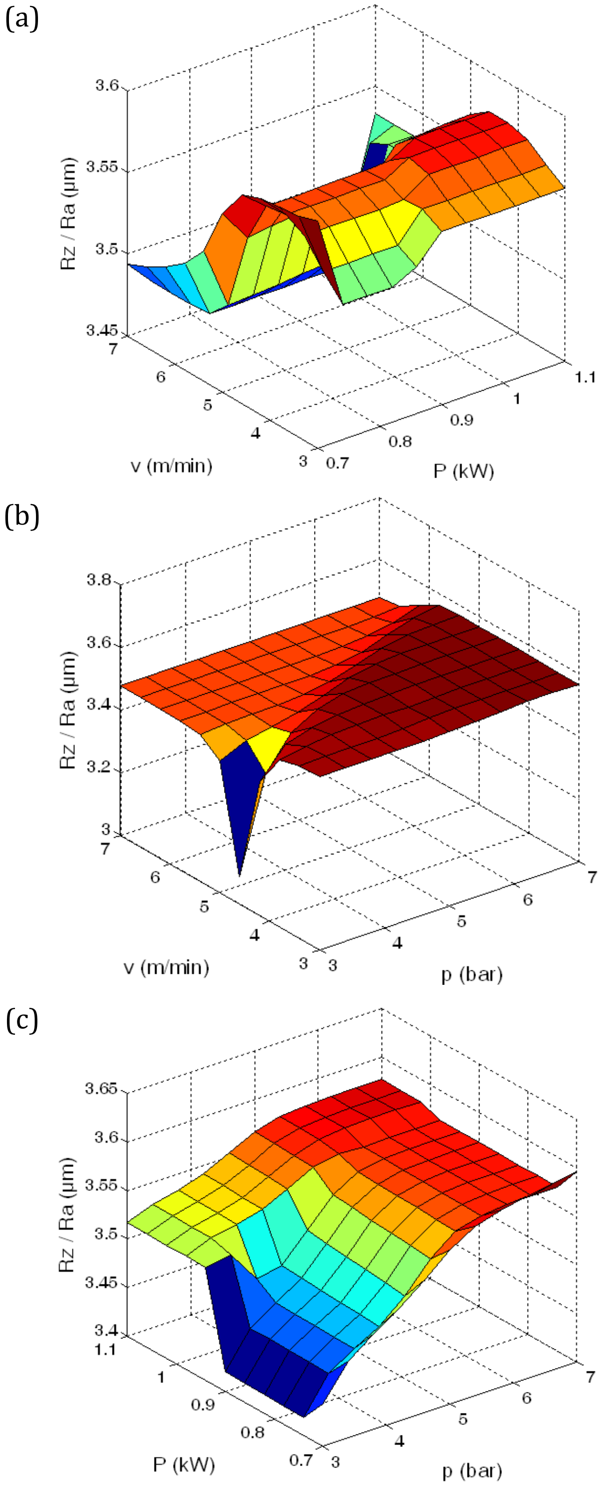

Fig. 2. Effect of laser cutting parameters on R_z/R_a ratio.

In general it is evident that the R_z/R_a ratio decreases with an increase in cutting speed (Fig. 2a). An increase in laser power, generally increases R_z/R_a ratio, however the effect of laser power should be considered through interaction with cutting speed and assist gas pressure (Fig. 2a, 2c). Similarly, an increase in assist gas pressure increases R_z/R_a ratio (Fig. 3c). In the case of cutting speed and assist gas pressure interaction plot (Figure 2b) it is seen that there exist a region with minimal R_z/R_a ratio of about 3.1 corresponding to minimal assist gas pressure of 3 bar and medium cutting speed of 5 m/min. From Fig. 2 it is seen that R_z/R_a ratio change between 3.1 and 3.6 indicating open profile form.

Further analysis of the developed mathematical models for R_a and R_z reveals that there is a very strong correlation between observed parameters with correlation coefficient of 0.98 (Fig. 3). Furthermore the relationship between R_a and R_z is nonlinear and can be expressed with a second degree polynomial in the form:

$$R_z = -0.616R_a^2 + 6.158R_a - 1.898. \qquad (2)$$

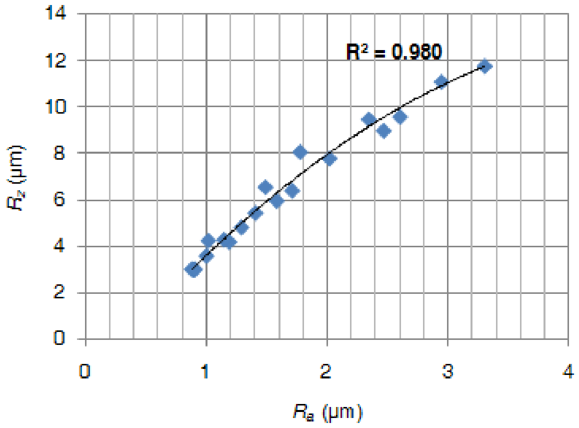

Fig. 3. Correlation between R_a and R_z.

5. CONCLUSION

In this paper mathematical models for estimating characteristics of surface roughness in CO₂ laser cutting of mild steel based on laser cutting parameters were developed. The models were developed using single hidden layer backpropagation ANNs. The conclusions drawn can be summarized by the following points:

- Functional dependence between laser cutting parameters, their interactions and surface roughness characteristics such as R_a and R_z is complex and non-linear,
- In experimental hyperspace covered, the effects of cutting speed and assist gas pressure were more pronounced than the effect of laser power on surface roughness characteristics,

- Minimal R_z/R_a ratio of about 3.1 corresponds to assist gas pressure of 3 bar and cutting speed of 5 m/min,
- The relationship between R_a and R_z is nonlinear and can be expressed with a second degree polynomial.

Acknowledgement

This work was carried out within the project TR 35034 financially supported by the Ministry of Education and Science of Republic of Serbia.

REFERENCES

[1] W.M. Steen: *Laser Material Processing*, Springer, Berlin, 1991.

[2] N. Rajaram, J. Sheikh-Ahmad, S.H. Cheraghi: *CO_2 laser cut quality of 4130 steel,* International Journal of Machine Tools and Manufacture, Vol. 43, No. 4, pp. 351-358, 2003.

[3] M. Kurt, Y. Kaynak, E. Bagci, H. Demirer, M. Kurt: *Dimensional analyses and surface quality of the laser cutting process for engineering plastics*, International Journal of Advanced Manufacturing Technology, Vol. 41, No. 3-4, pp. 259-267, 2009.

[4] A. Stournaras, P. Stavropoulos, K. Salonitis, G. Chryssolouris: *An investigation of quality in CO_2 laser cutting of aluminum,* CIRP Journal of Manuf. Science and Technology, Vol. 2, No. 1, pp. 61-69, 2009.

[5] M. Sundar, A.K. Nath, D.K. Bandyopadhyay, S.P. Chaudhuri, P.K. Dey, D. Misra: *Effect of process parameters on the cutting quality in lasox cutting of mild steel*, International Journal of Advanced Manufacturing Technology, Vol. 40, No. 9-10, pp. 865-874, 2009.

[6] I.A. Choudhury, S. Shirley S: *Laser cutting of polymeric materials: An experimental investigation*, Optics and Laser Technology, Vol. 42, No. 3, pp. 503-508, 2010.

[7] H.A. Eltawahni, A.G. Olabi, K.Y. Benyounis: *Investigating the CO_2 laser cutting parameters of MDF wood composite material*, Optics and Laser Technology, Vol. 43, No. 3, pp. 648-659, 2011.

[8] M. Madić, M. Radovanović: *Comparative modeling of CO_2 laser cutting using multiple regression analysis and artificial neural network*, International Journal of Physical Sciences, Vol. 7, No. 16, pp. 2422-2430, 2012.

[9] C.C. Syn, M. Mokhtar, C.J. Feng, Y.H.P. Manurung: *Approach to prediction of laser cutting quality by employing fuzzy expert system*, Expert Systems with Applications, Vol. 38, No. 6, pp. 7558-7568, 2011.

[10] F. Caiazzo, F. Curcio, G. Daurelio, F. Memola Capece Minutolo: *Laser cutting of different polymeric plastics (PE, PP and PC) by a CO_2 laser beam,* Journal of Materials Processing Technology, Vol. 159, No. 3, pp. 279-285, 2005.

[11] J.P. Davim, C. Oliveira, N. Barricas, M. Conceição: *Evaluation of cutting quality of PMMA using CO_2 lasers*, International Journal of Advanced Manufacturing Technology, Vol. 35, No. 9-10, pp. 875-879, 2008.

[12] A. Riveiro, F. Quintero, F. Lusquiños, R. Comesaña, J. Pou: *Parametric investigation of CO_2 laser cutting of 2024-T3 alloy*, Journal of Materials Processing Technology, Vol. 210, No. 9, pp. 1138-1152, 2010.

[13] A. Riveiro, F. Quintero, F. Lusquiños, R. Comesaña, J. Del Val, J. Pou: *The role of the assist gas nature in laser cutting of aluminum alloys*, Physics Procedia, Vol. 12, No. A, pp. 548-554, 2011.

[14] I. Black, S.A.J. Livingstone, K.L. Chua: *Laser beam machining (LBM) database for the cutting of ceramic tile*, Journal of Materials Processing Technology, Vol. 84, No. 1-3 pp.47-55, 1998.

[15] I. Black, K.L. Chua: *Laser cutting of thick ceramic tile*, Optics and Laser Technology, Vol. 29, No. 4, pp. 193-205, 1997.

[16] W.H. Yang, Y.S. Tang: *Design optimization of cutting parameters for turning operations based on the Taguchi method*, J Journal of Materials Processing Technology, Vol. 84, No. 1-3, pp. 122–129, 1998.

[17] D. Lazarević, M. Madić, P. Janković, A. Lazarević: *Cutting Parameters Optimization for Surface Roughness in Turning Operation of Polyethylene (PE) Using Taguchi Method*, Tribology in Industry, Vol. 34, No. 2, pp. 68-73, 2012.

[18] S. Sekulić: *Correlation Betwen Some Roughness Parameterst of the Machined Surface in Finish Turning*, Tribology in Industry, Vol. 23, No. 1&2, pp. 6-8, 2001.