Transactions of the VŠB – Technical University of Ostrava, Mechanical Series
No. 2, 2013, vol. LIX
article No. 1962

Miloš MADIĆ*, Miroslav RADOVANOVIĆ, Marin GOSTIMIROVIĆ*****

SELECTION OF NEAR OPTIMAL LASER CUTTING PARAMETERS IN CO_2 LASER CUTTING BY THE TAGUCHI METHOD

VOLBA OPTIMÁLNÍCH PARAMETRŮ LASERU PŘI CO_2 LASEROVÉM ŘEZÁNÍ POMOCÍ TAGUCHI METODY

Abstract

Identification of laser cutting conditions that are insensitive to parameter variations and noise is of great importance. This paper demonstrates the application of Taguchi method for optimization of surface roughness in CO_2 laser cutting of stainless steel. The laser cutting experiment was planned and conducted according to the Taguchi's experimental design using the L_{27} orthogonal array. Four laser cutting parameters such as laser power, cutting speed, assist gas pressure, and focus position were considered in the experiment. Using the analysis of means and analysis of variance, the significant laser cutting parameters were identified, and subsequently the optimal combination of laser cutting parameter levels was determined. The results showed that the cutting speed is the most significant parameter affecting the surface roughness whereas the influence of the assist gas pressure can be neglected. It was observed, however, that interaction effects have predominant influence over the main effects on the surface roughness.

Abstrakt

Identifikace podmínek řezání laserem, které jsou citlivé na změny parametrů a hluk jsou velmi důležité. Tento článek demonstruje použití Taguchi metody pro optimalizaci drsnosti povrchu v CO2 laserové řezání nerezové oceli. Experiment řezání laserem byl naplánován a proveden v souladu s Taguchiho experimentálním návrhem pomocí ortogonálního pole L_{27}. V experimentu byly uvažovány čtyři parametry řezání laserem jako síla laseru, rychlost řezání, tlak plynu a zaměření pozice.

1 INTRODUCTION

Laser cutting is one of the most used non-conventional machining processes for contour cutting of wide variety of materials. By focusing the laser beam on the workpiece surface, the high power density of the focused laser beam in the spot melts or evaporates material in a fraction of a second. The wide spectrum of industrial applications of the laser cutting technology is due to its: convenience of operation, high precision, small heat-affected zone, minimum deformity, low processing cost, high product quality, high cutting speed, low level of noise, flexibility, ease of automation etc.

Laser cutting is a complex process with numerous parameters which in consort have essential role on the process performance. To gain competitive advantage, manufacturers using laser cutting technology are interested in maximization of productivity and product quality and minimization of

* Ing., MSc., Production engineering, Faculty of Mechanical Engineering in Niš, University of Niš, A. Medvedeva 14, Niš, e-mail madic@masfak.ni.ac.rs
** Prof., Ing., PhD., Production engineering, Faculty of Mechanical Engineering in Niš, University of Niš, A. Medvedeva 14, Niš, e-mail mirado@masfak.ni.ac.rs
*** Prof., Ing., PhD., Production engineering, Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, Novi Sad, e-mail maring@uns.ac.rs

cost. Fulfilling these objectives, however, requires some trade-offs, since optimum parameter settings for one performance characteristic may deteriorate other performance characteristics.

Selection of optimal laser cutting parameters is often performed in two stage approach, i.e. mathematical modeling of the laser cutting process and optimization using an optimization method. This approach has been widely adopted and proved efficient and suitable. However it requires considerable knowledge at the intersection of several fields, including artificial intelligence, mathematical modeling, optimization and soft computing. Moreover, this approach is more time and computationally expensive and often requires a large number of experimental trials.

On the other hand, the application of the Taguchi method (TM) without formulation of any kind of model is an attractive alternative for determining near optimal laser cutting parameter settings. The open literature reveals that most of the applications of the TM consider optimization of kerf quality characteristics, material removal rate and surface roughness in Nd:YAG laser cutting [2, 4, 6, 9]. Reviewing the literature it was found that most of the experimental studies applied the TM for optimization of multi-quality characteristics by using the grey relational analysis.

This paper presents the application of the TM for determining of the near optimal laser cutting parameter settings which minimize surface roughness in CO_2 laser cutting of stainless steel. The laser cutting experiment was planned and conducted according to the Taguchi's experimental design using the L_{27} orthogonal array. Four laser cutting parameters such as the laser power, cutting speed, assist gas pressure, and focus position were considered in the experiment.

2 EXPERIMENTAL DETAILS

2.1 Workpiece material

In this study, AISI 304 (EN X5CrNi18.10) stainless steel material was used as the workpiece in plate form with thickness of 3 mm. This material was chosen because of its wide range of application in the industry.

2.2 Laser cutting conditions

The experiment trials were carried out using a ByVention 3015 (Bystronic) CO_2 laser cutting machine delivering a maximum output 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. Table 1 lists the details about the laser cutting conditions.

Tab. 1 Laser cutting conditions

Laser parameters	Description
Laser power (kW)	1.6 - 2
Cutting speed (m/min)	2 - 3
Assist gas pressure (MPa)	0.9 – 1.2
Focus position (mm)	–2.5 - –0.5
Material thickness (mm)	3
Laser mode	continuous wave
Lens focal length (mm)	127
Stand off distance (mm)	1
Nozzle diameter (mm)	2
Assist gas type	nitrogen, purity of 99.95%

2.3 Laser cutting experimental plan

Conducting an experiment using scientific design of experiment approach allows for systematic investigation and analysis of the effects of process parameters on process performance of a certain manufacturing process. While designing the experiment trials, the laser cutting parameter ranges that influence the surface roughness were selected based on the manufacturer's recommendation and past experimentation considering that the full cut is achieved. The laser cutting parameters and their levels are given in Table 2.

Tab. 2 Laser cutting parameters and levels

Coded	Cutting parameter	Level 1	Level 2	Level 3
A	laser power, *P* (kW)	1.6	1.8	2
B	cutting speed, *v* (m/min)	2	2.5	3
C	assist gas pressure, *p* (MPa)	9	10.5	12
D	focus position, *f* (mm)	–2.5	–1.5	–0.5

To save experimental time and reduce experimental cost, based on the selected laser cutting parameter levels, a design matrix was constructed (Table 3) in accordance with the standard L_{27} (3^{13}) Taguchi's orthogonal array. This design provided uniform distribution of experimental points within the selected experimental hyper-space and the experiment with high resolution. Likewise, this design was chosen due to its capability to check the interactions among parameters.

2.4 Laser cut quality characteristics

The appropriate selection of different laser cutting parameters and their levels have significant impact on the cut quality obtained. However, there are different quality characteristics which describe the laser cut quality. Because of its impact on several functional attributes and overall performance of end product, surface roughness in laser cutting is of great importance, and hence it was selected as performance measure. The average surface roughness (R_a) of the machined surface was measured using Surftest SJ-301 (Mitutoyo) profilometer. To ascertain surface roughness straight cuts each of 60 mm in length were made in each experimental trial. Each measurement was taken along the cut at approximately the middle of the thickness and the measurements were repeated to obtain averaged values (Figure 1).

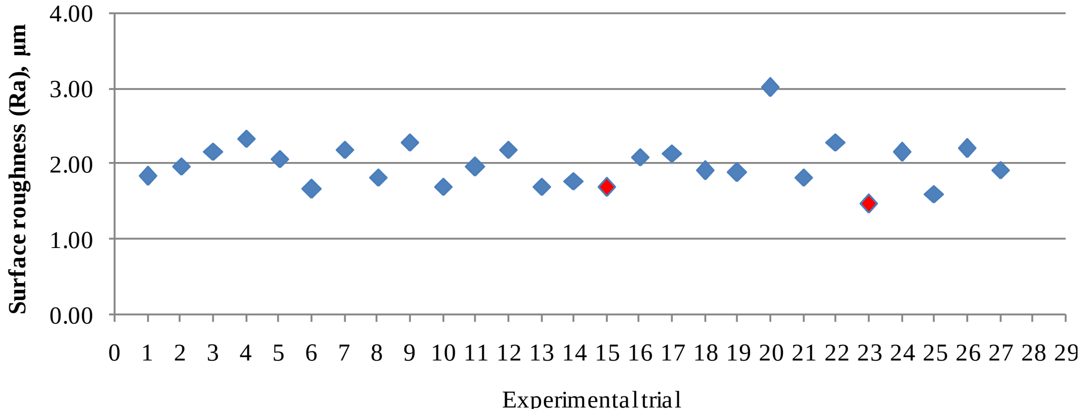

Fig. 1 Fishbone diagram for the ANN model performance

Tab. 3 Laser cutting experimental trials

Trial no.	Coded parameters				Natural parameters				S/N
	A	B	C	D	*P* (kW)	*v* (m/min)	*p* (MPa)	*f* (mm)	dB
1	1	1	1	1	1.6	2	0.9	-2.5	-4.861
2	1	1	2	2	1.6	2	1.05	-1.5	-6.607
3	1	1	3	3	1.6	2	1.2	-0.5	-6.444
4	1	2	1	2	1.6	2.5	0.9	-1.5	-7.218
5	1	2	2	3	1.6	2.5	1.05	-0.5	-6.921
6	1	2	3	1	1.6	2.5	1.2	-2.5	-5.065
7	1	3	1	3	1.6	3	0.9	-0.5	-7.617
8	1	3	2	1	1.6	3	1.05	-2.5	-5.249
9	1	3	3	2	1.6	3	1.2	-1.5	-7.847
10	2	1	1	2	1.8	2	0.9	-1.5	-4.725
11	2	1	2	3	1.8	2	1.05	-0.5	-4.556
12	2	1	3	1	1.8	2	1.2	-2.5	-6.281
13	2	2	1	3	1.8	2.5	0.9	-0.5	-4.537
14	2	2	2	1	1.8	2.5	1.05	-2.5	-4.699
15	**2**	**2**	**3**	**2**	**1.8**	**2.5**	**1.2**	**-1.5**	**-2.534**
16	2	3	1	1	1.8	3	0.9	-2.5	-7.818
17	2	3	2	2	1.8	3	1.05	-1.5	-6.204
18	2	3	3	3	1.8	3	1.2	-0.5	-6.446
19	3	1	1	3	2	2	0.9	-0.5	-6.044
20	3	1	2	1	2	2	1.05	-2.5	-9.559
21	3	1	3	2	2	2	1.2	-1.5	-6.193
22	3	2	1	1	2	2.5	0.9	-2.5	-6.753
23	*3*	*2*	*2*	*2*	*2*	*2.5*	*1.05*	*-1.5*	*-3.277*
24	3	2	3	3	2	2.5	1.2	-0.5	-6.162
25	3	3	1	2	2	3	0.9	-1.5	-4.884
26	3	3	2	3	2	3	1.05	-0.5	-6.718
27	3	3	3	1	2	3	1.2	-2.5	-6.337

2.5 Taguchi's optimization methodology

The TM is a powerful tool for product/process quality improvement. Taguchi has built upon W.E. Deming's observation that 85% of poor quality is attributable to the manufacturing process and only 15% to the worker [8]. This methodology allows for efficient identification of near optimal settings of the control parameters making the product/process insensitive to the noise factors [5]. The key principle of TM lies in the fact that the reduction in variation is obtained without removing its causes [3].

Two major tools used in TM are orthogonal arrays (OAs), and signal to noise (S/N) ratio [5]. An OA is a small fraction of full factorial design and allows experimenter to study the entire parameter space with minimum experiment trials. Taguchi suggested a summary statistic that combines information about the mean and variance into a single performance measure, known as the signal-to-noise (S/N) ratio. Taguchi found out empirically that S/N ratios give the (near) optimal combination of the parameters levels, where the variance is minimum, while keeping the mean close to the target value, without using any kind of model [3].

Application of TM is aimed at the following objectives [8]:

- To establish the best or the optimum condition for a products or a process,
- To estimate the contribution of individual parameters,
- To estimate the response under the optimum conditions.

A full explanation of the TM can be found in referential literature [5, 7, 8].

3 ANALYSIS AND DISCUSSION

TM was used to identify the near optimal laser cutting parameter levels so as to minimize the surface roughness. In CO_2 laser cutting process, lower values of surface roughness are desirable for maintaining high cut quality, therefore smaller-the-better S/N ratio can be calculated as:

$$S / N \equiv \eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

where:

y_i – i-th observed value of the response,

n – number of observations in a trial.

The surface roughness experimental results i.e. its corresponding S/N values were analyzed using the analysis of means (ANOM) and analysis of variance (ANOVA) with the help of MINITAB statistical software. The calculations of ANOM and ANOVA are described in detail in [7].

3.1 Determining the near optimal levels of the laser cutting parameters

On the basis of the calculated S/N values given in Table 3, using the ANOM the effects of main laser cutting parameters on mean S/N ratio are presented in graphical form (Figure 2).

The slope of the line in Figure 2 determines the power of the control parameters influence on the surface roughness. As can be seen, the laser power, cutting speed and focus position affect the surface roughness mostly. The effect of assist gas pressure is not very clearly defined. It could be seen however that higher assist gas pressure decreases surface roughness, but lower assist gas pressures favours lesser gas consumption. The optimum level of a laser cutting parameter for the

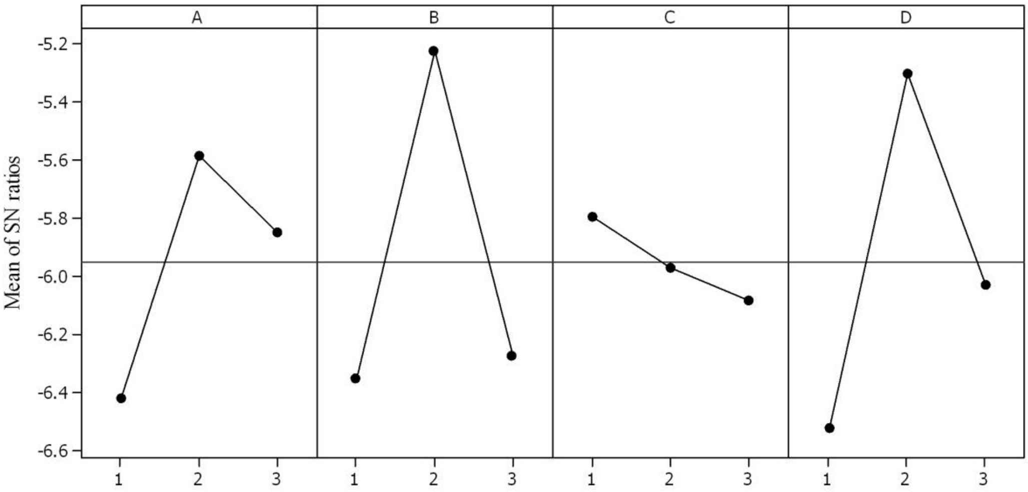

Fig. 2 Main effects plot for S/N ratios

surface roughness minimization is the level that gives the highest S/N values. Since the category smaller-the-better is adopted, it is evident from Figure 2 that the near optimal combination of laser cutting parameter levels, which gives the lowest value of the surface roughness, is A2B2C3D2.

3.2 Analysis of variance (ANOVA)

In order to more accurately quantify the influence of the laser cutting parameters ANOVA was performed. The S/N pooled ANOVA is given in Table 4.

Tab. 4 ANOVA for S/N ratio

Source	DF	SS	MS	F	P	ρ (%)
A	2	6.3083	3.1542	5.54	0.020	10.97
B	2	8.2763	4.1382	7.27	0.009	14.41
C	(2)	pooled				
D	2	3.2529	1.6264	2.86	0.097	5.67
AB	4	11.1907	2.9307	4.91	0.014	19.49
AD	4	21.5579	6.1585	9.47	0.001	37.55
Error	12	6.8309	0.8165			11.91
Total	26	57.4169				100
DF: degree of freedom, SS: sum of squares, MS: mean squares, F: value of Fisher's distribution, P: probability density, ρ: percentage contribution						
The standard tabulated value of F-ratio: $F_{0.1,2,12}$=2.81, $F_{0.05,2,12}$=3.89, $F_{0.05,4,12}$=3.26, $F_{0.01,2,12}$=6.93, $F_{0.01,4,12}$=5.41						

Pooling is a process of obtaining a more accurate estimate of error variance. Taguchi advocates pooling effects until the degrees of freedom for the error term is approximately equal to half the total degrees of freedom for the experiment [1]. In order to generate adequate degrees of freedom for analyzing variability, pooling was performed (by combining the degrees of freedom associated with those effects which are comparatively low in magnitude). In this case, since the contribution of parameter C (assist gas pressure) was the smallest that is less than 5%, it was considered insignificant. Thus, this parameter was pooled (combined) with the error term.

It is evident that the laser power and cutting speed are significant at 95% and 99% confidence level, respectively, and thus affect mean value and variation around the mean value of the surface roughness. Focus position is significant at 90% confidence level. In the case of interaction effects, it is clear that the interaction effect of the laser power and focus position is the most significant parameter at 99% confidence level, whereas the interaction effect of the laser power and cutting speed is statistically significant at 95% confidence level in ANOVA.

Regarding percentage contribution, it can be concluded that the interaction effects of the laser power and focus position and the laser power and cutting speed, followed by main effects of the cutting speed, laser power and focus position are the most significant parameters. It is also observed that main laser cutting parameters contribute to about 31 % of the total variation, whereas the interaction effects contribute nearly to 57 %. Hence it could be concluded that the interaction effects have a dominant influence on the mean value and variation around the mean value of the surface roughness. The percentage contribution of the error term can be attributed to the effects of other laser cutting parameter interaction effects and experimental noise.

On the basis of the ANOVA, ANOM graph (Figure 2), and analysis of the interaction effects (not shown here) of the laser cutting parameters one can conclude that the best combination of laser cutting parameter levels, in terms of minimizing surface roughness, is A2B2C3D2. It has to be noted that combination A3B2C2D2 which corresponds to laser cutting condition as in experimental trial 23 is also an appropriate combination since it yields second best S/N ratio value.

3.3 Confirmation experiment trial

Conducting confirmation experimental trial is necessary and important step. In this step, one needs to predict and verify the expected response through the confirmation experimental trial. Since the optimal combination (A2B2C3D2) corresponds to the 15-th experimental trial in the experimental matrix (Table 3), no confirmation experiment trials were conducted.

Taguchi prediction of S/N ratio under optimum conditions can be calculated using the following equation [5]:

$$\hat{\eta}_{opt} = \overline{\eta} + \sum_{i=1}^{p} (\overline{\eta}_{i,opt} - \overline{\eta}) \tag{2}$$

where:

η – total mean S/N ratio,

$\overline{\eta}_{i,opt}$ – mean S/N ratio for *i*-th parameter at the optimal level,

p – number of parameters that significantly affect the quality characteristic,

Using previous equation, $\hat{\eta}_{opt}$ = -3.03964 dB was obtained which is lower than observed in experiment (Table 3). In order to judge the closeness of the $\hat{\eta}_{opt}$ and observed value of S/N ratio, the confidence interval (CI) is determined. The CI is given by [7]:

$$CI = \sqrt{\frac{F_{\alpha(1,f_e)} \cdot V_e}{n}} \tag{3}$$

where:

$F_{\alpha(1;fe)}$ – F value at a confidence level of (1-α) at degrees of freedom (DF) =1 and error DF = 12,

V_e – error variance,

n – is defined as:

$$n = \frac{N}{1+\nu} \tag{4}$$

where:

N – total number of experiments,

ν – total DF of all parameters.

At the 95% confidence level, the CI is ± 1.468. Since the prediction error is within CI value the optimal combination of cutting parameter levels can be validated.

Regarding the near optimal laser cutting condition for surface roughness minimization, it has to be noted that at these conditions there is occurrence of dross formation. The surface pattern obtained under these conditions is given in Figure 3.

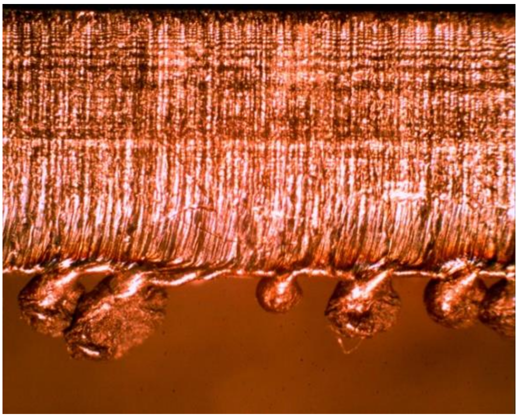

Fig. 3 Surface pattern obtained in the 15-th experimental trial

It is seen that laser cutting with the identified near optimal laser cutting parameters for surface roughness minimization requires post-processing to remove the laser cutting dross. Therefore, it can be said that complexity of the laser cutting process requires taking into account different process performance characteristics at the same time and their simultaneous optimization.

4 CONCLUSIONS

This paper presents the application of the Taguchi method for optimization of surface roughness in CO_2 laser nitrogen cutting of stainless steel. From the derived analysis and experimental results, the following conclusions are made:

- The cutting speed, laser power and focus position are the main parameters influencing the surface roughness.

- For the experimental range considered in the study, the assist gas pressure has no significant effect on the surface roughness.
- The results of ANOVA clearly indicate predominant influence of the interaction effects over the main effects on the surface roughness.
- Combination of intermediate levels of the laser power, cutting speed and focus position along with high level of assist gas pressure is necessary for minimization of the surface roughness by the Taguchi's framework.
- In order to be cost efficient method for large batch processing, where the variations of the product's quality are to be low, the application of the Taguchi method provides efficient and relatively easy way for laser cutting optimization.
- Complexity of the laser cutting process requires taking into account different process performance characteristics and multi-objective optimization.

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

REFERENCES

[1] ANTONY, J. *Design of experiments for engineers and scientists*, Elsevier Science & Technology Books, 2003. 190 pp. ISBN 9780750647090.

[2] CAYDAŞ, U. & HASÇALIK, A. Use of the grey relational analysis to determine optimum laser cutting parameters with multi-performance characteristics. *Optics and Laser Technology*, 2008, Vol. 40, No. 7, pp. 987-994. ISSN 0030-3992.

[3] MARINKOVIĆ, V. & Madić, M. Optimization of surface roughness in turning alloy steel by using Taguchi method. *Scientific Research and Essays*. 2011, Vol. 6, No. 16 pp. 3474-3484. ISSN 1992-2248.

[4] PANDEY, A. K. & DUBEY, A. K. Taguchi based fuzzy logic optimization of multiple quality characteristics in laser cutting of duralumin sheet. *Optics and Lasers in Engineering*, 2012, Vol. 50, No. 3, pp. 328-335. ISSN 0143-8166.

[5] PHADKE, M. S. *Quality engineering using robust design*. Prentice Hall, New Jersey, 1989. 334 pp. ISBN 0137451679.

[6] RAO, R. & YADAVA, V. Multi-objective optimization of Nd:YAG laser cutting of thin superalloy sheet using grey relational analysis with entropy measurement. *Optics and Laser Technology*, 2009, No. 41, No. 8, pp. 922-930. ISSN 0030-3992.

[7] ROSS, P. *Taguchi techniques for quality enginee*ring, McGraw Hill, 1988, 329 pp. ISBN 9780070539587.

[8] ROY, R., *A primer on the Taguchi method*, Van Nostrand Reinhold, 1990, 247 pp. ISBN 087263468X.

[9] SHARMA, A. & YADAVA, V. Modelling and optimization of cut quality during pulsed Nd:YAG laser cutting of thin Al-alloy sheet for straight profile. *Optics and Laser Technology*, 2012, Vol. 44, No. 1, pp. 159-168. ISSN 0030-3992.