Identification of the Robust Conditions for Minimization of the HAZ and Burr in CO_2 Laser Cutting

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This paper presents Taguchi optimization methodology for identification of the robust conditions for minimization of the heat affected zone (HAZ) and burr height in CO_2 laser cutting of AISI 304 stainless steel. The laser cutting experiment was designed and carried out on the basis of standard L_{27} Taguchi's orthogonal array in which four laser cutting parameters such as the laser power, cutting speed, assist gas pressure and focus position were arranged at three levels. From the analysis of means, analysis of variance and two-way interaction plots, the significant laser cutting parameters and the optimal combination of levels were identified. The results showed that the focus position is the most significant parameter affecting the HAZ and burr height, whereas the influence of the assist gas pressure can be neglected. The predicted responses at optimal laser cutting conditions were found to be in good agreement with the results from confirmation experiment.

Keywords: *CO_2 laser cutting, Taguchi optimization methodology, heat affected zone, burr height.*

1. INTRODUCTION

Laser cutting is one of the most important and widely used thermal-based advanced manufacturing processes. It is a high energy-density process that works quickly on complex shapes, and 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].

Nd:YAG and CO_2 are the two most widely used industrial lasers [2,3]. The technological improvements in laser machines made laser cutting technology more prevalent in today's production systems. Laser cutting finds many applications in various manufacturing industries where a variety of components in large numbers are required to be machined with high quality and close tolerance at low costs. A number of analytic, numerical and experimental modeling studies were carried out in order to analyze laser cutting process, with some of the findings summarized in recent comprehensive review papers [4-6]. Predictive modeling is essential for better understanding and optimization of the laser cutting process. In laser cutting process, modeling and prediction of cutting performances such as the material removal rate, kerf quality characteristics, surface quality, heat affected zone (HAZ), burr height is of high importance to manufacturers. Through appropriate selection and optimization of the laser and operating parameters, cutting performance characteristics can be considerably improved. Here, it should be noted that the optimum parameter settings for one quality characteristic may deteriorate other quality characteristic [7].

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Different methodologies for modelling the laser cutting process such as: multiple regression analysis [8], response surface method [9], fuzzy expert system [10], and artificial neural networks [1,11-14] were applied. Subsequently, the near optimal laser cutting conditions were identified by applying simulated annealing [11], genetic algorithm [12] and particle swarm optimization [13]. The afore-mentioned methods are powerful tools for systematic modelling, analysis and optimization of laser cutting process. These approaches integrate experimental, mathematical (statistical), and artificial intelligence methods, thus providing sufficient accuracy of calculations for the real conditions in which the laser cutting process takes place. However, these techniques are more time and computationally expensive and require a considerable knowledge in mathematical modelling and optimization as well as artificial intelligence.

The robust design methodology, proposed by Taguchi, is one of the appropriate methods for identifying the near optimal laser cutting conditions. Taguchi methodology provides a systematic, efficient and easy-to-use approach for the process optimization [15]. A number of researches applied Taguchi methodology for optimization of the laser cutting process. The open literature reveals that most of the applications of the Taguchi methodology consider multi-optimization of kerf quality characteristics [2,16-18], kerf quality characteristics and material removal rate [7,19] and kerf quality characteristics and surface roughness [3,20]. Caydaş, and Hasçalik [20] applied hybrid approach based on Taguchi methodology and grey relational analysis to determine optimal laser cutting parameters (cutting speed and laser power) for multi-performance characteristics (surface roughness, kerf width, and HAZ) in CO_2 laser cutting of 10 mm steel plate. El Taweel et al. [21] applied Taguchi methodology to identify the effect of the laser control parameters, i.e., laser power, cutting speed, material thickness, assist gas pressure and laser mode on the cut quality characteristics, namely, kerf width, kerf taper and burr height in CO_2 laser cutting of kevlar-49 composite. Using the analysis of variance (ANOVA) optimal laser cutting parameter settings for minimizing the selected cut quality characteristics were identified.

In mass production applications of laser cutting technology, identification of robust conditions for minimization of the product's quality variability is of prime importance. From the techno-economical point of view, reducing the burr formation and HAZ can be regarded as one of the most important criteria for assessing the laser cutting performance. Therefore, this paper discusses the application of Taguchi optimization methodology for identification of the near optimal laser cutting parameters which minimize the HAZ and burr height in CO_2 laser cutting of stainless steel. The laser cutting experiment was planned and conducted according to Taguchi's experimental design using L_{27} orthogonal array.

2. TAGUCHI OPTIMIZATION METHODOLOGY

Taguchi optimization methodology is a well-known, unique and powerful technique for product/process quality improvement. This methodology allows for efficient identification of optimal setting of the control parameters (factors) making the product/process insensitive to the noise factors [22]. Noise factors (external conditions, manufacturing imperfections, etc.) are unwanted sources of variation and can be uncontrollable or too expensive to control. The key principle of Taguchi philosophy lies in the fact that the reduction in variation is obtained without removing its causes [15]. Two major tools used in Taguchi optimization methodology are orthogonal arrays (OAs), and signal to noise (S/N) ratio [22].

An OA is a small fraction of full factorial design and allows experimenter to study the entire parameter space with minimum experiment trials. Fewer trials imply that time and costs are reduced. Furthermore, these experimental matrices assure a balanced comparison of levels of any parameter or interaction of parameters. The columns of an OA represent the control parameters to be optimized and the rows represent the individual trials (combinations of levels).

As the objective function for experimental matrices, Taguchi suggested a summary statistic, signal-to-noise (S/N) ratio which combines information about the mean and variance. The magnitude of this value indicates the robustness of the system against noise [23]. Taguchi found out empirically that S/N ratios give the (near) optimal combination of the parameter levels, where the variance is minimum, while keeping the mean close to the target value, without using any kind of model [15]. Depending on the criterion for the quality characteristic to be optimized, different S/N ratios can be chosen: smaller-the-better, larger-the-better and nominal-the-best [22]. Regardless of the category of the performance characteristic, the larger algebraic value of S/N ratio corresponds to the better performance characteristic, i.e. to the smaller variance of the output characteristic around the desired (target) value. Therefore, the optimal level of the parameter is the level that results in the highest value of S/N ratio in the experimental region. The optimal parameter levels are determined using the analysis of means (ANOM) and analysis of variance (ANOVA).

2.1 Analysis of means

ANOM is used to determine the optimal parameter settings and it is the process of estimating the main effects of each parameter [22]. The effect of parameter Q at level k can be calculated as [15]:

$$\overline{\eta}_{Qk} = \frac{1}{n_{Qk}} \sum_{l=1}^{n_{Qk}} \left[(S/N)_{Qk} \right]_l . \quad (1)$$

where n_{Qk} is the number of appearances of parameter Q at level k in experimental matrix, and $(S/N)_{Qk}$ is the S/N ratio related to parameter Q at level k. Using equation (1) the main effects of the process parameters on mean S/N ratio can be presented in graphical form by response graphs. The response graphs show the change in the response when a given parameter goes from lower level to higher level. The slope of the line determines the power of the control parameter influence on the response. From these graphs one can assume the optimal combination of process parameters.

2.2 Analysis of variance

The purpose of ANOVA is to quantify the relative significance of each process parameter in terms of percentage contribution to the response and to estimate the error variance. ANOVA is accomplished by separating the total variability of the S/N ratios (SS_{tot}), which is measured by the sum of the squared deviations from the total mean S/N ratio into contributions by each of the parameters and the error:

$$SS_{tot} = SS_T + SS_E . \quad (2)$$

The total sum of square deviations from the total mean S/N ratio, can be calculated as [24]:

$$SS_T = \sum_{i=1}^{n_t} (\eta_i - \overline{\eta})^2 . \quad (3)$$

where n_t is the total number of experiment trials, η_i is the S/N ratio in i-th trial in the OA and $\overline{\eta}$ is the total mean S/N ratio:

$$\overline{\eta} = \frac{1}{n_t} \sum_{i=1}^{n_t} \eta_i . \quad (4)$$

The sum of squares due to parameter Q can be computed as:

$$SS_Q = \sum_{i=1}^{k} n_{Qk} \left[\overline{\eta}_{Qk} - \overline{\eta}\right]_i^2 . \quad (5)$$

Subsequently, SS_T can be used to measure the relative influence of the process parameters on the response. The percentage contribution (ρ) of parameter Q can be calculated as:

$$\rho(\%) = \frac{SS_Q}{SS_T} \times 100 . \quad (6)$$

In situation where interaction effects of the parameters have significant effect on the process response, 2-way and 3-way ANOVA models are used to assess the interaction effect of more than one parameter. For example in 2-way ANOVA, the total variation can be partitioned into component parts corresponding to the variation in each parameter, interaction and random error as follows [25]:

$$SS = SS_A + SS_B + SS_{AB} + SS_E . \quad (6a)$$

where SS is the total sum of squares, SS_A is the sum of square due to parameter A, SS_B is the sum of square due to parameter B, and SS_{AB} is the sum of square due to interaction. The SS_{AB} can be calculated as follows:

$$SS_{AB} = \sum_{i=1}^{a} \sum_{j=1}^{b} n_{ij} \left(\overline{AB}_{ij} - \overline{A}_{i.} - \overline{B}_{.j} + \overline{\eta} \right). \quad (7)$$

where n_{ij} is the number of observations in the i-th level of parameter A and the j-th level of parameter B and a and b represents the number of levels of parameters A and B, respectively.

The final step in Taguchi optimization methodology is the verification of the improvement of the quality characteristic. For that purpose, a confirmation experiment should be carried out implying the (near) optimal levels of the control parameters.

As it is well-known, Taguchi optimization methodology limits the optimization to the specific levels of parameter values. However, some intermediate combination of parameter values may exist, which would yield better results. In most cases, the optimal parameter settings obtained is not the exact optimal solution, but the near optimal solution [26]. It should be noted that Taguchi optimization methodology belongs to the technique of single-criterion optimization. However, there are different approaches for solving multiple-response optimization problems [26, 27]. A novel approach to multi-response process optimization, based on Taguchi methodology and artificial intelligence was proposed [28].

3. EXPERIMENTAL DETAILS

3.1 Workpiece material

In this study, AISI 304 stainless steel was used as the workpiece material in plate form. The sheet dimensions were 500 x 500 mm with thickness of 3 mm. This material was chosen because of its wide range of application in the industry such as automotive, aircrafts, food, etc.

3.2 Laser cut quality evaluation

There are different quality characteristics which describe the laser cut quality. The standard SRPS ISO 9013 [29] describes criteria for evaluating the quality of cutting surfaces, quality classification and the dimensional tolerances. Evaluation of laser cut quality is based on: geometry of cut, surface of cut, burr formation and characteristics of material in zone of cut. The evaluation and consequences of the imperfections depends on the specific job requirements. In this study the experimental results after laser cutting were evaluated in terms of the width of HAZ and burr height. Each test piece was measured at three equally distanced measurement locations along the length of cut to obtained averaged values. The width of the HAZ and burr height was studied using optical microscope (Leitz, Germany), with 30 x magnification and 1 μm resolution.

3.3 Laser cutting conditions

The experimental trials were performed using a ByVention 3015 CO2 laser cutting machine with a nominal power of 2.2 kW. The nitrogen with purity of 99.95% was used as assist gas and it is passed through a conical shape nozzle (HK20) with nozzle diameter of 2 mm, which remained constant throughout the experiment. The laser beam was focused through a lens of focal length of 5 in (127 mm) and the distance between workpiece and nozzle was controlled at 1 mm. The cuts were performed with a Gaussian distribution beam mode (TEM_{00}). Laser power, cutting speed, assist gas pressure and focus position were selected as controllable parameters. The non-linear relationship among the process parameters, if it exists, can only be revealed if more than two levels of the parameters are considered [30]. Thus each selected parameter was set at three levels (Table 1).

Table 1. Cutting parameters and levels

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

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

3.4. Laser cutting experimental design

Based on the selected parameters and parameter levels, a design matrix was constructed (Table 2) in accordance with the standard L_{27} (3^{13}) Taguchi's OA. The L_{27} consists of 13 columns and 27 rows (experimental trials). Laser cutting parameters, laser power, cutting

Table 2. Laser cutting experimental plan and the results

Trial	Natural factor				Coded factor				Experimental results			
	P	*v*	*p*	*f*	A	B	C	D	*HAZ*	η_{HAZ}	*b*	η_b
	(kW)	(m/min)	(bar)	(mm)					(μm)	(dB)	(mm)	(dB)
1	1.6	2	9	-2.5	1	1	1	1	21.00	-26.4509	0.07	22.6360
2	1.6	2	10.5	-1.5	1	1	2	2	23.67	-27.4845	1.53	-4.3775
3	1.6	2	12	-0.5	1	1	3	3	23.33	-27.3613	1.25	-2.9776
4	1.6	2.5	9	-1.5	1	2	1	2	15.33	-23.7168	1.42	-3.6549
5	1.6	2.5	10.5	-0.5	1	2	2	3	20.67	-26.3077	1.37	-2.3805
6	1.6	2.5	12	-2.5	1	2	3	1	18.67	-25.4572	0.05	22.3657
7	1.6	3	9	-0.5	1	3	1	3	19.67	-25.9069	1.05	-1.4768
8	1.6	3	10.5	-2.5	1	3	2	1	17.67	-24.9462	0.11	18.2974
9	1.6	3	12	-1.5	1	3	3	2	20.00	-26.0278	0.65	3.14258
10	1.8	2	9	-1.5	2	1	1	2	30.33	-29.6395	1.37	-3.6549
11	1.8	2	10.5	-0.5	2	1	2	3	25.67	-28.1932	1.22	-1.8469
12	1.8	2	12	-2.5	2	1	3	1	20.33	-26.1665	0.08	8.8606
13	1.8	2.5	9	-0.5	2	2	1	3	26.00	-28.3037	1.38	-2.8780
14	1.8	2.5	10.5	-2.5	2	2	2	1	19.67	-25.8771	0.13	21.3966
15	1.8	2.5	12	-1.5	2	2	3	2	20.33	-26.1665	1.35	-3.2736
16	1.8	3	9	-2.5	2	3	1	1	18.33	-25.2677	0.06	26.4782
17	1.8	3	10.5	-1.5	2	3	2	2	17.00	-24.619	1.11	-2.3045
18	1.8	3	12	-0.5	2	3	3	3	19.33	-25.7287	1.64	-4.3457
19	2	2	9	-0.5	3	1	1	3	28.33	-29.0472	1.58	-4.3775
20	2	2	10.5	-2.5	3	1	2	1	19.33	-25.7287	1.23	-1.7026
21	2	2	12	-1.5	3	1	3	2	20.33	-26.1665	1.45	-3.4733
22	2	2.5	9	-2.5	3	2	1	1	19.67	-25.9069	0.96	-0.1703
23	2	2.5	10.5	-1.5	3	2	2	2	22.67	-27.1096	1.19	-2.4675
24	2	2.5	12	-0.5	3	2	3	3	26.33	-28.4115	1.46	-3.9794
25	2	3	9	-1.5	3	3	1	2	18.33	-25.2677	1.3	-2.8780
26	2	3	10.5	-0.5	3	3	2	3	20.67	-26.3144	1.61	-3.6922
27	2	3	12	-2.5	3	3	3	1	15.00	-23.5347	0.06	24.3180

speed, assist gas pressure and focus position were assigned to columns 1, 2, 5 and 9, respectively. This design provided uniform distribution of experimental points within the selected experimental hyper-space and the experiment with high resolution. Likewise, this OA was chosen due to its capability to check the interactions among parameters.

In CO_2 laser cutting process, lower values of the width of HAZ and burr height are desirable for maintaining high cut quality and avoide further processing, therefore smaller-the-better S/N ratio was calculated as [22]:

$$S/N \equiv \eta = -10\,log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right). \qquad (8)$$

where y_i are the i-th observed value of the response (quality characteristic), and n is the number of observations in a trial. The S/N ratios were computed using equation (2) for each of the 27 trials and the values are given in Table 2.

4. DATA ANALYSIS, RESULTS AND DISCUSSION

Taguchi methodology was used to identify the optimal laser cutting parameter levels so as to minimize the width of HAZ and burr height.

4.1 Determining the optimal levels of the laser cutting parameters for the width of HAZ

Using equation (1) the main effects of the laser cutting parameters on mean S/N ratio are presented in graphical form (Figure 1).

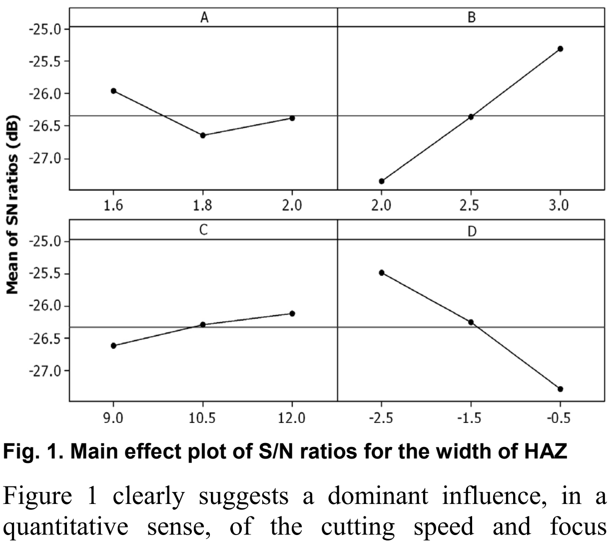

Fig. 1. Main effect plot of S/N ratios for the width of HAZ

Figure 1 clearly suggests a dominant influence, in a quantitative sense, of the cutting speed and focus position on the width of HAZ. The results of ANOM represented in the response diagram as shown in Figure 1 suggest that the optimal combination of laser cutting parameter levels, which gives the lowest value of the width of HAZ, is $A_1B_3C_3D_1$.

However, to find the relative contribution of each laser cutting parameter on the width of HAZ and confirm initial assumption of the optimal laser cutting condition, the statistical analysis through ANOVA was performed. To this aim the main as well as interaction effects of the laser cutting parameters were analyzed using 95% confidence interval.

Since there are 6 possible interactions between parameters (A×B, A×C, A×D, B×C, B×D and C×D), each counting for four degree of freedom (DOF), it was not possible to include them altogether along with the main factors in ANOVA. The plots of two parameter interaction effects on S/N ratio of the width of HAZ (Figure 2) are generated using MINITAB software.

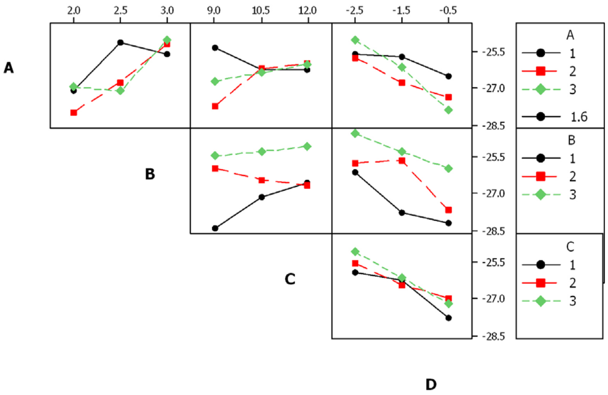

Fig. 2. Interaction effect plots of average S/N ratios for the width of HAZ

As clearly seen from Figure 2, highest S/N for the width of HAZ is obtained when using low focus position for all interaction effects. Therefore, level 1 of parameter D can be selected as optimal, and the further analysis can be directed on interactions A×B, A×C and B×C. From Figure 2 it is observed that there exists a considerable interaction effect of cutting speed variation on S/N ratio of the width of HAZ for any given value of the laser power. On the other hand, for any given cutting speed, the effect of laser power variation on S/N ratio is comparatively less. Further, when the cutting speed is either at low level (2 m/min) or at high level (3 m/min), the interaction effect due to laser power is less when compared to the interaction effect when cutting speed is at center level (2.5 m/min). In the case of A×C interaction, the effect of variations of assist gas pressure is less when the laser power is at center level (1.8 kW) and at high level (2 kW). Further, the degree of interaction effect of laser power variations on S/N ratio of the HAZ is more pronounced at low assist gas pressure (9 bar). In the case of B×C interaction, it can be seen that interaction effect of cutting speed variation is less at high assist gas pressure (12 bar) compared to lower assist gas pressures. Hence, the interaction effect of the cutting speed and assist gas pressure on variability of the width of HAZ is minimal at higher values of both cutting speed and assist gas pressure.

The ANOVA results for the laser cutting parameters and interactions A×B, A×C and B×C are given in Table 3. It can be observed that the ANOVA has resulted in around 2.53% of error contribution due to other interaction effect (not included in the analysis) and noise (uncontrollable) effects.

The results from Figures 1 and 2 and Table 3 suggest that level 1 of parameter A, level 3 of parameter B and level 1 of parameter D may provide the optimal cutting conditions minimizing the HAZ. A further examination of Figure 2, suggest that for interaction

Table 3. Results of ANOVA for S/N ratios

Source of variation	DOF	Sum of squares (SS)	Mean square (MS)	F	p	ρ (%)
A	2	2.2407	1.1204	5.50	0.044	3.93
B	2	19.2801	9.6401	47.29	0.000	33.82
C	2	1.1530	0.5765	2.83	0.136	2.02
D	2	14.7670	7.3835	36.22	0.000	25.9
A×B	4	6.8634	1.7159	8.42	0.012	12.04
A×C	4	6.4930	1.6232	7.96	0.014	11.39
B×C	4	4.9947	1.2487	6.13	0.026	8.76
Error	6	1.2231	0.2038			2.14
Total	26	57.0150				

Table 4. Optimal laser cutting conditions for the width of HAZ

Laser cutting parameter	Denoter	Optimal level
Laser power, kW	A_1	1.6
Cutting speed, m/min	B_3	3
Assist gas pressure, bar	C_1	9
Focus position, mm	D_1	-2.5

A×C, optimal level for the parameter C is level 1 and for interaction B×C, the optimal level for the parameter C is level 3. Here it should be noted that if the effect of some parameter is negligible, its optimal level can be determined considering two-way interactions with other significant parameters. Alternatively, one can take into account other considerations such as economy, operability or technicality [30]. As the influence of the parameter C is negligible, with percentage contribution of only 2.02 %, in this study, C_1 can be taken as optimal level for the assist gas pressure. The selection of low assist gas pressure is also economically justified. Hence, optimal combination of the laser cutting parameter levels where the width of HAZ is minimized is shown in Table 4.

4.2 Determining the optimal levels of the laser cutting parameters for the burr height

The ANOM response graph for the main effects of the laser cutting parameters on mean S/N ratio for the burr height is given in Figure 3. As shown in Figure 3, the focus position significantly affects the variations in the burr height, whereas the influence of the assist gas pressure is much smaller. As seen, the optimal laser cutting condition for minimizing the burr height is $A_1B_3C_3D_1$.

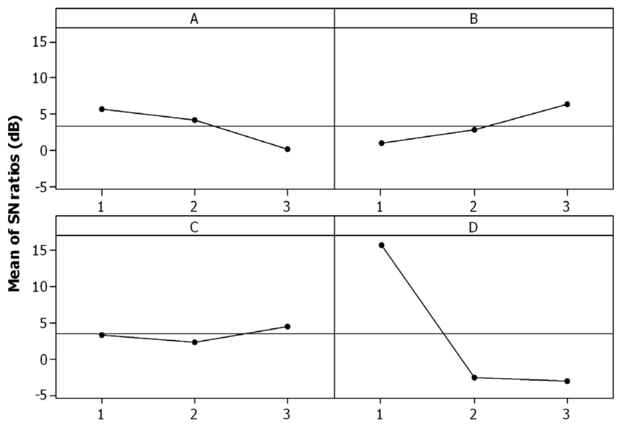

Fig. 3. Main effect plot of S/N ratios for the burr height

To more accurately determine the optimal parameter levels the interaction effect plot (Figure 4) and ANOVA analysis (Table 5) were generated. From Figure 4, in the case of A×B interaction, it can be observed that when using low laser power (1.6 kW), burr height is unaffected by the change in the cutting speed. However, high cutting speed assures higher productivity and hence level 3 of parameter B was selected as optimal.

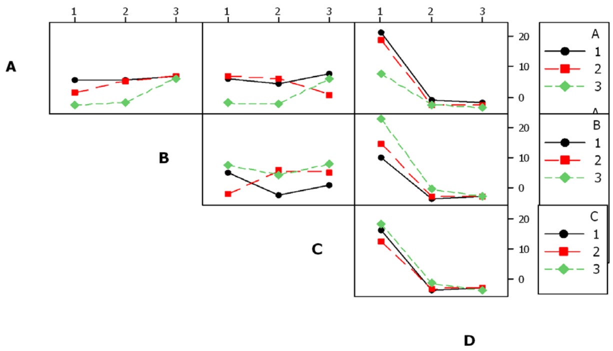

Fig. 4. Interaction effect plots of average S/N ratios for the burr height

Table 5. Results of ANOVA for S/N ratios (burr height)

Source of variation	DOF	Sum of squares (SS)	Mean square (MS)	F	p	ρ (%)
A	2	149.29	74.64	2.25	0.187	4.87
B	2	135.60	67.80	2.04	0.211	4.43
C	2	21.64	10.82	0.33	0.734	0.71
D	2	2090.26	1045.13	31.49	0.001	68.25
AxB	4	66.33	16.58	0.50	0.738	2.17
AxC	4	200.21	50.05	1.51	0.310	6.54
BxC	4	200.17	50.04	1.51	0.311	6.53
Error	6	199.12	33.19			6.5
Total	26	3062.61				

In the case of B×C interaction, the effect of variations of the assist gas pressure is less when the cutting speed is at high level (3 m/min). In this case, using both low assist gas pressure (9 bar) or high assist gas pressure (12 bar) is beneficial for burr height minimization. From the economical reasons, C_1 was taken as optimal level. Therefore, the combination $A_1B_3C_1D_1$ turned out to be beneficial for simultaneous optimization of the HAZ and burr height.

Finally, the experimental results (Figure 5) revealed that the focus position is most influencing parameter affecting the width of HAZ and burr height in CO_2 laser cutting of AISI 304 stainless steel. The assist gas pressure has little influence on the width of HAZ and burr height.

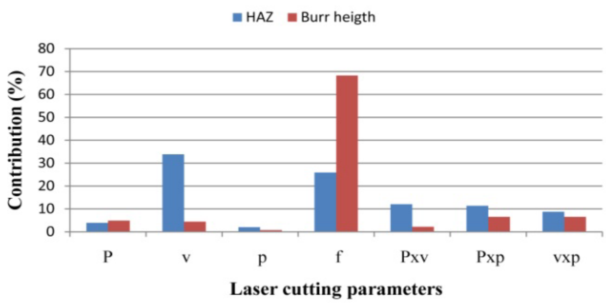

Fig. 5. Percentage contribution of the laser cutting parameters on the width of HAZ and burr height

4.3 Confirmation experiment

Confirmation testing is necessary and final step in Taguchi optimization methodology. Once the optimal combination of laser cutting parameters is selected, the final step is to predict and verify the expected response through the confirmation experiment. However, there is no need to run the confirmation test if the optimal laser cutting parameter combination is already included in the OA. It can be found that the optimal laser cutting levels combination ($A_1B_3C_1D_1$) was not included in experiment matrix (Table 2). The predicted S/N ratio using the optimal levels of the design factors ($\hat{\eta}_{opt}$) can be calculated as [23]:

$$\hat{\eta}_{opt} = \overline{\eta} + \sum_{i=1}^{p} (\overline{\eta}_{i,opt} - \overline{\eta}) . \tag{9}$$

where $\overline{\eta}_{i,opt}$ is the mean S/N ratio for i-th parameter at the optimal level, p is the number of parameters that significantly affect the quality characteristic.

In order to statistically judge the closeness of the predicted ($\hat{\eta}_{opt}$) and observed value of S/N ratio (η_{obs}), the confidence intervals (CIs) were determined. The CI is given by [31]:

$$CI = \sqrt{F_{\alpha(1,f_e)} \cdot V_e \left[\frac{1}{n} + \frac{1}{n_{ver}} \right]} . \tag{10}$$

where $F_{(1;fe)}$=5.99 is the F value from statistic table at a 95 % confidence level, f_e=6 is the degrees of freedom for the error, V_e is the mean square of error, n_{ver}=3 is the validation test trial number, and n is defined as:

$$n = \frac{N}{1+\nu} . \tag{11}$$

where N=27 is the total number of experiments and ν=22 is the total degrees of freedom of all parameters.

If the difference between $\hat{\eta}_{opt}$ and η_{obs} is within the CI value, then the optimum laser cutting parameter level combinations are valid. From Table 6 it can be observed that the calculated values of the prediction errors are within the CIs.

Table 6. Result of confirmation experiment under the optimal conditions ($A_1B_3C_1D_1$)

	Width of HAZ	Burr height
S/N predicted ($\hat{\eta}_{opt}$), dB	-24.0833	21.1148
S/N observed (η_{obs}), dB	-25.2090	24.4269
Prediction error, dB	1.1257	3.3121
CI, dB	±1.2028	±15.35

The predicted width of HAZ and burr height values under the optimal combination of laser cutting parameters ($A_1B_3C_1D_1$) can be determined from the simple relation:

$$HAZ = 10^{-\frac{\hat{\eta}_{HAZ,opt}}{20}} ; \; b = 10^{-\frac{\hat{\eta}_{b,opt}}{20}} . \tag{12}$$

The predicted values of the confirmation test using equation (12) are: width of HAZ = 16 μm and burr height, b = 0.088 mm. On the other hand, the experimental observations under the optimal combination of laser cutting parameters ($A_1B_3C_1D_1$) are: width of HAZ = 18.21 μm and burr height, b = 0.06 mm.

5. CONCLUSION

This paper presented Taguchi optimization methodology for minimization of the width of HAZ and burr height in CO_2 laser cutting of AISI 304 stainless steel. On the basis of the experimental results and derived analysis, the following conclusions can be drawn:

- Focus position is the most significant laser cutting parameter affecting the investigated quality characteristics.
- The effect of the assist gas pressure is negligible. However, its interaction effects with the laser power and cutting speed is not negligible.
- The response graphs and ANOVA results showed that the effects of two-way interactions of the laser power, cutting speed and assist gas pressure are statistically significant.
- The obtained results suggest that low laser power, assist gas pressure and focus position are beneficial for minimization of the width of HAZ and burr height, while the cutting speed should be kept at the highest level.

The results presented in this paper are restricted to CO_2 laser cutting of 3 mm thick stainless steel sheet. Sheet thickness is one of the main process parameters having a major impact on the complex thermo-chemical processes which take place in the material during the cutting process and should be considered when selecting other process parameter values. In the authors' opinion, whether using classical optimization methods or Taguchi optimization methodology, optimization of laser cutting process, i.e. identification of near optimal laser process parameter values is to be done for one sheet thickness.

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ИДЕНТИФИКАЦИЈА РОБУСТНИХ УСЛОВА ЗА МИНИМИЗАЦИЈУ ЗОНЕ ТОПЛОТНОГ УТИЦАЈА И ШЉАКЕ КОД CO_2 ЛАСЕРСКОГ СЕЧЕЊА

Милош Ј. Мадић, Мирослав Р. Радовановић

У овом раду представљена је Тагучијева оптимизациона методологија за идентификацију робустних услова у циљу минимизације зоне топлотног утицаја и шљаке код CO_2 ласерског сечења AISI 304 нерђајућег челика. Експеримент је планиран и извршен на основу стандардног Тагучијевог ортогоналног низа L_{27} у коме су четири параметра ласерског сечења као што су снага ласера, брзина сечења, притисак помоћног гаса и позиција фокуса мењани на три нивоа. На основу анализе варијансе, средњих вредности и графика интеракција идентификовани су значајни параметри као и оптимална комбинација њихових нивоа. Резултати су показали да је позиција фокуса најзначајнији параметар који утиче на ширину зоне топлотног утицаја и висину шљаке, док се утицај притиска помоћног гаса може занемарити. Утврђено је да су резултати Тагучијеве предикције под оптималним условима ласерског сечења у доброј сагласности са резултатима конфирмационог експеримента.