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Optimization of the kerf quality characteristics in CO_2 laser cutting of AISI 304 stainless steel based on Taguchi method

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1. Introduction

Laser cutting is a thermal energy based advanced machining process in which material is removed by focusing the laser beam on the workpiece surface. Depending upon the prevailing conditions, the material may be removed by different mechanisms such as vaporization, fusion, reactive fusion, ablation and controlled fracture [1]. 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. The wide spectrum of industrial application of the laser cutting is due to its: convenience of operation, high precision, small heat-affected zone (HAZ), minimum deformity, low cost, high product quality, high cutting speed, low level of noise, flexibility, ease of automation etc. As a noncontact process it is well suited for processing of advanced engineering materials such as difficult to cut materials, brittle materials, reflective metals, plastics, rubbers, ceramics, composites and soft materials.

For the above reasons, laser cutting became an area of great interest for research. A number of researchers performed theoretical as well as experimental investigations in order to examine the laser cutting process. Studies that focused on the development and applications of laser beam cutting techniques were reviewed in [2].

Maximization of productivity and quality along with costs minimization is of particular interest to manufacturers. To maintain a high productivity and an acceptable level of quality for the cut parts, it is important to select the optimum combination of process parameters, as these parameters impact on the special microscopic and macroscopic characteristics of the finished parts, as signified by the kerf width, HAZ and the surface roughness after processing [3]. Actually, the cut quality characteristics can be improved considerably via appropriate selection and optimization of a laser and operating parameters. It should be noted that the optimum parameter settings for one quality characteristic may deteriorate other quality characteristic [4].

Consequently, it is of great importance to exactly quantify the relationship between the laser cutting parameters and cutting performance through mathematical modeling and subsequently determine (near) optimal cutting conditions through the use of optimization algorithms, wherein the application of meta-heuristic optimization algorithms such as genetic algorithms and simulated annealing [5, 6] was proved efficient. Apart from mathematical modeling techniques such as response surface methodology (RSM) and artificial neural networks, one factor at a time and classical design of experiments (DOE) techniques were often employed for investigating the effect of the laser cutting parameters on performance characteristics. However, these techniques are more time and computationally expensive and often require a large number of experimental trials. To overcome this problem, researches applied Taguchi method (TM) which provides a systematic, efficient and easy-to-use approach for the process optimization. The application of TM in the field of laser cutting is reviewed in the following section.

Pandey and Dubey [1] presented an integrated approach based on TM and fuzzy logic theory for optimization of multiple responses in Nd:YAG laser cutting of duralumin sheet. The authors demonstrated the effectiveness of the method for simultaneous improvement of the kerf width and kerf deviations at top and bottom sides. Dubey and Yadava [4] demonstrated that hybrid TM and RSM (TMRSM) can be applied to Nd:YAG laser cutting optimization with multiple quality characteristics. The authors noted that the hybrid approach gives better quality results as compared to only TM. Simultaneous optimization of the kerf width and material removal rate (MRR) was based on second-order response models with assist gas pressure, pulse width, pulse frequency and cutting speed as input process parameters. Sharma and Yadava [7] presented hybrid approach comprising of TM and RSM for modeling and hybrid approach of TM and GRA coupled with entropy measurement methodology for multi-objective optimization of pulsed Nd:YAG laser cutting of thin aluminum alloy sheet. Optimization of the kerf taper and average surface roughness was performed considering oxygen pressure, pulse width, pulse frequency and cutting speed as input process parameters. Dubey and Yadava [8] applied a combined approach based on TM and principal component analysis (PCA) for multi-response optimization of Nd:YAG laser cutting process. Their investigation included the analysis of the laser cutting parameters on the cut quality characteristics such as kerf width, kerf deviation, and kerf taper. Dubey and Yadava [9] optimized simultaneously kerf deviation and kerf width obtained in pulsed Nd:YAG laser cutting of 8081 aluminum alloy sheet using Taguchi quality loss function. For simultaneous optimization, the normalized quality loss function was computed and weighted to obtain total normalized quality loss for each trial condition. Dubey and Yadava [10] applied TM to find the optimal cutting parameters for multi-objective optimization of the kerf taper and MRR. The authors compared the results of multi-objective optimization with the single-objective optimization and founded that the kerf taper was increased by 1.60% in multi-objective optimization while the MRR was the same in both cases. Rao and Yadava [11] presented a hybrid optimization approach based on TM and grey relational analysis (GRA) with entropy measurement for determining optimum laser cutting parameters which simultaneously minimize the kerf width, kerf taper, and kerf deviation during pulsed Nd:YAG laser cutting of nickel-based superalloy superni 718. Caydaş and Hasçalik [12] applied hybrid approach of TM and GRA to determine optimum laser cutting parameters (cutting speed and laser power) with multi-performance characteristics (surface roughness, kerf width, and HAZ) during CO_2 laser cutting of mild steel sheet. Chen et al. [13] presented an approach for evaluating the process parameters in CO_2 laser cutting of polymethylmethacrylate (PMMA) material using the TM and GRA. They investigated and optimized laser cutting parameters such as assist gas flow rate, pulse frequency, cutting speed and focus position. El Taweel et al. [14] applied TM to identify the effect of the laser power, cutting speed, material thickness, assist gas pressure and laser mode on the quality of cut parameters, namely, the kerf width, kerf taper and burr height in CO_2 laser cutting of kevlar-49 composite. Using the analysis of variance (ANOVA) optimal cutting parameter settings for minimizing the selected cut quality characteristics were identified.

The survey of literature is summarized in Table 1. It is seen that considerable research studies were carried out to improve the performance of laser cutting process previously with the use of TM. It is seen that most of the experimental studies applied TM for optimization of single but preferably multi-quality characteristics at a time using the Nd:YAG lasers. The analysis of literature revealed that there is a lack of research on the use of CO_2 lasers for such applications, and furthermore, there is no investigation reported on the stainless steel.

Table 1

Analysis of the literature on application of the TM in laser cutting optimization

Reference	Laser system	Material	Parameters[a]	Assist gas	Quality characteristics[b]	Multi-response	Method[c]
[1]	Nd:YAG	duralumin	v, p, p_w, p_f	O_2	K_w, top K_d, bottom K_d	yes	fuzzy logic
[4]	Nd:YAG	high silicon-alloy steel	v, p, p_w, p_f	O_2	K_w, MRR	yes	weighting method
[7]	Nd:YAG	Al alloy	v, p, p_w, p_f	O_2	K_t, R_a	yes	GRA with entropy measurement
[8]	Nd:YAG	superni 718	v, p, p_w, p_f	O_2	K_w, K_t, K_d	yes	PCA
[9]	Nd:YAG	8011 Al alloy	v, p, p_w, p_f	O_2	K_w, K_d	yes	weighting method
[10]	Nd:YAG	8011 Al alloy	v, p, p_w, p_f	O_2	K_t, MRR	yes	weighting method
[11]	Nd:YAG	superni 718	v, p, p_w, p_f	O_2	K_w, K_t, K_d	yes	GRA with entropy measurement
[12]	CO_2	St-37	v, P	O_2	K_w, R_a, HAZ	yes	GRA
[13]	CO_2	PMMA	v, p_f, f, q	compressed air	R_a, r	yes	GRA
[14]	CO_2	Kevlar-49	v, P, p, d, TEM	N_2	K_w, K_t, b	no	
This study	CO_2	AISI 304 steel	v, p, P, f	N_2	K_w, K_t	no	

[a] v: cutting speed, p: assist gas pressure, p_w: pulse width, p_f: pulse frequency, P: laser power, f: focus position, q: assist gas flow, d: material thickness

[b] K_w: kerf width, K_t: kerf taper, K_d: kerf deviation, R_a: surface roughness, HAZ: heat affected zone, MRR: material removal rate, r: optical transmittance ratio, b: burr height

[c] PCA: principal component analysis, GRA: grey relational analysis,

This paper demonstrates the application of the TM for analysis of the effect of laser cutting parameters on the kerf quality characteristics and identification of the optimal cutting parameter settings in CO_2 laser cutting of AISI 304 stainless steel. Four cutting parameters such as laser power, cutting speed, assist gas pressure and focus position were considered. The kerf quality characteristics considered were the kerf width and kerf taper. Initially, laser cutting experiment was performed by using L_{27} orthogonal array (OA) to obtain the results for single-objective optimization of the kerf quality characteristics. Furthermore, analysis of variance (ANOVA) was used to determine the percentage contribution of each laser cutting parameter to the kerf quality characteristics.

2. Experimental details

2.1. Material

In this study, AISI 304 stainless steel material was used as the workpiece. The chemical composition is given in Table 2. The sheet dimensions were 500 × 500 mm with thickness of 3 mm.

Table 2

Nominal chemical composition of AISI 304 stainless steel

Cr	Ni	C	Mn	Si	S	Fe
%						
18.9	9.22	0.07	1.64	0.5	0.006	Balance

2.2. Experimental procedure

The experiment trials were performed using a ByVention 3015 CO_2 laser cutting machine with a nominal power of 2.2 kW. The nitrogen was used as assist gas and it was 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 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 numerical values of selected parameters at different levels are shown in Table 3. The values range for each parameter was chosen such that full cut for each parameter combination is achieved and by considering manufacturer's recommendation for parameter settings.

Table 3

Laser cutting parameters and their levels

Cutting parameter	Unit	Level		
		1	2	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*	bar	9	10.5	12
D – focus position, *f*	mm	-2.5	-1.5	-0.5

2.3. Design of experiment

Based on the selected parameters and parameter levels, a design matrix was constructed (Table 4) in accordance with the standard L_{27} (3^{13}) Taguchi's OA. 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 factors. The L_{27} consists of 13 columns (parameters) and 27 rows (experimental trials). Laser cutting parameters, laser power, cutting speed, assist gas pressure and focus position were assigned to columns 1, 2, 5 and 9, respectively.

2.3. Laser cutting performance evaluation

The appropriate selection of different input parameters and their levels have significant impact on the cut quality obtained. In most reported studies on CO_2 laser cutting, kerf width, surface roughness and size of the HAZ, were commonly used as cut quality characteristics [15]. Kerf width is the measure of the amount of the workpiece that is wasted during material processing. Obtaining high material removal rate in laser cutting of thin sheets of steels is not a difficult task but the most important thing is to get narrow cut kerf [4].

Kerf width and kerf taper are one of the most important quality parameters in laser cutting that determine the geometrical accuracy of the finished parts. Due to converging–diverging shape of laser beam profile the kerf taper always exist during laser cutting (Fig. 1).

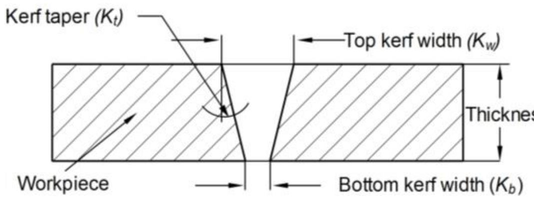

Fig. 1 Geometry of the laser cut kerf

The geometrical accuracy of the laser cut kerf was evaluated in terms of the measured output performance parameter such as kerf width and kerf taper. In this paper the kerf width (K_w) represents the top kerf width. The kerf taper (K_t) was calculated using the following formula:

$$K_t(^\circ) = abs\left(\frac{K_w - K_b}{2d}\right)\frac{180}{\pi}, \qquad (1)$$

where d is the workpiece thickness.

Straight cuts of 50 mm long are made for each experimental trial and kerf widths were measured at three different places along the length of cut on the top and the bottom side so as to calculate kerf taper values. The measurement locations were decided at equal distances. The kerf widths were measured using the optical optical microscope (Leitz, Germany). The average values of kerf width and kerf taper corresponding to each experimental trial are listed in Table 4.

3. Taguchi method

Taguchi method (TM) is a powerful yet relatively simple statistical technique for product/process quality improvement. It aims at optimizing process parameter settings such as the variation in responses due to noise factors is nullified. Noise factors (external conditions, manufacturing imperfections, etc.) are unwanted sources of variation and can be uncontrollable or too expensive to control. These factors are usually ignored in the classical DOE approach. The key principle of the Taguchi technique lies in the fact that the reduction in variation is obtained without removing its causes [16].

TM offers efficient DOE through the use of OAs, analysis of the effects of process parameters and their interactions on responses with the help of analysis of means (ANOM) and analysis of variance (ANOVA), and finally identification of the (near) optimal process parameter settings. In TM to study the entire parameter space with minimum number of experiments an OA, which is a small fraction of full factorial design, is used. The columns of an OA represent the experimental parameters to be optimized and the rows represent the individual trials (combinations of parameter levels). The array is called orthogonal because for every pair of parameters all combinations of parameter levels occurs an equal number of times.

Traditionally, data from experiments are directly used to analyze the mean response. However, in TM the mean and the variance of the response (experimental result) at each parameter setting in OA are combined into a single performance measure known as the signal-to-noise (*S/N*) ratio [17]. 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 [16].

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. During CO_2 laser cutting process, lower value of the kerf width and kerf taper are desirable for maintaining high cut quality and accuracy, therefore smaller-the-better *S/N* ratio was calculated as:

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

where: y_i is the i-*th* observed value of the response; n is the number of observations in a trial.

Table 4

L_{27} matrix for the experiment and experimental results

Trial	Natural factor				Coded factor				Experimental results			
	P (kW)	v (m/min)	p (bar)	f (mm)	A	B	C	D	K_w (mm)	η_w (dB)	K_t (°)	η_t (dB)
1	1.6	2	9	-2.5	1	1	1	1	0.517	5.7268	1.18	-1.534
2	1.6	2	10.5	-1.5	1	1	2	2	0.398	7.9516	0.60	4.2027
3	1.6	2	12	-0.5	1	1	3	3	0.353	8.8317	6.02	-15.6922
4	1.6	2.5	9	-1.5	1	2	1	2	0.393	8.2507	0.83	1.5924
5	1.6	2.5	10.5	-0.5	1	2	2	3	0.387	8.0539	3.63	-11.2191
6	1.6	2.5	12	-2.5	1	2	3	1	0.483	6.3047	1.46	-3.3163
7	1.6	3	9	-0.5	1	3	1	3	0.307	10.2380	4.07	-12.216
8	1.6	3	10.5	-2.5	1	3	2	1	0.512	6.0206	2.07	-6.5688
9	1.6	3	12	-1.5	1	3	3	2	0.366	9.0240	0.51	5.3491
10	1.8	2	9	-1.5	2	1	1	2	0.435	7.2247	4.46	-13.0656
11	1.8	2	10.5	-0.5	2	1	2	3	0.372	8.8428	4.93	-13.9115
12	1.8	2	12	-2.5	2	1	3	1	0.550	5.1841	1.34	-2.7521
13	1.8	2.5	9	-0.5	2	2	1	3	0.323	9.6430	5.63	-15.1078
14	1.8	2.5	10.5	-2.5	2	2	2	1	0.477	6.4276	1.27	-2.2946
15	1.8	2.5	12	-1.5	2	2	3	2	0.423	7.3921	3.12	-11.6442
16	1.8	3	9	-2.5	2	3	1	1	0.488	6.3047	1.50	-3.5614
17	1.8	3	10.5	-1.5	2	3	2	2	0.344	9.2215	3.09	-10.7489
18	1.8	3	12	-0.5	2	3	3	3	0.287	10.8478	4.01	-12.0644
19	2	2	9	-0.5	3	1	1	3	0.376	8.4114	5.06	-14.1045
20	2	2	10.5	-2.5	3	1	2	1	0.542	5.3755	1.15	-1.3216
21	2	2	12	-1.5	3	1	3	2	0.450	6.7951	5.57	-14.946
22	2	2.5	9	-2.5	3	2	1	1	0.493	6.1356	0.35	7.3185
23	2	2.5	10.5	-1.5	3	2	2	2	0.461	6.6736	5.25	-14.5839
24	2	2.5	12	-0.5	3	2	3	3	0.372	8.3674	5.95	-15.4986
25	2	3	9	-1.5	3	3	1	2	0.389	8.0558	4.84	-13.7235
26	2	3	10.5	-0.5	3	3	2	3	0.320	9.8632	6.49	-16.2571
27	2	3	12	-2.5	3	3	3	1	0.443	7.0517	1.11	-1.05036

The larger algebraic value of *S/N* ratio corresponds to the better performance characteristic, and hence the optimal level of the parameter is the level with the highest *S/N*. The predicted *S/N* ratio using the optimal levels of the parameters ($\hat{\eta}_{opt}$) can be calculated as [17]:

$$\hat{\eta}_{opt} = \overline{\eta} + \sum_{i=1}^{m} (\overline{\eta}_{i,opt} - \overline{\eta}), \tag{3}$$

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

$$\overline{\eta} = \frac{1}{n_t} \sum_{i=1}^{n_t} \eta_i, \tag{4}$$

where n_t is the total number of trials; η_i is the *S/N* ratio in *i*-th trial in the OA.

ANOM is a statistical approach of estimating the mean *S/N* ratios for each parameter and each of its levels. The effect of parameter Q at level k can be calculated as [16]:

$$\overline{\eta}_{Qk} = \frac{1}{n_{Qk}} \sum_{l=1}^{n_{Qk}} \left[(S/N)_{Qk} \right]_l, \tag{5}$$

where n_{Qk} is the number of appearances of parameter Q at level k in experimental plan; $(S/N)_{Qk}$ is the *S/N* ratio related to parameter Q at level k.

ANOM can be used as a tool for determining optimal parameter settings. However, ANOVA is a computational technique, which is used to estimate the relative significance of each process parameter in terms of percent contribution on the overall response so that the optimal combination of process parameter levels can be determined more accurately. It is also required for estimating the error variance and confidence interval (CI) of the prediction error.

In ANOVA, the ratio between the variance of the parameter and the error variance is called Fisher's ratio (F). It is used to determine whether the parameter has a significant effect on the quality characteristic by comparing the F test value of the parameter with the standard F table value (F_α) at the α % significance level. Greater the F-ratio more significant is the process parameter.

4. Analysis of experimental results and discussion

To analyze the effect of the laser cutting parameters on kerf quality characteristics main effect plots were generated. A main effect plot is a plot of the mean response values at each level of a design parameter [18]. The main effect of a parameter is defined as the average change in the response when the level of the parameter is changed from a low to a high level. A positive gradient indicates that with an increase in parameter value there is an increase in response value, and a negative gradient means a decrease in response value.

However, the relative contribution of each laser cutting parameter on the kerf quality characteristics was determined through ANOVA that enables more accurate determination of the optimal process parameter levels [17, 19].

4.1. Effect of the laser cutting parameters on the kerf width

Fig. 2 represents the main effects plot for the mean value of the kerf width against the laser power (A), cutting speed (B), assist gas pressure (C) and focus position (D). It can be seen that the kerf width generally increases with increasing laser power. This is due to the increase of thermal energy that is absorbed in material. These findings are in agreement with the previously reported results [20, 21]. However, the kerf width sharply decreases as the cutting speed increases. This is due to the fact that an increase in cutting speed decreases the thermal energy available at the workpiece surface, which in turn decreases the rate of energy transfer from the laser source to the workpiece material and which results in small size of the melt zone in the kerf. This is in a good agreement with previous findings [20, 21]. In the case of the focus position, it is notable that the kerf width decreases as the focus position increases, i.e. the focus position is approaching closer to the workpiece surface. Focusing the laser beam deep into the bulk of the workpiece (focus position of –2.5 mm in the present case) means that the position of the laser spot is moved which results in a wider kerf width. On the other hand, when the focus position is –0.5 mm, smaller kerf width is obtained. Similar findings were reported in [21]. Finally, from the Fig. 2 it can be seen that the assist gas pressure has no significant effects on the kerf width. This can be explained by the inert nature of nitrogen.

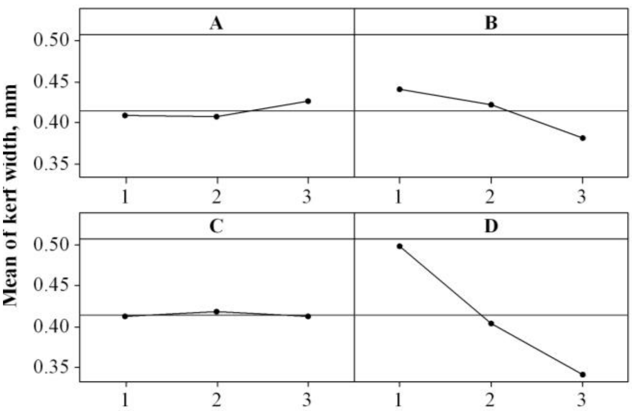

Fig. 2 Main effects plot (data means) for the kerf width

4.2. Effect of the laser cutting parameters on the kerf taper

Fig. 3 represents the main effects plot for the mean value of the kerf taper against the laser power (A), cutting speed (B), assist gas pressure (C), and focus position (C). It can be seen that increasing the laser power increases the kerf taper. This is because, as the laser power increases, the penetration increases, which makes the two sides of the cutting edges non-parallel to each other, so the resultant tilting edge of the kerf is larger [22]. On the contrary, with increasing cutting speed, the slope is decreased because of the wall sides of the cutting width and the difficulties of the molten material removal or blowing out through the kerf obstruct the gas flow [14]. In the case of the focus position, it is notable that as the focus position increases, the kerf taper increases. This is in agreement with the findings of Pfeifer et al. [23]. Nitrogen as an inert assist gas doesn't contribute to the reaction energy that comes from the focused laser beam, therefore the assist gas pressure has no significant effects on the kerf taper.

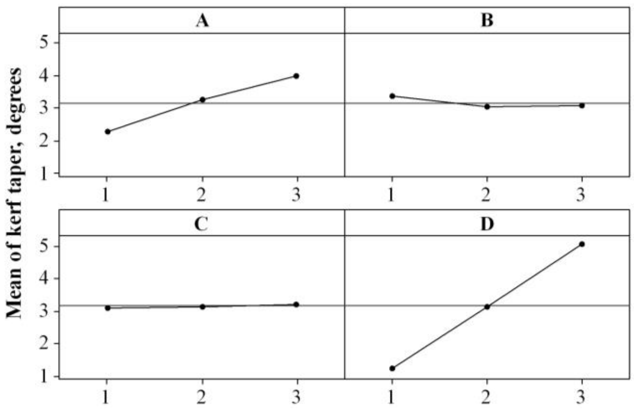

Fig. 3 Main effects plot (data means) for the kerf taper

4.3. Determining the optimal levels of the laser cutting parameters for the kerf width

Using the Eq. (6) the ANOM for *S/N* ratios was conducted from which the optimum levels of the laser cutting parameters can be determined (Table 5).

Table 5

Response table for mean S/N ratios for the kerf width

Parameter	Mean *S/N* ratio (dB)			$\Delta_{max\text{-}min}$	Rank
	level 1	level 2	level 3		
A	7.822	7.899*	7.414	0.484	3
B	7.149	7.472	8.514*	1.365	2
C	7.777*	7.603	7.755	0.173	4
D	6.059	7.843	9.233*	3.174	1
* Optimal level					

The results from Table 5 suggest that the optimal combination of the laser cutting parameters A2B3C1D3 could be achieved by using a laser power of 1.8 kW, cutting speed of 3 m/min, assist gas pressure of 9.5 bar, and focus position kept at –0.5 mm. To confirm this assumption the statistical analysis was also performed by using ANOVA. This analysis was carried out to find the relative effect of laser cutting parameters on the kerf width (Table 6).

Table 6

Results of ANOVA for S/N ratios (kerf width)

Source of variation	DOF	Sum of squares	Mean square	*F*	δ (%)
A	2	1.2209	0.6104	1.85	1.97
B	2	9.1586	4.5793	13.90	14.76
C	2	0.1609	0.0804	0.24	0.26
D	2	45.5729	22.7865	69.14	73.45
Error	18	5.932	0.3296		9.56
Total	26	62.0453			
$F_{0.05,\,2,\,18} = 3.55$, $F_{0.01,\,2,\,18} = 6.01$					

From the ANOVA results, it can be seen that cutting parameters, focus position (D) and cutting speed (B) are statistically significant with 99% confidence for affecting kerf width. The change of laser power and assist gas pressure in the range given in Table 4 have an insignificant effect on the kerf width.

The percent contribution of source to the total variation defines parameter sensitivity. It can be seen from Table 6 that changing the design parameters levels of A, B, C, and D contributes to about 90% of the total variation. Furthermore, the relatively small percent contribution of error confirms the absence of significant parameter interactions. Therefore, it is not necessary to perform the revision of the original solution to the optimal arrangement of parameter levels (A2B3C1D3). The focus position is the most significant parameter affecting the kerf width (73.45% contribution), followed by the cutting speed (14.7% contribution). However, the laser power has much smaller effect with contribution of 1.97%, whereas the the effect of assist gas pressure is negligible.

4.4. Determining the optimal levels of the laser cutting parameters for the kerf taper

The ANOM for *S/N* ratios was conducted and the results are given in Table 7.

Table 7

Response table for mean S/N ratios for the kerf taper

Parameter	Mean S/N ratio (dB)			$\Delta_{max\text{-}min}$	Rank
	level 1	level 2	level 3		
A	-4.379*	-9.461	-9.352	5.082	2
B	-8.126	-7.195*	-7.871	0.931	3
C	-7.156*	-8.078	-7.957	0.922	4
D	-1.676*	-7.508	-14.008	12.332	1

* Optimal level

The analysis of the results from Table 7 indicates that the optimal combination of laser cutting parameters is A1B2C1D1. However, it can be shown from ANOVA analysis of the main factors that there exists experimental error of about 40%. This means that there are significant interactions between main factors or that there are other influential parameters (controlled and uncontrolled) which were not included into the experiment. Since there are 6 possible interactions between factors (AB, AC, AD, BC, BD and CD), each counting for 4 DOF, it was not possible to include them altogether along with the main factors in ANOVA. Because of the possibility of the parameters interacting among them, a six two factor interactions are computed and plotted in Fig. 4.

It is evident from Fig. 4 that for interactions A×B, A×C, B×D and C×D there are no important changes in the average values of *S/N* ratio, which implies that A×B, A×C, B×D and C×D are not significant. Although the effects of B and C were found to be least pronounced (Table 7), its interaction effect (B×C) has some effects on the kerf taper. As it could be seen from Fig. 4 the interaction B×C suggest that B2 and C1 are optimal levels which produce no correction of the initial optimal solution. A further examination of Fig. 4 suggest that level 1 of parameter A (A1) and level 2 of parameter D (D2) provide optimal settings with highest values of *S/N* ratio – corresponding to minimal variations. From these reasons, the optimal cutting parameters combination (A1B2C1D2) can be regarded as optimal for the kerf taper.

To more accurately identify and confirm optimal combination of laser cutting parameters which significantly affect the kerf taper, ANOVA was carried out (Table 8).

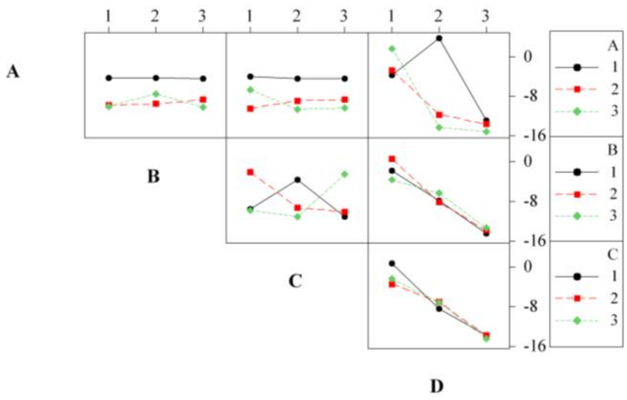

Fig. 4 Interaction effect plots of average S/N ratios for the kerf taper

Table 8

Results of ANOVA for S/N ratios (kerf taper)

Source of variation	DOF	Sum of squares	Mean square	*F*	δ (%)
A	2	151.73	75.86	12.88	10.75
B	2	4.17	2.08	0.35	0.29
C	2	4.52	2.26	0.38	0.32
D	2	684.98	342.49	58.16	48.51
AxD	4	484.20	121.05	20.55	34.29
Error	14	82.45	5.89		5.84
Total	26	1412.04			

$F_{0.05,\,2,\,14} = 3.74$, $F_{0.01,\,2,\,14} = 6.51$, $F_{0.05,\,4,\,14} = 3.11$, $F_{0.01,\,4,\,14} = 5.04$

It is seen that focus position (D), interaction between laser power and focus position (A×D) and laser power (A) are statistically significant with 99% confidence for affecting kerf taper. The changes of the cutting speed (B) and assist gas pressure (C) in the given ranges have insignificant effect on the kerf taper. The focus position (D) has the major contribution (48.51%) in optimizing kerf taper, followed by interaction between laser power and focus position (A×D) (34.29%) and laser power (A) (10.75%). Furthermore, the small percent contribution of error confirms the absence of other significant factor interactions. A further examination of Fig. 4 suggests that level 1 of parameter A (A1) and level 2 of parameter D (D2) provide optimal settings with highest values of *S/N* ratio – corresponding to minimal variations. From these reasons, the optimal cutting parameters combination (A1B2C1D2) can be regarded as optimal for kerf taper.

4.5. Confirmation experiment

The final step in analyzing the experimental results is the verification of the improvement of the quality characteristics. For that purpose, a confirmation experiment should be carried out implying the (near) optimal levels of the parameters. Therefore, a confirmation experiments were performed using optimal condition (A2B3C1D3) for the kerf width. Since the optimal combination (A1B2C1D2) for minimizing the kerf taper was already included in the OA, no confirmation experiment trials were conducted. The predicted *S/N* ratios under the optimal conditions are estimated using Eq. (4). The predicted and the experimentally observed kerf width and kerf taper values at the optimum levels of the laser cutting parameters are shown in Table 9.

Table 9
Results of the confirmation experiment for the kerf width and kerf taper

	Taguchi optimal parameter settings	
	Prediction	Experiment
Level	A2B3C1D3	A2B3C1D3
Kerf width (mm)	0.3	0.312
S/N ratio (dB)	10.2775	10.5469
Level	A1B2C1D2	A1B2C1D2
Kerf taper (º)	0.47	0.83
S/N ratio (dB)	4.8246	1.5924

As it can be seen in Table 9, the predicted and measured results for kerf width and kerf taper are close. However, in order to statistically judge the closeness of predicted to observed data, the CIs were determined. The CI is given by [19]:

$$CI = \sqrt{F_{\alpha(1,f_e)}\, V_e \left[\frac{1}{n} + \frac{1}{n_{ver}}\right]}, \tag{6}$$

where $F_{\alpha(1;fe)}$ is the F value from statistic table at a confidence level of (1-α) at DOF = 1, and error DOF = 18; n_{ver} is the validation test trial number = 3; V_e is the error variance; n is defined as:

$$n = \frac{N}{1+\nu}, \tag{7}$$

where N is the total number of experiments; ν is the total DOF of all parameters.

At the 95% confidence level, the CI are ± 0.984 and ± 4.591 for the kerf width and the kerf taper, respectively. Since the prediction errors for the kerf width (0.269) and the kerf taper (3.2322) are within CI values, the combination of cutting parameter levels for optimization of kerf width and kerf taper can be validated.

5. Conclusion

This study presented the Taguchi method for optimization of kerf width and kerf taper in CO_2 laser cutting of AISI 304 stainless steel using nitrogen as assist gas. The purpose of the Taguchi method was to analyze the effect of main cutting parameters such as laser power, cutting speed, assist gas pressure and focus position on the selected kerf quality characteristics and subsequently to determine the optimal cutting parameter settings.

On the basis of the experimental results and derived analysis, one can conclude that focus position has the most dominant effect on the kerf width and kerf taper. The influence of the cutting speed on the kerf width is much smaller, whereas the influence of the laser power and the assist gas pressure can be neglected. On the other hand, the combined effect of the laser power and the focus position is very strong on the kerf taper. Finally, the effects of the cutting speed and the assist gas pressure on the kerf taper are statistically insignificant.

The optimal laser parameter levels predicted in single objective optimization for minimum value of the kerf width (0.312 mm) are P = 1.8 kW, v = 3 m/min, p = 9 bar and f = –0.5 mm. On the other hand, laser cutting with P = 1.6 kW, v = 2.5 m/min, p = 9 bar and f = –1.5 mm is optimal combination of cutting parameter settings which minimizes the kerf taper to 0.83°.

In mass production applications of laser cutting technology where the dimensional accuracy with minimum variability is of prime importance, the application of Taguchi method provides a systematic, efficient and easy-to-use approach for the laser cutting process optimization.

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ĮPJOVOS KOKYBĖS CHARAKTERISTIKŲ, PJAUNANT NERŪDIJANTĮJĮ PLIENĄ AISI 304 CO_2 LAZERIU, OPTIMIZAVIMAS TAGUŠI METODU

R e z i u m ė

Šiame darbe pagrindinių lazerio pjovimo parametrų, tokių kaip galios, pjovimo greičio, pagalbinių dujų slėgio ir židinio padėties, dviejų įpjovų kokybinių charakteristikų – įpjovos pločio ir įpjovos kūgiškumo analizei taikytas Taguši metodas. Azotinis 3 mm storio nerūdijantysis plienas AISI 304 buvo pjaunamas 2,2 kW CO2 lazeriu. Lazerinio pjovimo eksperimentas buvo planuojamas ir atliekamas pagal Taguši eksperimentinę schemą naudojant ortogonaliąją matricą L27. Iš būvių analizės (ANOM), variantų analizės (ANOVA) ir signalo ir triukšmo (S/N) santykio lentelių buvo nustatyti svarbūs lazerio pjovimo parametrai ir tų parametrų lygių abiem įpjovos kokybės charakteristikoms optimalūs deriniai. Rezultatai rodo, kad įpjovos kokybei daugiausia įtakos turi židinio padėtis, o dujų slėgio galima nepaisyti. Nustačius optimalius lazerio pjovimo parametrus sumažėjo įpjovos plotis ir kūgiškumas – atitinkamai 0,312 mm ir 0,83°. Eksperimentų rezultatai gerai sutapo su skaičiavimo rezultatais. Šiame darbe pateikti rezultatai patvirtina Taguši lazerinio pjovimo proceso optimizavimo metodo efektyvumą.

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OPTIMIZATION OF THE KERF QUALITY CHARACTERISTICS IN CO_2 LASER CUTTING OF AISI 304 STAINLESS STEEL USING THE TAGUCHI METHOD

S u m m a r y

In this paper, Taguchi method was applied to analyze the effect of the main laser cutting parameters such as the laser power, cutting speed, assist gas pressure, and focus position on the two kerf quality characteristics such as the kerf width and kerf taper. Laser nitrogen cutting of a 3 mm thick AISI 304 stainless steel was performed on a 2.2 kW CO_2 laser cutting system. The laser cutting experiment was planned and conducted according to the Taguchi's experimental design using the L_{27} orthogonal array. From the analysis of means (ANOM), analysis of variance (ANOVA) and signal-to-noise (*S/N*) ratio response tables, the significant laser cutting parameters were identified and subsequently the optimal combination of parameters levels for both kerf quality characteristics were determined. The results showed that the focus position is the most significant parameter affecting the kerf quality characteristics whereas the influence of the assist gas pressure can be neglected. The optimal combination of the laser cutting parameter settings minimized the kerf width and kerf taper to 0.312 mm and 0.83°, respectively. Confirmatory experimental results showed good agreement with predicted results. The results presented in this work confirm the effectiveness of Taguchi's method in optimization of laser cutting process.

Keywords: optimization, Taguchi method, kerf width, kerf taper, laser cutting.

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