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The Cutting Parameter Optimization of CO2 Laser Cutting with Taguchi-Grey Relational Analysis Method

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Acrylic is extensively used in automotive, electronics, and advertising due to its light, transparent, and easily machinable properties. This research aimed to decide the optimal cutting parameters for acrylic in CO2 laser cutting using multi-response optimization via the Taguchi-Grey Relational Analysis (GRA) technique. Four parameters were considered, including laser power, feed rate, nozzle distance, and acrylic thickness. The effects of the four parameters on the surface roughness and dimensional inaccuracy (called responses) were investigated. By employing the Taguchi technique with an L16 orthogonal array and the Grey Relational Analysis (GRA), the optimal cutting parameters could be identified, including a laser power (LP) of 90, feed rate (F) of 10 mm/min, nozzle distance (ND) of 5 mm, and acrylic thickness (T) of 4 mm.

Keywords: Acrylic, Taguchi method, Grey Relational Analysis, CNC Laser Cutting Machine.

1. Introduction

In line with the era of Industrial Revolution 4.0 today, advances in laser technology have been widely adopted in various industries. Laser-cutting technology has been extensively utilized for cutting metals and non-metals. Laser cutting is considered excellent because it provides higher-quality results and proposes cost-saving advantages over other traditional cutting methods. It has the benefits of high precision, speed, reproducibility, and quality. Besides, it is relatively inexpensive and cutting with no contact [1]. Laser cutting works by centering the laser beam on the specimen surface. The heat generated by the centered beam causes the specimen to evaporate, forming the desired features. Subsequently, moving the laser beam will melt the cut material, and an additional gas will remove the melted material from the area [2].

Laser cutting is also capable of working on small shapes by focusing the laser beam in the desired zone. Further, it can be operated on a tiny area, thereby minimizing material loss [3]. There are three types of laser models, including Nd:YAG (Neodymium-Doped Yttrium Aluminium Garnet), carbon dioxide (CO_2), and fiber lasers [4]. Fiber lasers are preferred to cut thick metals. Meanwhile, Nd:YAG and CO_2 lasers, which have lower power, are appropriate for cutting thin materials or non-metals, such as acrylic.

The quality of the laser cutting machine is determined by the surface roughness, suitable geometric dimensions, morphology, and metallurgical characteristics of the cut specimens. The desired quality of the cutting results relies on the selection of the cutting parameters. Research has identified that laser power, cutting speed, laser mode, focal distance, type of additional gas, and pressure are the parameters that most significantly influence the cutting quality [5]-[6]. Hence, finding the optimal combinations of the cutting parameters is crucial to achieving high-quality cutting surfaces with high production rates. Surface roughness, kerf width, hardness, and workpiece are several critical characteristics of the laser cutting process directly related to the cutting parameters [7].

This research begins with the investigations of previous research on the optimization of laser cutting parameters on various materials. It revealed that most of the studies focused on cutting relatively thin metal sheets (≤ 10 mm) [8]-[11]. Meanwhile, non-metals, especially acrylic or Polymethyl-Methacrylate (PMMA), remain rarely used in related studies. The cutting parameters for the laser cutting machine must be analyzed to obtain cutting results with the correct shape and smooth surface roughness. In this study, four cutting parameters were considered, including cutting speed, laser power, nozzle distance, and specimen thickness [12]-[15]. The cutting speed needs to be optimized since high-speed cutting produces imprecise cuts, while the slow speed can potentially damage the specimens. Besides, the heat generated during the cutting process will affect the surface quality of a product and the dimensional accuracy. Hence, two responses to the four cutting parameters were considered in this research, including surface roughness and dimensional accuracy. Overall, this study reported the use of the experimental design using the Taguchi method and Grey Relational Analysis (GRA) approach to determine the optimal cutting parameters of CO_2 laser cutting on acrylic with minimized surface roughness and maximized dimensional accuracy.

2. Methods and Methodology:

a. Tools and Materials

In industries, thicker acrylics are usually cut by computer numerical control (CNC) routers [16]-[18]. Meanwhile, the specimen for the cutting process in this study was acrylics or Polymethyl-Methacrylate (PMMA) with thickness values ranging from 2-5 mm (Figure 4). The tool employed was a CO_2 laser cutting machine controlled by CNC. The mechanical and physical properties of PMMA material, according to the IS14753 (1999) standard, are displayed in Table 1. The physical properties include density (D) and water absorption (WA). The mechanical properties include tensile strength (TS), tensile modulus, tensile elongation (TE), flexural strength (FS), flexural modulus (FM), compressive strength (CS), compressive modulus (CM), hardness (H), and IZOD Notched Impact (NI).

The measurements of each specimen were conducted on three different points with equal intervals, following the Turkkan approach [19]. The results were averaged and recorded as the surface roughness of each specimen. Besides, the dimensional accuracy of the cutting results was examined.

Taguchi is one commonly employed design experiment analysis technique to determine optimal cutting parameters in various numerical and experimental studies [20]-[21]. This method used an orthogonal array (OA) according to the degree of freedom (DOF) determined in the experimental steps.

Based on Table III and Figure 3, the L16 44 orthogonal array was established, indicating that 16 experimental treatments have been performed on four factors and four levels (Table II) to create combinations of cutting parameters. The responses obtained were the surface roughness of the specimen and dimensional accuracy (Table III). The Signal-to-Noise (S/N) ratio and responses are depicted in Table III. The distance between the maximum and minimum S/N ratios indicates the influence of each factor on the responses, as shown in Figures 4 and 5. The results obtained conform to previous research [19].

This research employed the CNC Laser Cutting machine type Z1390 for the experiment. During the cutting process, the machine had laser power percentages of about 80-95%, cutting feed rates of about 6 – 12 mm/min, effective nozzle distances of about 4 – 8 mm, and acrylic thicknesses of about 2 – 5 mm. This parameter setting was the result of various systematic experiments aimed at improving the efficiency and accuracy of the cutting on acrylic materials. By considering variations in the parameters, significant outcomes in cutting acrylic material have been achieved. Further, this research contributes to the development of precision cutting technology, providing a deeper understanding of the influence of cutting parameters on the specimen features.

Figure 1. Z1390 type CO_2 Laser CNC Machine

Table I. Mechanical and physical properties of PMMA material

ASTM or UL test	Properties	Acrylic
PHYSICAL		
D792	D (lb/in³) (g/cm³)	0.043 1.18
D570	WA 24 must (%)	0.3
MECHANICAL		
D638	TS (psi)	8.000 - 11.000
D638	TM (psi)	350.000 - 500.000
D638	TE (%)	2
D790	FS (psi)	12.000 - 17.000
D790	FM (psi)	350.000 - 500.000

D695	CS (psi)	11.000 - 19.000
D695	CM (psi)	-
D785	H	M80 - M100
D256	NI (ft-lb/in)	0.3

b. Experimental Setup

The cutting process using the CO_2 laser machine involved maintaining the nozzle distance between the specimens varied from 4 to 8 mm, utilizing a nozzle diameter of 3 mm, and employing a continuous wave (CW) laser mode. The parameters, including factors and levels used in the cutting process, were based on the initial reviews conducted by the researcher regarding the optimization of cutting parameters on CO_2 laser machines.

After selecting the parameters, the next step was to determine the orthogonal array, which serves as a reference in creating and measuring the specimens. The type of the orthogonal array (OA) from the Taguchi Method was L16. It requires 16 experimental treatments according to the detailed layout of the L16 44 orthogonal array.

After the cutting process, the surface roughness values of the acrylics were estimated with a surface roughness tester (SJ–201P Mitutoyo) (Figure 2a). The results were in the form of Ra value, which is the average deviation from the profile centerline. The dimensional accuracy was measured using a dial caliper (Mitutoyo 505 series) with a precision of 0.02 mm (Figure 2b). Table II presents the cutting parameters, including factors and levels.

(a)

(b)

Figure 2. (a) Roughness surface tester and (b) Dial capiler

Table II. Cutting parameters employed in this study

No	Factor	Name	Units	Levels			
				I	II	III	IV
1	Lasers Power (LP)	A	%	80	85	90	95
2	Feed rate (F)	B	mm/min	6	8	10	12
3	Nozzle Distance (ND)	C	mm	4	5	6	8
4	Thickness (T)	D	mm	2	3	4	5

The results of experiments and measurements are shown in Table III. It shows the influences of the cutting parameters on the values of the responses, including surface area (SA) and dimensional accuracy (DA). Besides, Table III also presents the values of the responses corresponding to Signal-to-Noise (S/N) ratio calculations. Overall, Table III provides a comprehensive overview of the results. Besides, it demonstrates the relationship between the variables and their associated S/N ratios.

Table III. The values of responses and S/N ratios of the acrylics cut with CO_2 cutting laser with varied cutting parameters

	Factor				Responses		S/N Ratios	
Exp. No	LP (%)	F (mm/min)	ND (mm)	T (mm)	SR (μm)	AD (%)	SR (μm)	AD (%)
1	80	6	4	2	0.576	98.645	4.792	39.882
2	80	8	5	3	1.190	98.136	-1.511	39.837
3	80	10	6	4	1.524	98.537	-3.660	39.872
4	80	12	8	5	1.406	98.585	-2.960	39.876
5	85	6	5	4	0.558	98.804	5.067	39.896
6	85	8	4	5	0.846	97.970	1.453	39.822
7	85	10	8	2	1.048	97.567	-0.407	39.786
8	85	12	6	3	0.734	98.438	2.686	39.863
9	90	6	6	5	0.856	98.410	1.351	39.861
10	90	8	8	4	1.222	98.835	-1.741	39.898
11	90	10	4	3	1.138	98.776	-1.123	39.893
12	90	12	5	2	1.390	98.283	-2.860	39.850
13	95	6	8	3	0.876	97.251	1.150	39.758
14	95	8	6	2	0.708	97.603	2.999	39.789
15	95	10	5	5	0.970	98.851	0.265	39.900
16	95	12	4	4	0.740	98.658	2.615	39.883

3. Results: Present the findings of the research paper in this section.

The experimental results were responses, including surface area and dimensional accuracy, obtained from varied laser cutting parameters, specifically laser powers, cutting feed rates, nozzle distances, and acrylic thicknesses. Here, the Taguchi approach was utilized to find the optimal combinations of the cutting parameters that yield superior performance based on the responses obtained.

The results presented in Table III indicate that certain combinations of laser power, feed rate, nozzle distance, and material thickness significantly influenced the overall effectiveness of the cutting process. Besides, the GRA was utilized to quantify the relationships between these parameters and multiple responses. Further, it provides a comprehensive understanding of their interdependencies. Through this approach, the optimal parameters for obtaining laser cutting results with good precision, efficiency, and quality could be identified.

This research discussed the effects of each parameter on various responses, revealing the dynamics of the Taguchi technique combined with GRA for multi-response optimization in laser cutting applications. Additionally, this study can improve our understanding of the relationships in parameters. In addition, this study contributes to the advancement of laser cutting technology, mainly when applied to materials with varying thicknesses, especially in the range of 2 – 5 mm.

The S/N ratios, shown in Table 3 and Figures 3 and 4, were obtained from data processing using Equations (1) and (2). Here, the S/N ratio characteristics of the dimension specimen differed from those of surface roughness and dimensional accuracy responses. "The larger is better" quality characteristic is used for the dimensional response because the largest value is closer to dimensional accuracy. In contrast, the "The smaller is better" quality attribute is utilized for surface roughness response. The selection of quality characteristics aligns with previous research [19]. This occurs because the smallest S/N ratio value obtained and concluded was found in the sample with the smallest surface roughness. Equation (1) presents the S/N ratio for the characteristic 'smaller the better' [19].

$$\sigma_j^i = -10log_{10}\left[\frac{1}{l}\sum_{k=1}^{i}\left({y_{jk}^{i}}^{2}\right)\right].0 \le y_{jk}^{i} < \infty \quad (1)$$

S/N ratio from characteristics large is the better stated as follows:

$$\sigma_j^i = -10log_{10}\left[\frac{1}{l}\sum_{k=1}^{i}\frac{1}{{y_{jk}^{i}}^{2}}\right].0 \le y_{jk}^{i} < \infty \quad (2)$$

Where:

y_{jk}^{i}= value response j-th in the experiment.

Figure 3 depicts the plots of the main influences of S/N on the values of surface roughness with various cutting parameters. It shows that the small S/N ratio is better for providing a graph of the results of surface roughness, the condition that provides the best results. Figure 4 displays the plots of the main effects of S/N ratios on the values of dimensional accuracy with various cutting parameters. It shows that the larger S/N ratio is better to provide a graphical view of the conditions that support improved dimensional accuracy. The results explain the relationship between the selected parameters and the desired response.

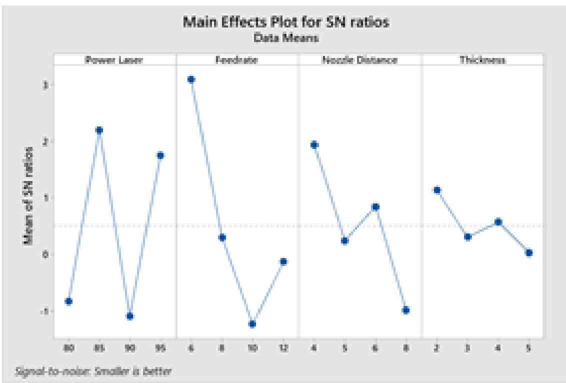

Figure 3. The plots of main effects for S/N ratios of surface roughness

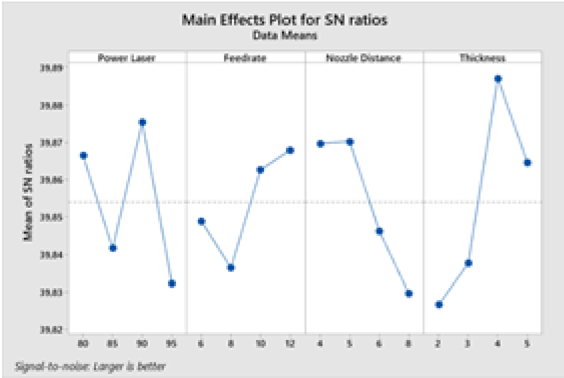

Figure 4. The plots of main effects for S/N ratios of dimensional accuracy

Analysis of Variance (ANOVA) is the statistical approach mostly applied to determine participation ratio and rank parameters according to the analysis results. Here, the ANOVA with a 95% confidence level was used to describe the influence of each cutting parameter on the response (surface roughness and dimensional accuracy). Taguchi technique was employed not only to describe the parameters in multiple responses but also for the GRA method, which was efficiently utilized to determine the relationships among multiple responses. Through the application of this methodology, initially, the performance of response orders underwent a transformation into a comparable order. Additionally, the calculation of the Grey Relational Coefficient (GRC) between all comparable and ideal target orders was performed. Nevertheless, the use of GRC allows for the acceptance of reference orders and comparable orders. Achieving an optimal response becomes possible when the comparison order is transposed to the response with the highest Relational Gray Value (GRG) calculated between the reference and comparable orders.

Before applying GRA, this research normalized the input data using Equation (3). This normalization step was necessary because the desired surface roughness was calculated using Equation (1), and dimensional accuracy was computed via Equation (2). In Equation 3, $minx_i^0(k)$ and $maxx_i^0(k)$ are the minimum and maximum values of $x_i^0(k)$, respectively. $y_i(k)$ points to that normalized mark x^0 also denotes the best-optimized mark.

$$y_i\,(k) = \frac{maxx_i^0(k) - x_i^0(k)}{maxx_i^0(k) - minx_i^0(k)} \qquad (3)$$

After the normalization stage, the GRC was computed via Equations 4 and 5 to determine the connection between real and ideal orders. Determining a factor weight for each response is very important in the GRA method. Nevertheless, it affects the surface roughness and dimensional accuracy of surface cutting quality more significantly than other characteristics. Therefore, weight responses should not be selected without a reasonable quantitative basis for adding or subtracting essential items. In most studies, the weight response generally becomes equivalent [22-26]. ξ denotes the coefficient for identification as 0 . . . 1 and is accepted as 0.5. Δmax and Δmin denote the maximum and the minimum values of Δ_{0i}, respectively. $y_0(k)$ and $y_i(k)$ depict the comparable and reference orders, respectively. Δ_{0i} also denotes the difference between $y_0(k)$ and $y_i\,(k)$.

$$\gamma i(k) = \frac{\Delta min + \xi \Delta max}{\Delta_{oi}(k) + \xi \Delta max} \quad (4)$$

$$\Delta_{oi}(k) = \|y_0(k) - y_i(k)\| \quad (5)$$

In the final step, the GRG values were attained by normalizing the factor weights. The GRC value was between the comparable and reference levels. The highest GRG determines the best optimization of the cutting parameters.

$$GRG = \sum_{k=1}^{n} \omega_k \, \gamma_i(k) \quad (6)$$

In which ω_k shows that each response factor weight is normalized, then $\sum_{k=1}^{n} \omega_k = 1$

In a statistical test, a smaller P value indicates a higher level of significance. In this case, the LP (lasers power) factor achieved the lowest P-value of 0.207, followed by the F (feed rate) factor of 0.229. The values indicate a relatively higher level of significance compared to the P-values for ND (Nozzle distance) (0.449) and T (thickness) (0.949). ANOVA was applied to compute the ratio of the influence factors of each cutting parameter on kerf width and surface roughness (Table 4). The results demonstrated that LP and F were the essential parameters for surface roughness. Accordingly, the order of the vital parameters in surface roughness (SR) was LP > F > ND > T. Further, the results obtained by ANOVA and the Taguchi method were similar for every response.

Table IV. Contribution ratio and ANOVA results on roughness surface.

Factor	DF	Adj SS	Adj MS	F-Value	P-Value	Contri (%)
Lasers Power	3	0.5002	0.166734	2.84	0.207	36.92
Feed rate	3	0.45263	0.150878	2.57	0.229	33.41
Nozzle Distance	3	0.20654	0.068848	1.17	0.449	15.25
Thickness	3	0.01932	0.006439	0.11	0.949	1.43
Error	3	0.17607	0.05869			
Total	15	1.35476				

Table V. Contribution ratio and ANOVA results on dimensional accuracy

Factor	DF	Adj SS	Adj MS	F-Value	P-Value	Contri (%)
Lasers Power	3	0.6292	0.2097	0.59	0.66	17.71
Feed rate	3	0.3075	0.1025	0.29	0.831	22.30
Nozzle Distance	3	0.5944	0.1981	0.56	0.676	18.14
Thickness	3	1.1375	0.3792	1.07	0.477	12.80
Error	3	1.0584	0.3528			
Total	15	3.7271				

Table V presents the results of ANOVA on dimensional accuracy, revealing that the T and LP parameters were essential for dimensional accuracy. Accordingly, the order of importance for dimensional accuracy (AD) was T > LP > ND > F. The material thickness was considered the most crucial parameter, with a P value of 0.477.

The Taguchi and ANOVA results demonstrated that four distinct parameter combinations were necessary to obtain the minimum surface roughness and maximum dimensional accuracy. Nevertheless, optimizing the two parameters simultaneously to obtain cutting results with good quality is very important to simplify the process. GRC of surface roughness (GRC_{SR}) and GRC of dimensional accuracy (GRC_{AD}) were calculated using Equations (3) and (4), and the yields are presented in Table VI.

Table VI. GRC and GRG values for surface roughness and dimensional accuracy

	Factor				GRC		GRG	
Exp. No	LP (%)	F (mm/min)	ND (mm)	T (mm)	SR	AD	Grade	Rank
1	80	6	4	2	0.341	0.797	0.379	10
2	80	8	5	3	0.670	0.529	0.400	9
3	80	10	6	4	1.000	0.720	0.573	1
4	80	12	8	5	0.862	0.752	0.538	3
5	85	6	5	4	0.333	0.945	0.426	7
6	85	8	4	5	0.460	0.477	0.312	14
7	85	10	8	2	0.573	0.384	0.319	13
8	85	12	6	3	0.407	0.661	0.356	12
9	90	6	6	5	0.466	0.646	0.371	11
10	90	8	8	4	0.695	0.981	0.558	2
11	90	10	4	3	0.632	0.915	0.516	4
12	90	12	5	2	0.845	0.586	0.477	6
13	95	6	8	3	0.476	0.333	0.270	15
14	95	8	6	2	0.396	0.391	0.262	16
15	95	10	5	5	0.526	1.000	0.509	5
16	95	12	4	4	0.410	0.806	0.406	8

This study built response graphs for each combined parameter (factor and level) with the help of GRG values. Table VII reveals that the combination of LP1, F3, ND3, and T3 achieved the highest GRG value. Therefore, the next experiment (LP1, F3, ND3, T3) with LP of 80%, F of 10mm/min, ND of 6 mm, and T of 4 mm was the optimal parameters combination to operate the laser cutting machine.

The ANOVA was used to compute the contribution of each parameter to multiple responses. Based on Table VII, laser power (LP) parameters were the most critical variable in multi-response, with an influence value of 36.70%. Thickness (T) and feed rate (F) were the second and third most crucial cutting parameters. Hence, it can be clearly emphasized that the results attained with ANOVA were in line with those obtained with GRG.

Table VII. Results of Grey Relational Grade (GRG) and ANOVA.

Factor	DF	Adj SS	Adj MS	F-Value	P-Value	Contri (%)
Lasers Power	3	0.056811	0.018937	4.15	0.137	36.70649
Feed rate	3	0.035391	0.011797	2.58	0.228	22.86669
Nozzle Distance	3	0.008804	0.002935	0.64	0.637	5.688404
Thickness	3	0.040064	0.013355	2.92	0.201	25.88599
Error	3	0.013701	0.004567			
Total	15	0.154771				

4. Conclusion – Summarize the main outcomes and their significance.

This study employed the Taguchi–GRA technique to determine the optimal cutting parameters of the CO_2 laser cutting machine for cutting acrylic. The technique has been proven to be highly effective in determining optimal cutting parameters. The cutting parameters, which were the factors in the experiments, included laser power, feed rate, nozzle distance, and thickness. Those parameters were studied for their impacts on surface roughness and dimensional accuracy. The optimal cutting parameters resulting from the experiments were as follows: laser power of 80%, feed rate of 10 mm/minute, nozzle distance of 6 mm, and acrylic thickness of 4 mm. The optimal parameters produced the surface roughness (SR) and dimensional accuracy (DA) of 1.524 µm and 98.537%, respectively. The optimal cutting parameters hold the potential to serve as a standard reference for the CO_2 laser cutting industry and researchers. However, further research can be directed towards the development of comprehensive cutting quality monitoring, including surface roughness, dimensional accuracy, and energy consumption. This aims to minimize natural product defects through an improved laser-cutting process.

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