JOURNAL of
MATERIALS and MECHATRONICS:A

e-ISSN 2717-8811
JournalMM, 2023, 4(2), 459-474
https://doi.org/10.55546/jmm.1359453

Araştırma Makalesi / Research Article

Statistical Investigation of the Effect of CO_2 Laser Cutting Parameters on Kerf Width and Heat Affected Zone in Thermoplastic Materials

Oğuzhan DER[1*], Gökhan BAŞAR[2], Muhammed ORDU[3]

[1] Bandırma Onyedi Eylül University, Faculty of Maritime, Department of Marine Vehicles Management Engineering, Balıkesir, Turkey,
ORCID ID: https://orcid.org/0000-0001-5679-2594, oder@bandirma.edu.tr
[2] Osmaniye Korkut Ata University, Faculty of Engineering and Natural Sciences, Department of Industrial Engineering, Osmaniye, Turkey,
ORCID ID: https://orcid.org/0000-0002-9696-7579, gokhanbasar@osmaniye.edu.tr
[3] Osmaniye Korkut Ata University, Faculty of Engineering and Natural Sciences, Department of Industrial Engineering, Osmaniye, Turkey,
ORCID ID: https://orcid.org/0000-0003-4764-9379, muhammedordu@osmaniye.edu.tr

Geliş/ Received: 13.09.2023; **Kabul / Accepted:** 25.10.2023

ABSTRACT: Understanding and optimizing the CO_2 laser cutting process of thermoplastic materials is critical for improving product quality, reducing waste, and achieving efficient manufacturing processes. This study aimed to investigate the effects of a number of input parameters (i.e., material type, power, and cutting speed) on the key output parameters (i.e., kerf width and heat affected zone) in CO_2 laser cutting of thermoplastic materials. The laser cutting process was performed based on the Taguchi L_{18} (2^1x3^2) orthogonal array design. The effects of cutting parameters on the outputs were calculated by using the signal-to-noise (S/N) ratio and analysis of variance (ANOVA) techniques. Furthermore, first and second-degree mathematical models were established by using regression analysis to estimate the values of kerf width and heat affected zone. The optimum laser cutting parameters for kerf width and heat affected zone were determined as and Polyvinyl Chloride (PVC) material type, 80 W power, and 15 mm/s cutting speed. The ANOVA results showed that the most efficient parameter on kerf width was power with 53.99% while the most efficient parameter on heat affected zone was material type with 40.96%. In addition, the coefficient of determination (R^2) values for the regression equations developed for the outputs are significantly high. The R^2 values of the first- and second-degree regression equations for KW are 97.26% and 99.71%, respectively, whereas 93.43% and 98.18% for HAZ.

Keywords: CO_2 Laser Cutting, Kerf Width, Heat Affected Zone, ANOVA, Regression Analysis

*Sorumlu yazar / Corresponding author: oder@bandirma.edu.tr

Bu makaleye atıf yapmak için /To cite this article

Der, O., Başar, G., Ordu, M. (2023). Statistical Investigation of the Effect of CO_2 Laser Cutting Parameters on Kerf Width and Heat Affected Zone in Thermoplastic Materials. Journal of Materials and Mechatronics: A (JournalMM), 4(2), 459-474.

1. INTRODUCTION

Thermoplastic materials, primarily Polyethylene (PE) and Polyvinyl Chloride (PVC), possess a unique combination of properties making them pivotal in numerous applications across diverse industries (Soutis, 2005). PE, characterized by its lightweight, high durability, and resistance to environmental stress, finds broad applications in packaging, agriculture, and the automotive industry (Huda et al., 2008). PVC, on the other hand, stands out for its excellent mechanical strength, chemical resistance, and electrical insulation properties, becoming an essential material in construction, healthcare, and electronics (De Leon et al., 2021). Both PE and PVC are thermoplastics, meaning they can be repeatedly melted and reshaped without losing their material properties, thereby offering extensive reusability and recyclability that contributes significantly to sustainability (Evode et al., 2021).

The application of CO_2 laser cutting for thermoplastics, including PE and PVC, represents a significant advance in manufacturing technology. This technique uses a high-intensity CO_2 laser beam to precisely cut or engrave thermoplastics, resulting in smooth, clean edges with minimal material waste (Der et al., 2022). Due to the non-contact nature of the process, there is significantly reduced mechanical stress on the thermoplastic, preventing deformation and ensuring high-quality finished products. However, process parameters (i.e., laser power, focal position and cutting speed) can significantly influence cutting quality and efficiency, necessitating rigorous process optimization (Der et al., 2019).

Researchers and practitioners focus on two crucial output parameters of CO_2 laser cutting processes: the heat-affected zone (HAZ) and kerf width (KW) (Rajaram et al., 2003). Kerf width, the width of material removed during the cutting process, is an essential factor for precision engineering, as it directly affects the accuracy of the cut and the finish of the product (Jadam et al., 2019). Meanwhile, the HAZ, the area surrounding the cut where the material's properties might have altered due to the heat from the laser, can affect the structural integrity and performance of the final product (You et al., 2020). Therefore, optimizing both kerf width and HAZ through appropriate selection and control of process parameters is of paramount importance in enhancing product quality, reducing material waste, and increasing process efficiency in CO_2 laser cutting of thermoplastics.

There are numerous studies on the machinability of materials, for example, Ordu and Fedai (2021) applied the hybrid MCDM methods to determine the optimum cutting parameters in the milling process of AISI 4140 steel. Fedai et al. (2022) used Gray Relationship Analysis to specify the optimum drilling condition in the drilling process of MWCNTs Reinforced GFRP composites. Ge et al. (2023) aimed to minimize hole damage and increase production efficiency in drilling Carbon-fibre-reinforced-polyetherketonketone (CF/PEKK) composites. Karamimoghadam et al. (2023) investigated the effect of 3D printing and CO_2 laser cutting parameters on the surface morphology of polylactic acid (PLA) material. Petousis et al. (2023) manufactured PLA/CNT (carbon nanotubes) nanocomposites with material extrusion. They increased the shape accuracy and surface quality of nanocomposites by CO_2 laser cutting. Huang et al. (2023) performed fiber laser cutting of glass fiber reinforced plastic (GFRP) materials. They used ANOVA for the effect of cutting parameters on quality characteristics, conducted the regression analysis for the relationship between cutting parameters and quality characteristics, and developed an integrative model to predict and optimize quality characteristics. In a study conducted by Yalçın et al. (2023), the micro-drilling tendencies of Al-PE laminate composites were investigated using the Taguchi L_{16} orthogonal array and ANOVA analyses, focusing on parameters such as thrust force, exit burr height, and hole diameter. Key findings highlighted the significant influence of the tool's point angle on thrust force and burr height, the role of cutting speed in determining hole diameter, and the identification of the fifth experiment as the optimal cutting condition for minimized thrust, burr height, and diameter change. In fact, multi-objective optimization studies are carried out on thermoplastic materials, and it is a remarkable issue in material selection (Ordu and Der, 2023a; Ordu and Der, 2023b). On the other hand, the effect of cutting parameters of thermoplastic materials on a number of outputs was also investigated. For example, the taper kerf on polymethyl methacrylate (PMMA) obtained after laser cutting was examined by using statistical methods (Varsey and Shaikh, 2019). This research delved into the impact of scanning speed, laser power parameters, and the number of sweeping steps by utilizing variance analysis. In another research, exploring the cutting processes using statistical methods was performed (Haddadi et al., 2019). Taguchi method was employed in order to improve the surface quality of microchannels developed by laser cutting process on PMMA materials. An average roughness of 110 nm was achieved by optimizing a number of output parameters (i.e., power parameters, process duration and scanning speed) (Chen et al., 2017). High-density polyethylene pipes were cut and drilled by a CO_2 laser. The study analyzed the influence of the thickness of the workpiece and the laser power on the KW and HAZ (Saleh et al., 2019). Taguchi method was performed for analyzing the impact of input parameters (i.e., laser speed, power and so on) on the surface quality of polycarbonate gears (Gruescu et al., 2012). The findings of studies focussing on laser cutting of fiber-reinforced polymer composites were compiled. Their review pointed out that most research concentrated on HAZ, KW and the depth of the kerf. The findings recommended to select short pulses, low laser intensity, high speed, and pressure to minimize the HAZ (El-Hofy and El-Hofy, 2019). Algorithms were developed to estimate the count of laser scanning steps in laser cutting process on PMMA materials to obtain a certain kerf depth (Varsi and Shaikh, 2018).

In this study, the Taguchi method was used to determine the optimum processing parameters for CO_2 laser cutting of PE and PVC thermoplastic materials. To do this, an experimental setup was developed for laser cutting of the thermoplastic materials. Then, control factors and levels were determined. Material type, power and cutting speed were selected as control factors. Material type is determined as two levels, power and cutting speed are determined as three levels. Taguchi L_{18} experimental design was chosen in accordance with the control factors and levels. KW and HAZ were determined as quality characteristics. First of all, the optimum experimental condition for minimum KW and HAZ was specified by using the Taguchi method. Analysis of variance was then applied to investigate the effect of control factors on quality characteristics. Finally, regression analysis was used to measure the relationship between quality characteristics and control factors. First and second order regression equations were developed through this analysis. Therefore, the results from this study will contribute to determining the appropriate cutting conditions for thermoplastic materials in CO_2 laser cutting processes, providing valuable insights for practitioners in the field.

The remaining of the paper is organized as follows: the thermoplastic materials are introduced, how to the materials were cut by using CO_2 laser machine, and experimental setup and design are described, and the methods (i.e., S/N ratio, ANOVA and regression analyzes) used in this study are explained in Section 2. After that, the findings of the study are presented and discussed in Section 3. Final section concludes the study, respectively.

2. MATERIALS AND METHODS

2.1 Experimental Procedure

Polyethylene (PE) is a high molecular weight thermoplastic polymer derived from the polymerization of ethylene gas under specific conditions (Yu et al., 2006). It is available in several forms based on its density and branching characteristics, with the two most common forms being high-density polyethylene (HDPE) and low-density polyethylene (LDPE). PE is known for its excellent chemical resistance, low moisture absorption, and high impact resistance. Its flexible and durable nature makes it ideal for a range of applications, from film and sheeting to piping and containers. However, PE also has a relatively low softening point, which necessitates careful handling during laser cutting processes to avoid unnecessary melting or deformation (Choudhury and Shirley, 2010).

Polyvinyl Chloride (PVC), on the other hand, is a thermoplastic composed of 57% chlorine and 43% carbon, obtained from ethylene and chlorine gas (Oberoi and Malik, 2022). PVC is available in two primary forms: rigid and flexible, the latter achieved through the addition of plasticizers (Rahman and Brazel, 2006). Notable for its high tensile strength, flame retardancy, and excellent electrical insulation properties, PVC is a prevalent material in construction, electrical, and healthcare applications. In terms of laser cutting, PVC poses some challenges as it releases hydrochloric acid upon heating, which can corrode equipment and poses health risks. Therefore, handling PVC in laser-cutting processes demands careful consideration of safety measures and protective equipment (Akovali, 2012).

A number of properties (i.e., physical, thermal and mechanical) of materials plays an important role in determining their suitability for laser-cutting operations. Physical properties such as density and melting point can greatly influence the cutting process and the resultant product's quality. Density refers to the mass per unit volume, dictating how much material is present in a given volume, which can affect the material's behavior under the laser. The melting point, the temperature at which a material transitions from a solid to a liquid state, also significantly impacts the laser-cutting process, particularly for thermoplastics. Mechanical properties reflect a material's response to an applied force. For example, Tensile strength is known as the maximum stress which a material is able to resist without failing during pulling or stretching whereas Young's Modulus represents a measure the material's stiffness or its resistance to elastic deformation. Both properties are essential for laser cutting as they influence the material's reaction to stress and deformation. Thermal properties describe how a material responds to temperature changes and its interaction with heat. A material's thermal conductivity, indicating its ability to conduct heat, can greatly affect the precision of the cut and the size of the heat-affected zone (HAZ) in the laser cutting process (Callister, 1991). Table 1 demonstrates the mechanical, physical, and thermal characteristics of PE and PVC.

Tests were performed using a laser setup, which included a 100 W CO_2 laser from the LazerFix LF7010 Laser Cutting Machine. The system was also equipped with a CNC-controlled table that operates on three axes and provides a workspace of 70 cm x 100 cm x 20 cm, as shown in Figure 1.

Before beginning the laser cutting process, the PE and PVC material must be properly prepared. This typically involves cleaning the material surface to remove any dust or contaminants that could potentially interfere with the laser beam. The design to be cut into the thermoplastic is input into the laser cutter's computer system. This design was developed by computer-aided design (CAD) software. The design is then processed and interpreted by the machine's software.

Table 1. The properties of PE and PVC (Fleck et al., 2010)

Property	Unit	PE	PVC
Density	(g/cm³)	0.95	1.45
Thermal Conductivity	(W/m.K)	0.42	0.22
Tensile Strength	(MPa)	33	53
Young's Modulus	(GPa)	0.76	3.1
Elongation at Break	(%)	150	30
Melting Point	(°C)	125	88

Figure 1. LazerFix LF7010 laser cutting machine

Figure 2 presents a comprehensive illustration of a laser-cutting operation on polymeric materials, detailing various geometric patterns. The data derived from these cuttings were scrutinized to quantify the HAZ. In the same figure, to evaluate the kerf width - a critical parameter in cutting - a component was sliced. This procedure entailed making a linear incision on a rectangular plate with dimensions of 10 mm x 100 mm, facilitating the assessment of kerf widths against nine distinct parameters.

Given the specific material properties of PE and PVC, the laser cutter's settings must be properly adjusted. This typically entails setting the laser power, cutting speed, and the focal point of the laser. These settings are pivotal in achieving precision in the cut and minimizing the HAZ. For this purpose, an optimum focal point of 7 mm for the laser was selected. Before the main cut, it is generally advised to conduct a test cut on a small sample piece to verify the suitability of the machine settings for the particular material and thickness. Upon fine-tuning the machine settings, the actual cutting process is initiated. The laser beam follows the path specified by the input design, cutting the material precisely. The high-intensity laser beam rapidly heats the thermoplastic, leading to vaporization and thereby creating a cut. Once the laser cutting process is completed, the cut piece is left to cool down. Any remaining debris from the cutting process can subsequently be removed. The edges of the cut are typically smooth, due to the laser cutting process, but further post-processing (like edge polishing) can be undertaken if necessary. However, since a highly successful cut was achieved in this study, no additional post-processing was required.

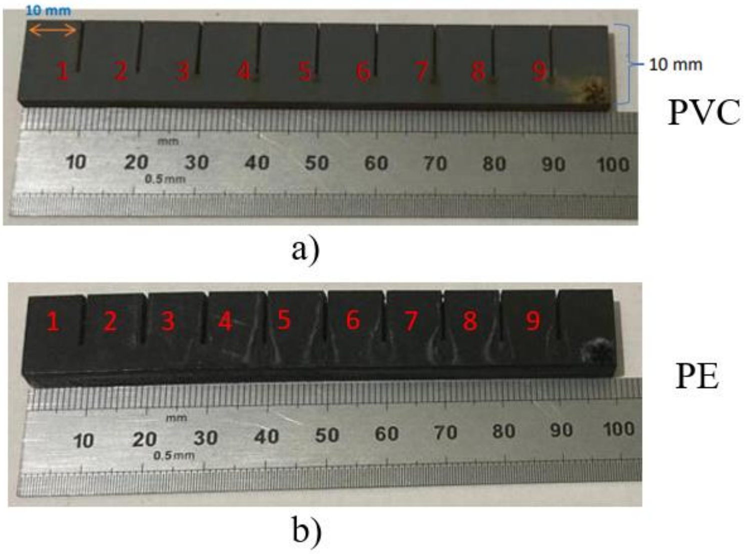

Figure 2. Thermoplastic materials used in the experiments, a) PVC, b) PE

2.2 Kerf Width and Heat-Affected Zone Measurements

The kerf width and heat-affected zone resulting from laser cutting of thermoplastic materials were measured using a computer-connected Dino-Lite AM4113T digital microscope. The measurements were performed using the Dino Capture 2.0 software, and images were captured at a magnification of 55x. The digital microscope and the areas where the measurements were taken are illustrated in Figure 3.

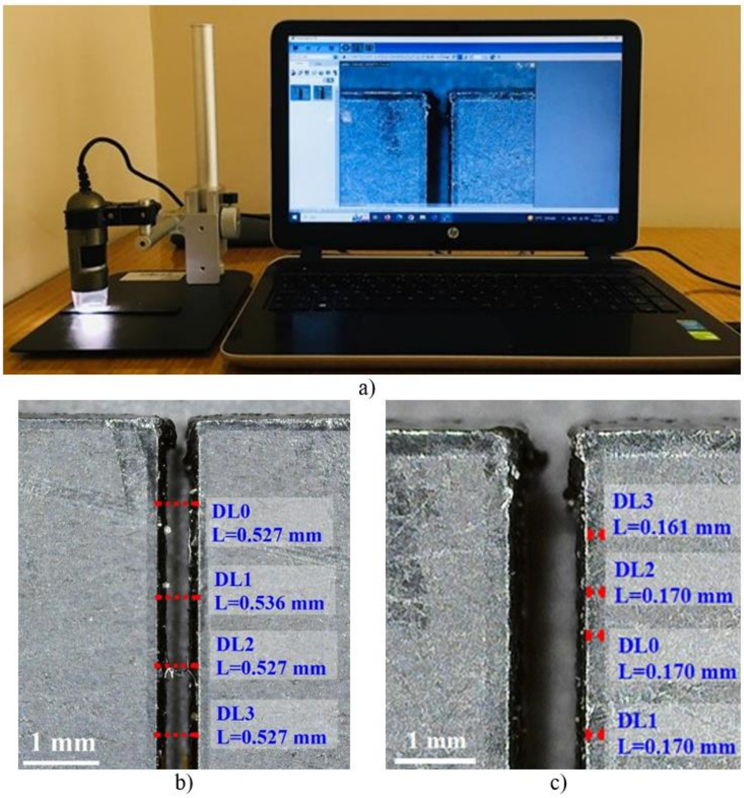

Figure 3. Measurement setup: a) Digital microscope, b) Kerf width measurement, c) Heat Affected Zone measurement.

2.3 Experimental Design Using the Taguchi Method

In the laser cutting of thermoplastic materials, the control factors are selected as cutting speed, material type and power, whereas the quality characteristics are considered as KW and HAZ. The effects of control factors on quality characteristics have been determined using the Taguchi method. In the experiments, the most suitable orthogonal array L_{18} (2^1x3^2) was used, taking into account the total degrees of freedom of the control factors (Roy, 1990). The Taguchi method enables the optimizing the quality characteristics while determining the optimal experimental condition (Roy, 1990; Bilge et al., 2017). Based on the studies carried out in the literature, the appropriate levels of the control factors have been specified and are given in Table 2.

Table 2. Control factors and levels.

Control factors	Symbol	Level 1	Level 2	Level 3
Material type	MT	PE	PVC	-
Power (W)	P	80	90	100
Cutting speed (mm/s)	Vc	5	10	15

In order to achieve low KW and HAZ values in the CO_2 laser cutting of thermoplastic materials, the dependent variable, which is the quality characteristic, was calculated using the signal-to-noise (S/N) ratio in dB according to the "smaller is better" approach, as shown in Equation (1) (Özlü, 2021).

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

n means the number of experiments, and y_i represents the i-th observed response for each data point (Motorcu and Ekici, 2016). The effects of each level of the control factors on KW and HAZ were analyzed using the S/N ratios. Additionally, the contribution ratios of the control factors to the quality characteristics were calculated with the help of analysis of variance (ANOVA). The ANOVA tests were conducted at a 95% confidence level. Finally, first and second-degree regression equations were established for estimating KW and HAZ.

3. RESULTS AND DISCUSSION

3.1 Signal-to-Noise (S/N) Ratio Analysis

The cutting process of thermoplastic materials using a CO_2 laser was conducted based on the Taguchi L_{18} orthogonal array. The effects of cutting parameters on output parameters (i.e., KW and HAZ) were investigated. Signal-to-Noise (S/N) analysis was preferred to determine the optimal levels of the control factors. In this study, the "Smaller is better" objective function was selected to achieve higher product quality and lower costs for KW and HAZ. Equation (1) gives the calculation of the S/N ratios for KW and HAZ. The measured KW and HAZ values along with the calculated S/N ratios are given in Table 3 for the laser cutting experiments. The average KW and HAZ values obtained from the laser cutting process are calculated as 0.460 mm and 0.132 mm, respectively. In addition, the average S/N ratios for KW and HAZ values are obtained as 6.812 dB and 17.661 dB, respectively.

An S/N response table was used to analyze the effects of each control factor on KW and HAZ. The calculated S/N ratios for each level of the control factors for KW and HAZ are provided in Table 4. The optimal cutting parameters for the lowest KW and HAZ values are indicated by the levels with the highest S/N ratios in Table 4. From these results, the cutting parameters determined for the lowest

KW and HAZ values are MT (Level 2, S/N=7.320 dB and S/N=7.320 dB), P (Level 1, S/N= 7.934 dB and S/N=18.29 dB), and Vc (Level 3, S/N=7.428 dB and S/N=18.56 dB). The lowest KW and HAZ values were measured as 0.346 mm and 0.097 mm, respectively, under conditions where the material type was PVC, the power was 80 W, and the cutting speed was 15 mm/s. The S/N ratio graphs for the control factors of KW and HAZ in the laser cutting process are shown in Figures 4 and 5, respectively.

Table 3. Experimental results and S/N ratios.

Experiment number	Control factors			KW (mm)	S/N ratio for KW (dB)	HAZ (mm)	S/N ratio for HAZ (dB)
	Material type	Power (W)	Cutting speed (mm/s)				
1	PE	80	5	0.466	6.632	0.156	16.138
2	PE	80	10	0.419	7.556	0.136	17.329
3	PE	80	15	0.402	7.915	0.122	18.273
4	PE	90	5	0.538	5.384	0.164	15.703
5	PE	90	10	0.491	6.178	0.139	17.140
6	PE	90	15	0.462	6.707	0.125	18.062
7	PE	100	5	0.569	4.898	0.167	15.546
8	PE	100	10	0.530	5.514	0.151	16.420
9	PE	100	15	0.504	5.951	0.135	17.393
10	PVC	80	5	0.418	7.576	0.115	18.786
11	PVC	80	10	0.367	8.707	0.113	18.938
12	PVC	80	15	0.346	9.218	0.097	20.265
13	PVC	90	5	0.488	6.232	0.128	17.856
14	PVC	90	10	0.435	7.230	0.125	18.062
15	PVC	90	15	0.413	7.681	0.110	19.172
16	PVC	100	5	0.516	5.747	0.143	16.893
17	PVC	100	10	0.479	6.393	0.130	17.721
18	PVC	100	15	0.442	7.092	0.123	18.202

Table 4. S/N response table for KW and HAZ.

Levels	Control factors					
	KW			HAZ		
	MT	P	Vc	MT	P	Vc
1	6.304	**7.934***	6.078	16.89	**18.29***	16.82
2	**7.320***	6.569	6.930	**18.43***	17.67	17.60
3	-	5.933	**7.428***		17.03	**18.56***
Delta	1.015	2.002	1.349	1.54	1.26	1.74
Rank	3	1	2	2	3	1

***** The significant parameter

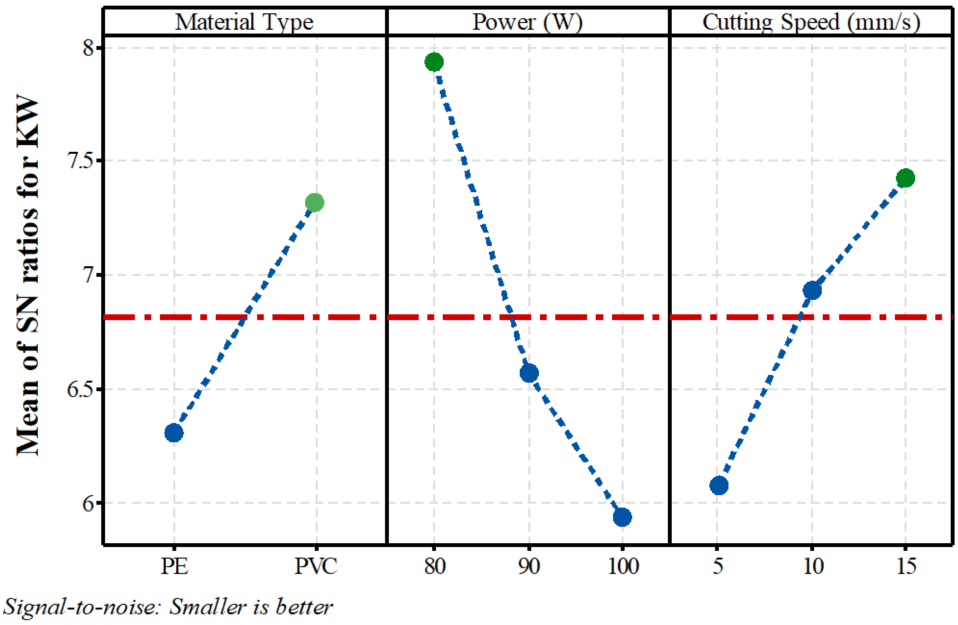

Figure 4. The effects of input parameters on average S/N ratio for KW

The differences in KW and HAZ during CO_2 laser cutting of PVC and PE thermoplastics can be attributed to their unique thermal properties, absorption properties, and melt characteristics. PVC's lower melting point allows for easier cutting, which can potentially result in a narrower KW and smaller HAZ. PVC's ability to absorb CO_2 laser wavelength more effectively than PE due to the presence of chlorine atoms also contributes to more efficient cutting. Lastly, PVC vaporizes rather than melts at its decomposition temperature, leading to cleaner material removal and thus a narrower kerf and lesser HAZ. On the other hand, PE's less efficient absorption of the CO_2 laser wavelength and its tendency to melt rather than vaporize may lead to a wider kerf and larger HAZ.

Our analysis indicated that the minimum KW, referring to the width of the material removed by the laser cut, is obtained under certain conditions - specifically, the minimum laser power and the maximum cutting speed. At low laser power, the heat generated is less intense, hence, inducing less melting and a narrower kerf. Simultaneously, a higher cutting speed guarantees swift movement of the laser, limiting heat accumulation and thereby resulting in a narrower KW (Moradi et al., 2017).

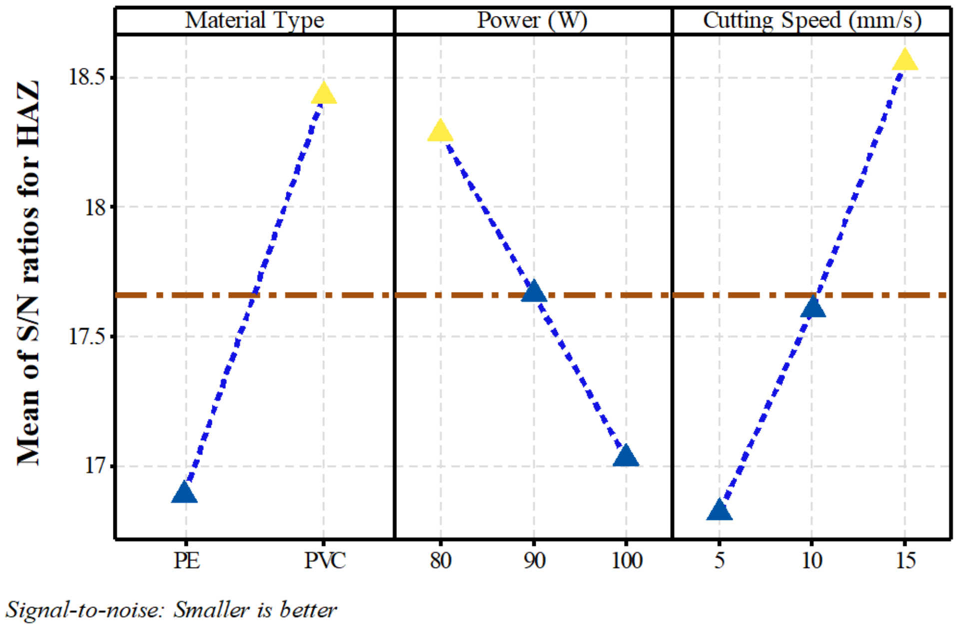

Figure 5. The effects of input parameters on average S/N ratio for HAZ

On the other hand, we discovered a key relationship between the laser power, cutting speed, and the size of the HAZ - an area of material with altered properties due to the heat of the laser. The size of the HAZ and laser power are directly proportional to each other, meaning the greater the laser power, the larger the HAZ. This relationship signifies that an increase in laser power expands the material area affected by heat. However, the HAZ and cutting speed are inversely proportional to each other. This suggests that a faster cutting speed results in a smaller HAZ. A higher cutting speed reduces the dwell time of the laser on the material, leading to less heat spread and subsequently a reduction in the HAZ size (Choudhury and Shirley, 2010; Moradi et al., 2017).

The most advantageous conditions for both minimizing the HAZ and achieving the narrowest KW in our study were determined to be a PVC material type, a laser power of 80 W and a cutting speed of 15 mm/s.

3.2 Analysis of Variance

Analysis of variance (ANOVA) was employed for determining the contribution ratios of the control factors on KW and HAZ in the CO_2 laser cutting experiments. The ANOVA test was performed within a confidence level of 95% and the results are tabulated in Table 5.

In case of the P-value is less than 0.05, it indicates statistical significance, meaning that the control factors are considered statistically significant. Otherwise, it suggests a lack of statistical significance (Akkuş and Yaka, 2018). The control factor that has the greatest impact on the output is determined by considering the largest F-value in the ANOVA test results (Yaka, 2021). The contribution rates (%) obtained from the ANOVA test results illustrated in Figure 6. Accordingly, the percentage contributions of material type, power, and cutting speed on KW were calculated as 20.49%, 53.99%, and 25.18%, respectively. Additionally, the contribution percentages of material type, power, and cutting speed on HAZ were computed as 40.96%, 16.71%, and 35.78%, respectively. According to the ANOVA results, power was found to have the highest influence on KW with a contribution percentage of 53.99%, whereas material type had the highest influence on HAZ with a contribution percentage of 40.96%. Additionally, the low error values for KW and HAZ (i.e., 0.34% and 6.55%, respectively) indicate that the experimental study yielded significant results.

Table 5. ANOVA results for KW and HAZ.

Variance Source	Degree of Freedom	Sum of Squares	Mean Square	F Ratio	P Value
			KW		
MT	1	0.012641	0.012641	725	0
P	2	0.033307	0.016654	955.18	0
Vc	2	0.015536	0.007768	445.55	0
Error	12	0.000209	0.000017		
Total	17	0.061694			
R^2: 99.66					
			HAZ		
MT	1	0.002473	0.002473	75.06	0
P	2	0.001009	0.000505	15.31	0
Vc	2	0.002160	0.001080	32.78	0
Error	12	0.000395	0.000033		
Total	17	0.006039			
R^2: 93.45					

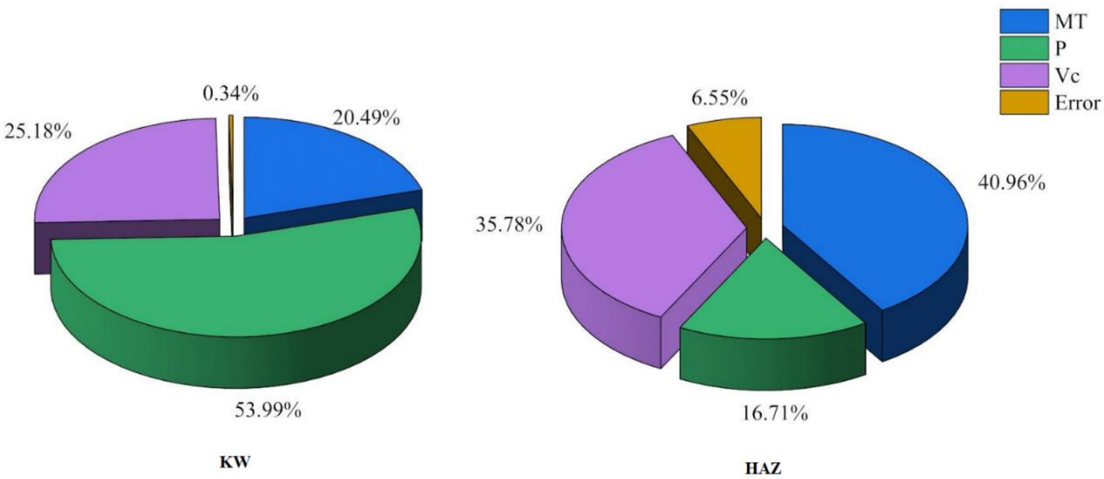

Figure 6. The contribution rates (%)

3.3 Regression Analysis

Regression analysis helps to mathematically express the relationship between dependent and independent variables (Basar et al., 2018). In this study, first and second-degree regression equations were developed for KW and HAZ. In laser cutting process, the independent variables are material type, power, and cutting speed, whearas the dependent variables are KW and HAZ. In Table 6, the first and second-degree regression equations for estimated KW based on the material type are given as Equation (2)-(3) and (4)-(5). In Table 7, the regression equations for estimated HAZ based on the material type are shown as Equation (6)-(7) and (8)-(9), respectively. The determination coefficients (R^2) obtained from the first and second-degree regression equations for KW were calculated as 97.26% and 99.71%. Furthermore, the R^2 obtained from the regression equations for HAZ are determined as 93.43% and 98.18% respectively.

Table 6. Regression equations for KW.

First Degree Regression Equations		
Material Type		
PE	$KW = 0.0913 + 0.005183 \cdot P - 0.0071 \cdot Vc$	(2)
PVC	$KW = 0.0383 + 0.005183 \cdot P - 0.0071 \cdot Vc$	(3)
R^2: 97.26		
Second Degree Regression Equations		
PE	$KW = -1.204 + 0.03474 \cdot P - 0.01429 \cdot Vc - 0.000163 \cdot P^2 + 0.000407 \cdot Vc^2 - 0.000007 \cdot P \cdot Vc$	(4)
PVC	$KW = -1.237 + 0.03458 \cdot P - 0.01483 \cdot Vc - 0.000163 \cdot P^2 + 0.000407 \cdot Vc^2 - 0.000007 \cdot P \cdot Vc$	(5)
R^2: 99.71		

Table 7. Regression equations for HAZ.

First Degree Regression Equations		
Material Type		
PE	$HAZ = 0.0882 + 0.000917 \cdot P - 0.002683 \cdot V_c$	(6)
PVC	$HAZ = 0.0648 + 0.000917 \cdot P - 0.002683 \cdot V_c$	(7)
R^2: 93.43		
Second Degree Regression Equations		
PE	$HAZ = 0.160 - 0.00025 \cdot P - 0.0033 \cdot V_c + 0.000005 \cdot P^2 - 0.00001 \cdot V_C^2$	(8)
PVC	$HAZ = 0.072 - 0.00028 \cdot P - 0.00167 \cdot V_c + 0.000005 \cdot P^2 - 0.00001 \cdot V_C^2$	(9)
R^2: 98.18		

4. CONCLUSION

In this experimental study, the effects of cutting parameters, including material type, cutting speed, and power on the kerf width (KW) and heat-affected zone (HAZ) of 2 mm thick thermoplastic materials using a CO_2 laser were investigated. The aim was to determine the optimum levels of cutting parameters for achieving minimum KW and HAZ. Furthermore, the contribution ratios of the control factors on the quality characteristics were specified by using variance analysis. Finally, mathematical equations for the estimation of KW and HAZ were obtained using regression analysis. The results obtained are presented below:

• According to the experimental results, it was observed that the kerf width ranged from 0.569 mm to 0.346 mm, whereas the heat affected zone ranged from 0.167 mm to 0.097 mm.

• The optimum laser cutting parameters for achieving the lowest KW and HAZ were determined to be PVC material type, 80W power, and 15 mm/s cutting speed.

• The measured values for the KW and HAZ, obtained from the optimum laser cutting parameters, were 0.346 mm and 0.097 mm, respectively.

• The highest values for the KW and HAZ were obtained with the PE material type, 100 W power, and 5 mm/s cutting speed.

• It was determined that the measured values of KW and HAZ for the PVC material were lower than those for the PE material under all experimental conditions.

• It was found that the KW and HAZ decrease with decreasing power and increasing cutting speed.

• According to the ANOVA results, the contribution percentages of the laser cutting parameters on KW were determined as follows: power (53.99%), cutting speed (25.18%), and material type (20.49%).

• In the ANOVA results for HAZ, the contribution percentages of the laser cutting parameters were determined as follows: material type (40.96%), cutting speed (35.78%), and power (16.71%).

• The coefficient of determination (R^2) values for the first and second-degree regression equations for KW were obtained as 97.26% and 99.71%, respectively.

• The R^2 values for the first and second-degree regression equations for HAZ were determined as 93.43% and 98.18%, respectively.

• It was determined that the cutting parameters identified are more suitable for the CO_2 laser cutting of PVC material.

Building on the findings of this study, future research could delve into exploring the effects of other variables such as laser beam diameter, focal point settings, and gas pressure on KW and HAZ. It would also be intriguing to investigate how varying material thicknesses might influence the observed outcomes, and whether other thermoplastic materials exhibit similar or contrasting behaviors under CO_2 laser cutting. Additionally, an extended exploration into the environmental impact of using different cutting parameters and their implications for waste and energy consumption might offer valuable insights for sustainable manufacturing practices. In essence, while this study has unveiled key relationships between certain parameters and laser cutting results, the arena of laser cutting is vast and teeming with myriad opportunities for further exploration.

5. ACKNOWLEDGEMENTS

This work has been supported by Osmaniye Korkut Ata University Scientific Research Projects Coordination Unit under grant number #OKUBAP-2022-PT1-003.

6. CONFLICT OF INTEREST

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

7. AUTHOR CONTRIBUTION

All authors have equal contributions to the study.

8. REFERENCES

Akkuş H., Yaka H. Optimization of Turning Process by Using Taguchi Method. Sakarya Üniversitesi Fen Bilimleri Enstitüsü Dergisi 22 (5), 1444-1448, 2018.

Akovali G. Plastic Materials: Polyvinyl Chloride (PVC). In Toxicity of Building Materials. Woodhead Publishing, Sawston, UK, pp. 23-53, 2012.

Basar G., Kirli Akin H., Kahraman F., Fedai Y. Modeling and Optimization of Face Milling Process Parameters for AISI 4140 Steel. Tehnički Glasnik 12 (1), 5-10, 2018.

Bilge T., Motorcu A.R., Ivanov A. Kompakt Laminat Kompozit Malzemenin Tungsten Karbür Takımlarla Delinmesinde Delaminasyon Faktörünün Değerlendirilmesi. Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi 23 (4), 427-436, 2017.

Callister W.D. Materials Science and Engineering: An Introduction, 2nd Edition, Jr John Wiley & Sons, New York, 1991.

Chen X., Li T., Zhai K., Hu Z., Zhou M. Using Orthogonal Experimental Method Optimizing Surface Quality of CO_2 Laser Cutting Process for PMMA Microchannels. The International Journal of Advanced Manufacturing Technology 88, 2727-2733, 2017.

Choudhury I.A., Shirley S. Laser Cutting of Polymeric Materials: An Experimental Investigation. Optics & Laser Technology 42 (3), 503-508, 2010.

De Leon A.C., Da Silva Í.G., Pangilinan K.D., Chen Q., Caldona E.B., Advincula R.C. High Performance Polymers for Oil and Gas Applications. Reactive and Functional Polymers 162, 104878, 2021.

Der O., Edwardson S., Bertola V. Manufacturing Low-Cost Fluidic and Heat Transfer Devices with Polymer Materials by Selective Transmission Laser Welding. In Encyclopedia of Materials: Plastics and Polymers. Elsevier; 2022.

Der O., Edwardson S., Marengo M., Bertola V. Engineered Composite Polymer Sheets with Enhanced Thermal Conductivity. IOP Conference Series: Materials Science and Engineering 613 (1), 012008, 2019.

El-Hofy M.H., El-Hofy H. Laser Beam Machining of Carbon Fiber Reinforced Composites: A Review. The International Journal of Advanced Manufacturing Technology 101 (9-12), 2965-2975, 2019.

Evode N., Qamar S.A., Bilal M., Barceló D., Iqbal H.M. Plastic Waste and Its Management Strategies for Environmental Sustainability. Case Studies in Chemical and Environmental Engineering 4, 100142, 2021.

Fedai Y., Basar G., Kirli Akin H. Multi-Response Optimization in Drilling of MWCNTs Reinforced GFRP Using Grey Relational Analysis. Tehnički Vjesnik 29 (3), 742-751, 2022.

Fleck N.A., Deshpande V.S., Ashby M.F. Micro-Architectured Materials: Past, Present and Future. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 466 (2121), 2495-2516, 2010.

Ge J., Zhang W., Luo M., Catalanotti G., Falzon B.G., Higgins C., Zhang D., Jin Y., Sun D. Multi-Objective Optimization of Thermoplastic CF/PEKK Drilling Through a Hybrid Method: An Approach Towards Sustainable Manufacturing. Composites Part A: Applied Science and Manufacturing 167, 107418, 2023.

Gruescu C.M., Ionescu C.L., Nicoara I., Lovasz A. Experimental Optimization of Process Parameters in Laser Cutting of Polycarbonate Gears. Mechanics 18 (2), 233-238, 2012.

Haddadi E., Moradi M., Ghavidel A.K., Ghavidel A.K., Meiabadi S. Experimental and Parametric Evaluation of Cut Quality Characteristics in CO_2 Laser Cutting of Polystyrene. Optik 184, 103-114, 2019.

Huang S., Fu Z., Liu C., Li J. Multi-Objective Optimization of Fiber Laser Cutting Quality Characteristics of Glass Fiber Reinforced Plastic (GFRP) Materials. Optics & Laser Technology 167, 109720, 2023.

Huda M.S., Drzal L.T., Ray D., Mohanty A.K., Mishra M. Natural-Fiber Composites in the Automotive Sector. In Properties and Performance of Natural-Fibre Composites, Woodhead Publishing, Sawston, UK, pp. 221-268, 2008.

Jadam T., Datta S., Masanta M. Study of Surface Integrity and Machining Performance During Main/Rough Cut and Trim/Finish Cut Mode of WEDM on Ti–6Al–4V: Effects of ire Material. Journal of the Brazilian Society of Mechanical Sciences and Engineering 41, 1-23, 2019.

Karamimoghadam M., Dezaki M.L., Zolfagharian A., Bodaghi M. Influence of Post-Processing CO_2 Laser Cutting and FFF 3D Printing Parameters on the Surface Morphology of PLAs: Statistical Modelling and RSM Optimisation. International Journal of Lightweight Materials and Manufacture 6 (2), 285-295, 2023.

Moradi M., Mehrabi O., Azdast T., Benyounis K.Y. Enhancement of Low Power CO_2 Laser Cutting Process for Injection Molded Polycarbonate. Optics & Laser Technology 96, 208-218, 2017.

Motorcu A.R., Ekici E. Al/B4C Kompozitlerin Karbür Matkaplarla Delinmesinin Değerlendirilmesi. Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi 22 (4), 259-66, 2016.

Oberoi S., Malik M. Polyvinyl Chloride (PVC), Chlorinated Polyethylene (CPE), Chlorinated Polyvinyl Chloride (CPVC), Chlorosulfonated Polyethylene (CSPE), Polychloroprene Rubber (CR)—Chemistry, Applications and Ecological Impacts - I. In: Malik, J.A., Marathe, S. (eds) Ecological and Health Effects of Building Materials. Springer, Cham, pp. 33-52, 2022.

Ordu M., Der O. Polymeric Materials Selection for Flexible Pulsating Heat Pipe Manufacturing Using a Comparative Hybrid MCDM Approach. Polymers 15 (13), 2933, 2023a.

Ordu M., Der O. Yeşil Üretim İçin Çevresel Etki Temelli Termoplastik Malzeme Seçimi: Karşılaştırmalı Bir Hibrid ÇKKV Yaklaşımı. Erciyes Üniversitesi Fen Bilimleri Enstitüsü Dergisi 39 (1), 100-115, 2023b.

Ordu M., Fedai Y. A Novel Decision Support System Based on Fuzzy Multi Criteria Decision Making for Optimizing Machining Parameters. Journal of Engineering Research 2021.

Özlü B. St-37 Malzemesinin Lazer Kesiminde İşleme Parametrelerinin Deneysel ve İstatiksel Olarak İncelenmesi. Fırat Üniversitesi Mühendislik Bilimleri Dergisi 33 (1), 161-71, 2021.

Petousis M., Ninikas K., Vidakis N., Mountakis N., Kechagias J.D. Multifunctional PLA/CNTs Nanocomposites Hybrid 3D Printing Integrating Material Extrusion and CO_2 Laser Cutting. Journal of Manufacturing Processes 86, 237-252, 2023.

Rahman M., Brazel C.S. Ionic Liquids: New Generation Stable Plasticizers for Poly (Vinyl Chloride). Polymer Degradation and Stability 91 (12), 3371-3382, 2006.

Rajaram N., Sheikh-Ahmad J., Cheraghi S.H. CO_2 Laser Cut Quality of 4130 Steel. International Journal of Machine Tools and Manufacture 43 (4), 351-358, 2003.

Roy R.K. A Primer on the Taguchi Method. Competitive Manufacturing Series. 1st ed., Van Nostrand Reinhold, New York, USA, 1990.

Saleh S.J., Qaisy A., Karataş C. Laser Cutting of High Density Polyethylene (Hdpe) Pipes Pe100 Using CO_2 Gas Laser. International Journal of Engineering and Advanced Technology (IJEAT) 9 (1), 6193–6199, 2019.

Soutis C. Carbon Fiber Reinforced Plastics in Aircraft Construction. Materials Science and Engineering: A 412 (1-2), 171-176, 2005.

Varsey A.M., Shaikh A.H. Experimental and Statistical Study on Kerf Taper Angle During CO_2 Laser Cutting of Thermoplastic Material. Journal of Laser Applications 31 (3), 032010, 2019.

Varsi A.M., Shaikh A.H. Developing an Algorithm for Predicting Depth as well as Number of Passes During CO_2 Laser Machining on Thermoplastic Material. Journal of Laser Applications 30 (4), 042007, 2018.

Yaka H. Tornalama Sonrası Çıkan Talaşlardan Elde Edilen Alüminyum 5000 Alaşımının Yüzey Pürüzlülüğünün Taguchi Yöntemi ile Analizi. Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi 11 (1), 464-473, 2021.

Yalçın B., Yüksel A., Aslantaş K., Der O., Ercetin A. Optimization of Micro-Drilling of Laminated Aluminum Composite Panel (Al–PE) Using Taguchi Orthogonal Array Design. Materials 16 (13), 4528, 2023.

You K., Yan G., Luo X., Gilchrist M.D., Fang F. Advances in Laser Assisted Machining of Hard and Brittle Materials. Journal of Manufacturing Processes 58, 677-692, 2020.

Yu L., Dean K., Li L. Polymer Blends and Composites from Renewable Resources. Progress in Polymer Science 31 (6), 576-602, 2006.