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Experimental Analysis of Kerf Width in CO_2 Laser Cutting of PMMA Using a Full Factorial Design

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Abstract— **This paper presents an experimental investigation of the influence of process parameters in CO_2 laser cutting of polymethyl methacrylate (PMMA) material on kerf width. Laser power, cutting speed, and focal position were considered as the key process parameters. The experimental study was conducted using a full factorial experimental design 2^3, which enables simultaneous analysis of main effects and interactions among the investigated factors with a relatively small number of experimental trials. Kerf width was measured using a digital optical microscope, and the obtained experimental data were statistically processed to ensure the reliability of the results. Based on the experimental data, an empirical mathematical model describing the dependence of kerf width on the process parameters was developed. The results indicate that focal position has a dominant influence on kerf width, while laser power and cutting speed exhibit significant corrective effects. The developed mathematical model shows a high level of agreement with the experimental data and can be used for the analysis and optimization of the CO_2 laser cutting process of PMMA material within the investigated domain.**

Keywords— ***CO_2 laser cutting, PMMA, kerf width, design of experiments, mathematical modeling***

I. INTRODUCTION

Laser cutting represents one of the most significant non-conventional material processing technologies, which has undergone intensive development and widespread application in modern manufacturing systems over the past decades. Compared to conventional machining processes, laser cutting enables high precision, narrow kerf width, good dimensional accuracy, and a minimal heat-affected zone, while eliminating mechanical contact between the tool and the material [1]. These characteristics make laser cutting particularly suitable for automated and flexible manufacturing systems, where a high level of repeatability and process stability is required, especially in serial and mass production conditions [1]. In this context, control of the geometric characteristics of the cut represents one of the key requirements, as it directly affects product quality, the need for additional post-processing, and the overall efficiency of the manufacturing process [1].

CO_2 laser cutting has particular importance in industrial practice, especially in the processing of non-metallic materials. CO_2 lasers emit radiation with a wavelength of 10.6 μm, which is characterized by high absorption in most polymeric materials, enabling efficient melting and vaporization of the material with relatively good cut edge quality [1], [2]. Due to these characteristics, CO_2 lasers are widely applied in the processing of plastics, wood, composites, and similar materials [2]. An additional reason for the extensive industrial application of CO_2 laser cutting is its ability to ensure stable processing of various non-metallic materials with relatively simple adjustment of process parameters. This flexibility enables the use of CO_2 lasers in the production of parts with different geometries, thicknesses, and functional purposes, while cut quality remains one of the primary criteria for process performance [2], [3].

Polymethyl methacrylate (PMMA) is one of the most commonly used thermoplastic polymers in industry due to its favorable optical properties, advantageous strength-to-weight ratio, and aesthetically pleasing surface appearance. Owing to its structural and thermal characteristics, PMMA is particularly suitable for CO_2 laser cutting, where smooth and visually high-quality cut edges can be achieved [1], [3]. PMMA is widely used in the production of optical components, protective panels, advertising structures, and electronic device housings, where aesthetic criteria are important alongside functional requirements. Consequently, ensuring dimensional accuracy and controlling kerf width are of particular importance, especially when parts are used without additional finishing operations [3].

The quality of the CO_2 laser cutting process of PMMA largely depends on the proper selection of process parameters. Among the most significant parameters are laser power, cutting speed, and focal position, which directly affect the energy concentration in the processing zone, process stability, and cut geometry. Numerous studies indicate that variations in these parameters have a pronounced and often nonlinear influence on kerf width, cut taper, and the width of the heat-affected zone [4].

Kerf width represents one of the key indicators of the quality of laser-cut parts, as it directly affects dimensional accuracy and material utilization. A smaller and more uniform kerf width enables more precise part fabrication and reduces the need for additional processing. Therefore, analysis of the influence of process parameters on kerf width is a frequent research topic in the field of laser material processing [5].

Controlling kerf width during CO₂ laser cutting of PMMA material represents a complex task due to the simultaneous action of multiple process parameters and their mutual interdependence. A change in one parameter often affects the influence of the others, which may result in complex variations in cut geometry. For this reason, a systematic approach to process investigation is required, enabling the assessment of both individual and combined effects of process parameters on kerf width [4], [5].

Considering the complexity of the laser cutting process and the interdependence of process parameters, the application of design of experiments (DOE) represents an efficient approach for systematic investigation of their influence. Full factorial experimental designs enable simultaneous analysis of main effects and factor interactions with a relatively small number of experimental trials, thereby providing a high level of information content in the obtained results [6], [7].

In this paper, an experimental analysis of the influence of laser power, cutting speed, and focal position on kerf width during CO₂ laser cutting of PMMA material is presented. The investigation was carried out using a full factorial experimental design 2^3, which enabled evaluation of both individual and interaction effects of the investigated parameters. Based on the obtained experimental results, an empirical mathematical model for kerf width prediction was developed, which can serve as a basis for process optimization and selection of optimal cutting regimes.

II. EXPERIMENTAL METHODOLOGY AND RESEARCH PLAN

A. *Material and Equipment*

The experimental investigation was conducted using a CO₂ laser cutting machine of type SR 7050, which is intended for processing non-metallic materials. The machine enables stable operation in continuous mode, with precise control of laser power, cutting speed, and focal position, which is of crucial importance for experimental studies of CO₂ laser cutting of polymer materials [2]. The technical characteristics of the laser cutting machine are presented in Table I [10].

TABLE I. Technical characteristics of the CO₂ laser cutting machine SR 7050

Characteristics	**Value**	**Units**
Rated power	100	W
Working area	700 x 500	mm
Guide rails	15	mm
Engraving speed	0-1000	mm/s
Cutting speed	0-200	mm/s
Accuracy	0.001	mm
Maximum material thickness	30	mm

Polymethyl methacrylate (PMMA) was used as the test material, as it is commonly processed by CO₂ laser cutting in practice due to its favorable thermal and optical properties. Good absorption of laser radiation with a wavelength of 10.6 µm in PMMA enables a stable cutting process and good cut edge quality [1], [2].

B. *Selection of Process Parameters*

The selection of process parameters was based on an analysis of relevant literature and previous studies in the field of CO₂ laser cutting of polymers. Laser power, cutting speed, and focal position were identified as the dominant parameters, as they have a direct influence on the energy concentration in the processing zone and the cut geometry [4], [9].

TABLE II. Investigated Process Parameters and Their Levels

Parameter	**Level 1**	**Level 2**
Focal position (mm)	-2.5	0
Cutting speed (mm/s)	7.5	8
Laser power (W)	50	60

Laser power directly determines the energy input into the processing zone, while cutting speed defines the interaction time between the laser beam and the material. The focal position affects the spot size, power density, and energy distribution, and consequently the geometric characteristics of the cut, as confirmed by numerous studies on laser processing of non-metallic materials [2], [5].

C. *Experimental Design*

To conduct the experimental investigation, a full factorial experimental design $2^3$was applied, enabling simultaneous analysis of the main effects and interactions among the three process parameters. This approach is widely accepted in technological process research, as it provides a high level of information content with a relatively small number of experimental trials [7].

The total number of experiments was eight, in accordance with the requirements of the full factorial design 2^3. The experiments were carried out according to a predefined plan, while the remaining process parameters were kept constant throughout the investigation. Samples with dimensions of 20 × 20 mm were laser cut from a PMMA plate. The cutting path was defined in advance. The cutting process was initiated by initial material perforation in pulsed laser mode. After piercing, the laser was switched to continuous mode and followed the predefined cutting contour to the final point. The arrangement of samples on the working surface of the laser machine was defined using AutoCAD software. The samples were arranged in two rows with three samples per row, with a spacing of 5 mm between adjacent samples, in order to avoid thermal interaction between neighboring samples during the cutting process [10]. Fig. 1 shows the defined cutting path and the sample after cutting, while Fig. 2 presents the arrangement of samples with the specified spacing.

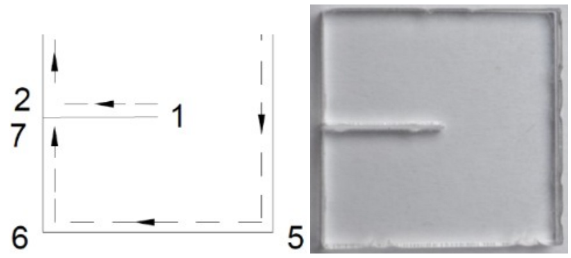

Fig. 1. Defined cutting path and sample after cutting

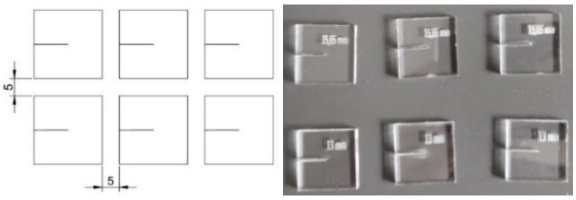

Fig. 2. Arrangement of samples with defined spacing

D. *Kerf Width Measurement Method*

Kerf width was considered as the primary output response, as it represents one of the key indicators of dimensional accuracy in CO_2 laser cutting [8]. Measurements were performed using a digital optical microscope with the following technical specifications: optical zoom range of 50×–1600×, focus range of 15–60 mm, maximum resolution of 1920 × 1440 pixels, and integrated measurement software (HIVIEW). The microscope enables high-precision geometric analysis of the cut edges, which is essential for reliable determination of kerf width.

For each combination of process parameters, at least three repeated measurements were performed. Kerf width was measured at predefined characteristic positions along the cutting path (entry zone, middle section, and exit zone), and the mean value was used as the representative response for each experimental run. This procedure reduces the influence of local geometrical irregularities and random measurement deviations, thereby increasing the repeatability and reliability of the obtained results.

Microscopic images were additionally used for qualitative assessment of cut symmetry and edge uniformity.

Measurement Limitations and Repeatability

Kerf width measurement in polymer materials may be affected by local variations of the cut edge due to changes in energy input and the thermal behavior of the material. Therefore, kerf width was determined at several characteristic locations along the cutting path, and the results were expressed as mean values. This approach enables a more reliable estimation of the output response and reduces the influence of random deviations, thereby increasing the repeatability and stability of the conclusions derived from the experimental data.

E. *Processing of Experimental Data*

The obtained experimental data were processed using the mean values of the measured kerf width for each investigated cutting regime. This approach reduces the influence of random measurement deviations and increases the reliability of the input data used in further calculations. The use of averaged values provides a stable basis for determining the effects of the process parameters and for developing an empirical mathematical model, in accordance with the principles of the theory of design of experiments [6], [7].

III. CALCULATION AND MATHEMATICAL MODEL OF KERF WIDTH

A. *Basis of Calculation*

Based on the experimental results obtained using a full factorial design 2^3, the effects of the process parameters were calculated and an empirical mathematical model describing the dependence of kerf width on laser power, cutting speed, and focal position was developed. The calculations were performed in accordance with the principles of design of experiments, with the analysis including both the main effects of the factors and their interaction effects, using the mean values of kerf width for each experimental run [7].

For each experimental condition, the mean values of the measured kerf width were used, ensuring the stability and representativeness of the input data for the calculations. Based on the experimental matrix and the corresponding response values, a set of coefficients was determined that quantitatively describes the influence of individual process parameters, as well as their mutual interactions, on the observed output variable, in accordance with standard procedures for full factorial experimental designs [7].

B. *Empirical Mathematical Model*

Based on the experimental design matrix and the corresponding measured response values (kerf width) for each experimental run, an empirical mathematical model was formulated to quantitatively describe the effects of the process parameters on kerf width. For a full factorial 2^3 design, the model can be represented by a linear function including interaction terms (quasi-linear model), as follows [7]:

$$y = \beta 0 + \beta 1 * A + \beta 2 * B + \beta 3 * C + \beta 12 * AB + \beta 13 * AC + \beta 23 * BC \tag{1}$$

Using the calculated regression coefficients, the specific empirical model obtained in this study is expressed as:

$$y = 0.196875 - 0.065625A - 0.004625B + 0.009625C + 0.001375AB + 0.000625AC - 0.002875BC \tag{2}$$

Where A, B and C denote the coded values of focus position, cutting speed, and laser power, respectively.

The model coefficients were determined based on the experimental data, where their sign and relative magnitude indicate the direction and intensity of the influence of the corresponding process parameters on the kerf width, in accordance with the theoretical principles of design and analysis of experiments [7]. The developed mathematical model is valid within the experimental domain defined by the selected levels of the process parameters and enables the prediction of kerf width for different combinations of laser power, cutting speed, and focal position.

C. *Influence of Process Parameters*

The sign and relative magnitude of the coefficients of the mathematical model indicate the direction and intensity of the influence of individual process parameters on the kerf width. Positive coefficient values indicate an increase in kerf width with an increase in the corresponding factor, while negative values indicate the opposite effect [7]. The analysis of the obtained model shows that focal position has a dominant influence on kerf width, while laser power and cutting speed exhibit a significant corrective effect. The presence of interaction terms in the mathematical model indicates the mutual dependence of the process parameters, whose effects are quantitatively reflected through the values of the corresponding coefficients [7].

The developed mathematical model is valid within the experimental domain defined by the levels of the process parameters used in the study and represents a basis for further discussion of the obtained results.

D. Statistical Evaluation of Model Adequacy

The adequacy of the developed empirical model was evaluated using the coefficient of determination and the sum of squares obtained from the factorial design calculations. The total sum of squares was $SST=0.035452875$, while the residual sum of squares was $SS_{res}=0.000003125$. The coefficient of determination was $R^2=0.999911855$, indicating that the model explains more than 99.99% of the variability of the experimental data within the investigated domain. The individual contributions of the factors and their interactions, expressed through the sum of squares values (SSA, SSB, SSC, SSAB, SSAC, SSBC), confirm that focus position has the dominant influence on kerf width, followed by laser power and cutting speed.

E. Analysis of the Mathematical Model

The developed empirical mathematical model enables a quantitative analysis of the influence of process parameters on kerf width within the experimental domain defined by the selected factor levels. The sign and relative magnitude of the model coefficients provide a basis for identifying dominant factors and interaction effects, where each coefficient numerically describes the contribution of the corresponding parameter to the observed output variable.

The presence of interaction terms in the model indicates that the effects of process parameters cannot be considered in isolation, but only through their combined action, which is characteristic of complex thermal processes such as CO_2 laser cutting of polymer materials [6], [7].

IV. DISCUSSION OF RESULTS

Based on the developed empirical mathematical model, the influence of individual process parameters of CO_2 laser cutting of PMMA material on kerf width was analyzed. The sum of squares analysis indicates that focal position has the dominant influence on kerf width within the investigated experimental domain. However, laser power and cutting speed also exhibit significant effects and play an important role in defining the optimal cutting regime. An increase in laser power leads to a higher energy input into the processing zone, resulting in more intensive melting and vaporization of the material and, consequently, the formation of a wider kerf. This observed process behavior is consistent with the fundamental physical mechanisms of CO_2 laser cutting and has been confirmed in previous relevant studies.

As shown in Fig. 3, kerf width increases with increasing laser power, confirming the positive effect of energy input on cut geometry.

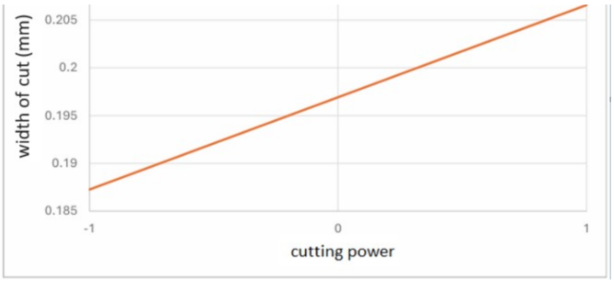

Fig. 3. Main effect of laser power on kerf width

Cutting speed exhibits an opposite effect compared to laser power. With an increase in cutting speed, the interaction time between the laser beam and the material is reduced, which decreases the total energy input per unit length of the cut [5], [8]. As a result, a reduction in kerf width is observed, which is consistent with the sign of the corresponding coefficients in the mathematical model. The focal position significantly affects the energy distribution of the laser radiation within the processing zone. By changing the focal position, the energy concentration along the material thickness is altered, which directly influences the kerf geometry. The obtained results indicate that proper adjustment of the focal position enables a more stable cutting process and more favorable kerf width values.

As shown in Fig. 4, kerf width decreases with increasing cutting speed, indicating a negative correlation between cutting speed and kerf width. Higher cutting speeds reduce the interaction time between the laser beam and the material, resulting in a narrower kerf and improved dimensional accuracy.

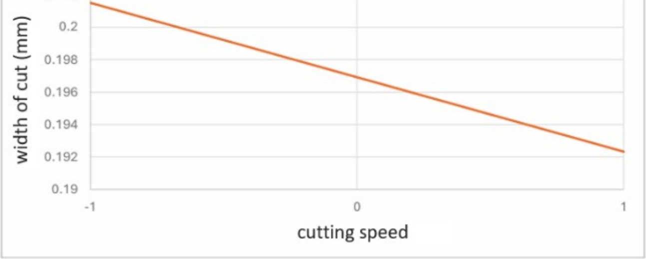

Fig. 4. Main effect of cutting speed on kerf width

The presence of interaction terms in the mathematical model confirms that the effects of process parameters cannot be considered in isolation. In particular, a pronounced interaction between laser power and cutting speed is observed, where a combination of higher laser power and lower cutting speeds leads to a significant increase in kerf width. These findings indicate the necessity of selecting optimal process parameters while simultaneously considering their combined effects. The experimentally established relationships between the process parameters and kerf width confirm the justification for applying the theory of design of experiments in the analysis and optimization of the CO_2 laser cutting process of PMMA material, while the developed mathematical model represents a reliable tool for evaluating the influence of process parameters on cutting quality.

In addition to the interpretation of factor effects, the developed empirical model enables preliminary process optimization within the investigated experimental domain. Based on the obtained regression equation, a narrower kerf width can be achieved by selecting lower laser power and higher cutting speed levels, combined with appropriate adjustment of the focal position. This illustrates the practical applicability of the model for selecting process parameters that ensure improved dimensional accuracy. However, additional validation experiments would be necessary to confirm the predictive capability of the model outside the investigated parameter range.

The identified effects of the process parameters are in agreement with the results of previous studies in the field of CO_2 laser cutting of polymer materials. The literature reports that an increase in laser power leads to an increase in kerf width due to higher energy input and more intensive material melting, whereas higher cutting speeds have the opposite effect as a consequence of shorter laser–material interaction time [4], [5], [8]. Furthermore, the importance of focal position in controlling kerf geometry has been emphasized in several studies, where it has been shown that proper focus adjustment enables a more stable process and more favorable kerf width values. This confirms the reliability of the conducted experimental procedure and the applied mathematical model.

The high value of the coefficient of determination ($R^2 = 0.999911855$) indicates that the developed mathematical model successfully describes variations in kerf width. Accordingly, it can be concluded that nearly the entire variability of the experimental data can be explained by the included process parameters and their interactions. The low value of the residual sum of squares confirms good agreement between the experimental and predicted values, without significant systematic deviations. It should be emphasized that the reliability of the model is limited to the investigated ranges of the process parameters, while its applicability outside this domain is not guaranteed [7].

The obtained results have significant practical implications for the application of CO_2 laser cutting of PMMA material under industrial conditions. Knowledge of the influence of laser power, cutting speed, and focal position on kerf width enables appropriate adjustment of process parameters to achieve the required dimensional accuracy, while simultaneously reducing unnecessary material consumption and the need for additional finishing operations.

The application of the developed mathematical model can contribute to more rational planning of production processes, particularly in small-batch and batch production, where process stability is of critical importance. In this way, the number of trial cuts and experimental adjustments can be reduced, resulting in shorter production preparation time and increased overall process efficiency.

In addition to the presented results, the conducted research indicates possibilities for further extension of the analysis. Future studies may focus on expanding the experimental domain of the process parameters, as well as including additional factors, such as laser pulse frequency and pulse duration, while considering additional output variables, such as cut edge roughness. Moreover, methodological improvements could be achieved by applying an extended factorial design with a larger number of factors and levels, for example a full factorial design 3^3, which would enable a more detailed examination of nonlinear effects and interactions among process parameters, as well as process optimization. Additional experimental investigations would allow verification of the applicability of the developed model outside the investigated parameter ranges and support its broader application in industrial practice.

V. CONCLUSION

This paper presents an experimental investigation of the influence of process parameters in CO_2 laser cutting of PMMA material on kerf width. The study was conducted using a full factorial design of experiments (2^3), which enabled a systematic evaluation of the main effects of laser power, cutting speed, and focal position, as well as their mutual interactions, with a relatively small number of experimental runs.

Based on the experimental results, an empirical mathematical model was developed to quantitatively describe the dependence of kerf width on the observed process parameters. The analysis of the model revealed that focal position has a dominant influence on kerf width according to the sum of squares contribution, while laser power and cutting speed exhibit significant corrective effects. The optimal cutting regime corresponds to a combination of lower laser power, higher cutting speed, and properly adjusted focal position. The presence of interaction terms in the mathematical model confirms that the CO_2 laser cutting process cannot be fully described by considering individual parameters alone, but requires evaluation of their combined effects.

The high value of the coefficient of determination ($R^2 = 0.999911855$) indicates that the developed mathematical model describes the behavior of kerf width within the investigated experimental domain with high reliability. Accordingly, the included process parameters and their interactions explain most of the variability in the experimental data, while the low residual error confirms good agreement between experimental and predicted kerf width values. However, the applicability of the model is limited to the investigated parameter ranges, and its use outside this domain requires additional experimental validation.

The obtained results confirm the suitability of applying the design of experiments methodology in the analysis and optimization of the CO_2 laser cutting process of PMMA material. The developed mathematical model represents a practical tool for selecting optimal process parameters, contributing to improved dimensional accuracy, reduced material waste, and enhanced process stability under industrial conditions.

The presented results and the applied methodological approach provide a solid basis for further research in the field of laser processing of polymer materials. Future studies may focus on expanding the number of process parameters and factor levels, as well as considering additional output variables, which would enable a more detailed examination of nonlinear effects and broader application of the developed model in engineering practice.

A particular contribution of this work lies in the application of a systematic experimental approach for the quantitative analysis of the CO_2 laser cutting process of PMMA material. The combination of design of experiments theory and empirical mathematical modeling enables clear identification of process parameter effects and provides a reliable foundation for further process optimization in engineering applications.

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