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Research article

Analysis of the Effects of Laser Cutting Process Parameters on the Kerf Width of Plywood Using the Taguchi Method

Muhammad Ikhsan[1a], Alang Sundin[2a]*

[a] Department of Mechanical Engineering, Politeknik Bosowa, Sulawesi Selatan 90245, Indonesia

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CORRESPONDENCE

E-mail: ikhsanmibr@gmail.com

A B S T R A C T

Laser cutting is widely used in the manufacturing industry due to its ability to produce high-precision cuts. However, the quality of the cutting results is strongly influenced by the process parameters applied. This study aims to analyze the effects of laser cutting process parameters on the kerf width of plywood material and to determine the optimal parameter conditions using the Taguchi method and analysis of variance (ANOVA). The investigated parameters include material thickness (1, 2, and 3 mm), cutting speed (30, 40, and 50 mm/s), and laser current (20, 30, and 40 A). The experimental design was developed using a Taguchi orthogonal array, with the quality characteristic defined as a smaller-is-better criterion. The analysis results indicate that material thickness is the most influential factor affecting kerf width, accounting for 94.99%. Cutting speed and laser current exhibit smaller effects and are not statistically significant. The optimal conditions for minimizing kerf width are obtained at a material thickness of 3 mm, a cutting speed of 50 mm/s, and a laser current of 20 A. The ANOVA results confirm the consistency of the Taguchi analysis, leading to the conclusion that controlling process parameters—particularly material thickness—plays a crucial role in improving the precision and quality of laser-cut plywood.

1. INTRODUCTION

Plywood has good mechanical properties, relatively high dimensional stability, and good formability, making it widely used in various manufacturing applications, such as aeromodeling, furniture, and light construction. As explained by Jorda et al. (2020), plywood has long been used for aircraft components and curved structures. Three-dimensional molded plywood can be formed into complex geometries; incorporating natural fiber reinforcements, such as flax, significantly enhances load-bearing capacity and stiffness (approximately 76% and 38%, respectively). The layered structure with cross-oriented fiber directions enables plywood to maintain strength and dimensional accuracy; however, it also requires precise cutting methods to prevent damage to the material layers.

CNC laser cutting of plywood is a cutting or engraving process applied to plywood sheets using a CNC (Computer Numerical Control) machine that precisely directs a high-power laser beam according to a digital design. This process is widely employed in the furniture, construction, prototyping, and craft industries due to its speed, accuracy, and flexibility.

The working principle of laser cutting is to focus a high-energy laser beam onto the surface of a material, such as plywood, causing it to burn, melt, or vaporize in a controlled manner, thereby producing highly precise cuts. This method offers several advantages, making it a superior choice for modern cutting processes. First, laser cutting can achieve high precision, even for fine details and

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complex patterns (Eltawahni et al., 2013). Second, the resulting cut edges tend to be smooth and free from tearing or cracking, maintaining a high-quality surface finish (Zhan et al., 2020). In addition, this method produces a very narrow kerf, thereby minimizing material waste (Gabdrakhmanov et al., 2019). Another advantage is the capability for full automation from the CAD/CAM design stage to mass production, which enhances efficiency and consistency of results (Anrinal et al., 2023). Finally, since the process involves no mechanical contact, it does not induce stress or deformation in the material, thus preserving the integrity of the cut shape and structure (Zhan et al., 2020).

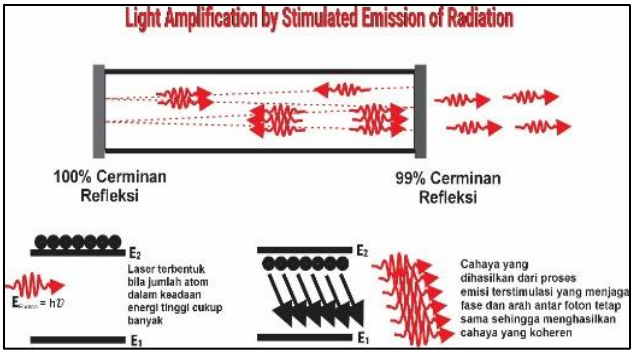

Figure 1. Laser Beam Characteristics.

The cutting quality of diode-based CNC laser cutting systems significantly influences cutting precision, manufacturing efficiency, and the overall quality of the final product. Optimal cutting quality is characterized by smooth, clean cut edges; minimal defects such as carbonization, striations, and dross; and the ability to maintain dimensional accuracy in accordance with design specifications (Suharto, 2020). High cutting precision ensures that dimensions and geometric details closely match the intended design, making it a critical factor for products that require high accuracy. In contrast, poor cutting quality may result in various surface defects, including carbonization, striations (surface grooves), and dross (molten residue), which not only degrade surface appearance but also reduce the mechanical strength and functional performance of the product. Previous studies have demonstrated that the application of diode lasers with optimized process parameters can significantly minimize the occurrence of such defects (Vasanth & Muthuramalingam, 2021; Vasanth et al., 2023).

Kerf width is one of the key indicators used to evaluate cutting quality in laser cutting processes and comprises several main components (Elsheikh et al., 2020). The Top Kerf Width (TKW) is the cut width at the top surface of the material, which is generally larger because the laser energy intensity is highest at the initial cutting point. Meanwhile, the Bottom Kerf Width (BKW) is the cut width at the bottom surface of the material, which tends to be smaller due to reduced laser energy after the material has been penetrated. The difference between TKW and BKW is called the Kerf Taper (KT), which represents the inclination of the cut sidewalls; a large KT value indicates a non-perpendicular cut and may reduce cutting precision. An optimal kerf width produces precise cuts, smooth edges, and minimizes the heat-affected zone (HAZ). Variations in kerf width are strongly influenced by several process parameters, including laser power, cutting speed, assist gas pressure, and material thickness.

The stand-off distance and laser focal position are two key parameters that significantly affect cutting quality in the laser cutting process. Proper adjustment of these parameters can enhance precision, reduce defects, and optimize cutting efficiency.

Laser focus adjustment plays a crucial role in determining cutting quality. An optimally positioned focus—generally located at the material surface or slightly below it—can produce minimal kerf width and perpendicular cuts. In contrast, when the focus is positioned too far from the material surface, the kerf width tends to increase and cutting precision decreases significantly (Kechagias et al., 2024; Lopez et al., 2017). In addition, surface roughness is also influenced by the focal distance. For thin materials, focusing within the 6–7.5 mm range has been shown to reduce surface roughness to below 4 µm, whereas improper focus positioning may result in rougher surfaces and an increased risk of defects (Khdair & Melaibari, 2023).

In the heat-affected zone (HAZ), positioning the focus slightly above the material surface can reduce the HAZ width, whereas placing it below the surface tends to deepen the HAZ. An excessively large HAZ can negatively impact structural strength and the quality of the cut edges (Rahman et al.,

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2013). Finally, the efficiency and stability of the cutting process depend strongly on the accuracy of the focus adjustment. Proper focus positioning not only improves efficiency and reduces power consumption but also maintains overall process stability. Conversely, focal misalignment can degrade cutting quality and may even lead to process failure (Niu et al., 2024).

3. METHOD

This study aims to optimize laser cutting process parameters to improve the cutting quality of plywood material using a CNC CO_2 Laser Cutting machine. The experimental method used a Design of Experiments (DOE) approach, in which process parameters were systematically varied to analyze their effects on kerf width and angle.
A CO_2 laser system consists of a laser tube (resonator) containing a mixture of CO_2, N_2, and He gases. When a high voltage is applied between the cathode and anode, CO_2 gas molecules are excited and emit infrared radiation at approximately 10.6 μm via stimulated emission. Three reflective mirrors direct the generated laser beam toward the cutting head (laser head). Inside the laser head, the laser beam is focused by a converging lens into a high-energy focal point, which is precisely directed onto the plywood surface.
An assist gas is simultaneously supplied through the nozzle to help remove molten material from the cutting gap and to maintain the cleanliness and quality of the cutting results. The overall system schematic is shown in Figure 2.

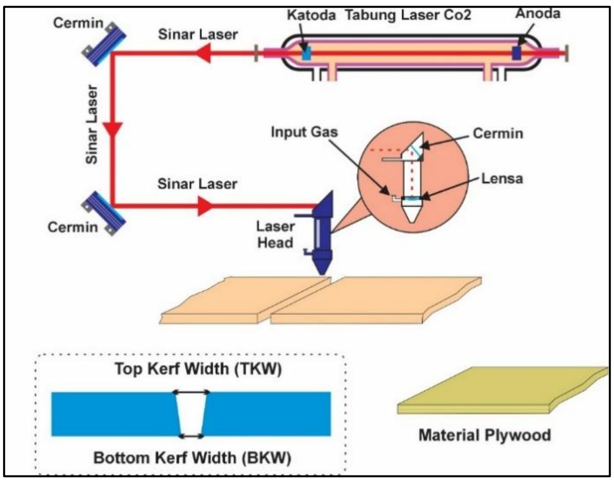


Figure 2. Schematic of the Laser Cutting Process.

Table 1. Parameter of three-level (3^3) Design

No.	Parameter	Level 1	Level 2	Level 3
1	Material Thickness(mm)	1	2	3
2	Cutting Speed (mm/s)	20	30	40
3	Current (Ampere)	30	40	50

4. RESULT AND DISCUSSIONS

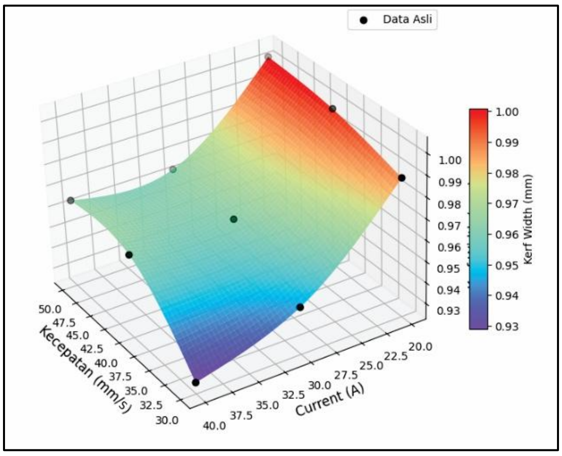
This study was conducted through experimental testing of the laser cutting process to evaluate the accuracy and precision of the cutting results, particularly the kerf width. The cutting process was performed with variations in cutting speed (30, 40, and 50 mm/s), laser current (20, 30, and 40 A), and plywood material thickness (1 mm, 2 mm, and 3 mm). Based on these experiments, the following results were obtained.

Table 2. Experimental array for the kerf width

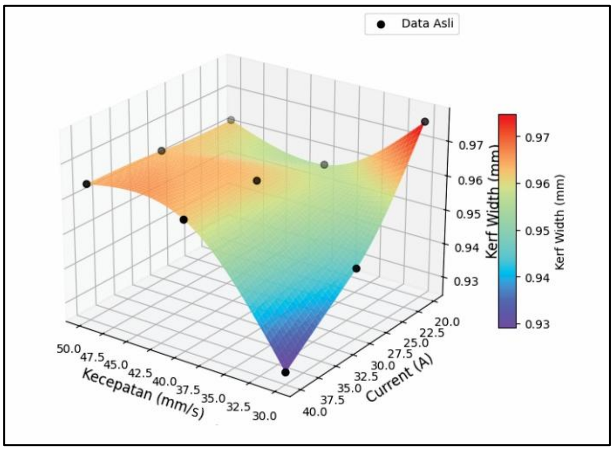
No	Thickness mm	Kecepatan / Cutting Speed (CS) mm/s	Current Ampere	Kerf Widht mm
1	1	30	20	0,988
2	1	30	30	0,945
3	1	30	40	0,928
4	1	40	20	0,998
5	1	40	30	0,962
6	1	40	40	0,963
7	1	50	20	1,002
8	1	50	30	0,962
9	1	50	40	0,964
10	2	30	20	0,976
11	2	30	30	0,965
12	2	30	40	0,93
13	2	40	20	0,956
14	2	40	30	0,932
15	2	40	40	0,927
16	2	50	20	0,942
17	2	50	30	0,933
18	2	50	40	0,922
19	3	30	20	0,91
20	3	30	30	0,875

21	3	30	40	0,824
22	3	40	20	0,889
23	3	40	30	0,841
24	3	40	40	0,814
25	3	50	20	0,875
26	3	50	30	0,839
27	3	50	40	0,798

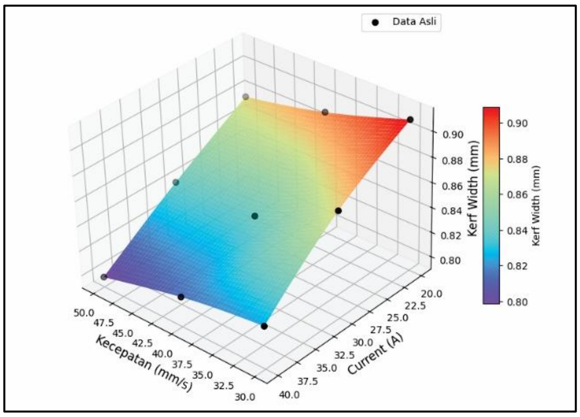
Based on the graphical visualization, the electrical current and cutting speed parameters are observed to significantly influence kerf width, exhibiting different response characteristics at each material thickness.



(a) Kerf Width at a Material Thickness of 1 mm



(b) Kerf Width at a Material Thickness of 2 mm



(c) Kerf width at a Material 3 mm Thickness

In general, increasing the laser current and cutting speed tends to reduce the kerf width, though the magnitude of their effect depends on the workpiece thickness. For 1 mm-thick materials, electrical current has a greater effect than cutting speed. The highest kerf width is obtained at a current of 20 A and a cutting speed of 30 mm/s. Increasing the current up to 40 A, particularly when combined with higher cutting speeds, results in a smaller kerf width. This indicates that, for thin materials, higher electrical energy results in a more focused and stable cutting process.

At a thickness of 2 mm, the effects of current and cutting speed tend to be more balanced. Kerf width decreases with increasing current, while cutting speed begins to show a noticeable influence on material melt behavior. The minimum kerf width is achieved at a combination of high current and low to medium cutting speed, indicating the need to

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balance thermal energy input and cutting interaction time.

Meanwhile, for materials with a thickness of 3 mm, cutting speed becomes the dominant parameter. Increasing cutting speed consistently reduces kerf width, particularly at higher current levels. The combination of a 40 A current and a cutting speed of 50 mm/s yields the lowest kerf width value, indicating that higher cutting energy and shorter interaction time can reduce kerf widening in the cutting zone.

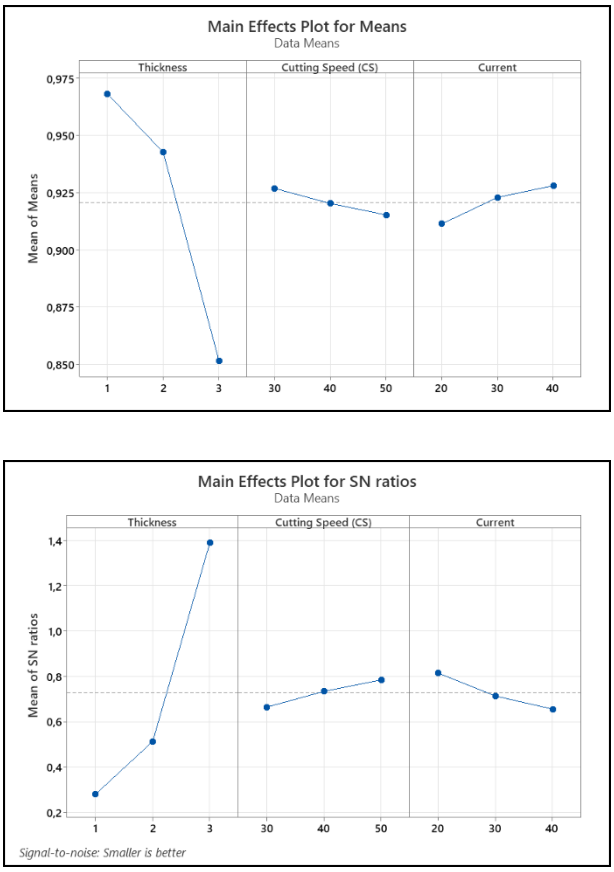

Figure 3. Main Effects Plot for Means Result.

From the Main Effects Plot for Means, the material thickness parameter exhibits the most dominant influence on kerf width. Increasing the thickness from 1 mm to 3 mm results in a significant decrease in the average kerf width. The highest kerf width is observed at a thickness of 1 mm, while the lowest value occurs at 3 mm. This phenomenon can be attributed to the fact that thicker materials have a greater ability to absorb and distribute laser thermal energy more uniformly, thereby minimizing the widening of the cutting gap.

The effect of cutting speed (CS) on kerf width shows a decreasing trend as CS increases from 30 mm/s to 50 mm/s. At lower cutting speeds, the interaction time between the laser beam and the material is longer, leading to greater thermal energy accumulation and, consequently, a wider kerf. In contrast, higher cutting speeds reduce heat exposure duration, resulting in smaller kerf widths and a more controlled cutting process.

Meanwhile, the laser current parameter shows a tendency for kerf width to increase as the current rises from 20 A to 40 A. This behavior is directly related to the increase in laser power, as higher thermal energy produces a larger molten zone and a wider cutting gap. Therefore, excessively high laser current can degrade the dimensional quality of the cut.

The Main Effects Plot analysis of the Signal-to-Noise (S/N) ratio with the smaller-is-better characteristic reinforces the findings of the mean-value analysis. The highest S/N ratio is obtained at a material thickness of 3 mm, a cutting speed of 50 mm/s, and a laser current of 20 A, indicating the most optimal condition for achieving minimum kerf width with low variation. Conversely, the lowest S/N ratio occurs at a thickness of 1 mm and a laser current of 40 A, indicating high variability and a tendency toward larger kerf widths.

Table 3. ANOVA for Kerf width

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Thickness	2	0,022442	94,99%	0,022442	0,011221	41,22	0,024
Cutting Speed (CS)	2	0,000202	0,85%	0,000202	0,000101	0,37	0,730
Current	2	0,000437	1,85%	0,000437	0,000219	0,80	0,555
Error	2	0,000544	2,30%	0,000544	0,000272		
Total	8	0,023625	100,00%				

The analysis of variance (ANOVA) results indicate that material thickness is the most influential parameter affecting the observed response in the laser cutting process. This parameter has a p-value of 0.024 ($p < 0.05$) and a contribution of 94.99%, indicating that material thickness is statistically significant and the dominant factor in determining variations in cutting outcomes. The significant effect of material thickness suggests that the material's ability to absorb and distribute laser thermal energy plays a crucial role in defining the resulting kerf characteristics during the cutting process.

In contrast, the cutting speed and laser current parameters do not show a statistically significant effect on the analyzed response, with p-values of 0.730 and 0.555, respectively ($p > 0.05$). The contributions of these parameters are relatively small, at 0.85% for cutting speed and 1.85% for laser current, indicating that variations in these parameters within the investigated range do not have a substantial impact on response changes compared to the effect of material thickness. The low error contribution of 2.30% indicates that the results adequately represent the relationship between the process parameters and the response.

5. CONCLUSION

Based on the analysis, it can be concluded that material thickness is the most influential factor affecting kerf width, followed by cutting speed and laser current. The Taguchi method analysis indicates that the combination of a 3 mm material thickness, a cutting speed of 50 mm/s, and a laser current of 20 A represents the optimal condition for achieving minimum kerf width. Proper adjustment of process parameters is therefore an important aspect in improving precision in laser cutting systems. Furthermore, the analysis of variance (ANOVA) confirms the Taguchi analysis, identifying material thickness as the dominant, statistically significant factor in optimizing laser cutting quality.

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