

Influence of Diode Laser Cutting Parameters on Kerf and Heat-affected Zone in Oak and Walnut

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The influence of diode laser cutting parameters—feed rate, laser power, and cutting angle—was investigated relative to the kerf width and heat-affected zone (HAZ) in 2.5-mm-thick oak and walnut veneers. Utilizing a 445 nm diode laser, experimental data were analyzed via analysis of variance (ANOVA) and Tukey honestly significant difference (HSD) tests to quantify the thermo-mechanical responses of these anisotropic hardwood species. Results demonstrated that in ring-porous oak, kerf geometry is primarily dictated by the cutting angle ($p < 0.05$), whereas the HAZ expansion is significantly governed by energy input variables, specifically laser power and feed rate. Conversely, semi-ring-porous walnut exhibited pronounced thermal stability against feed rate fluctuations; its kerf width remained dependent on the cutting angle, while HAZ dimensions were strictly correlated with laser power. The findings establish a clear dichotomy where mechanical removal efficiency (kerf) is regulated by beam-angle interactions, while thermal degradation (HAZ) is modulated by thermal energy deposition. Overall, kerf width increased up to 0.226 mm in oak at 60° cutting angle, while HAZ values reached 0.104 mm under high power and low feed rates, confirming species-specific optimization requirements. These species-specific thermodynamic insights provide a foundation for optimizing industrial diode laser processing and developing predictive models for lignocellulosic materials.

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INTRODUCTION

Laser cutting, a non-contact thermal process, offers significant advantages in precision and material waste reduction for woodworking applications (Sobri *et al.* 2025). However, the selection of appropriate process parameters is critical to mitigate undesirable effects, such as substantial KERF (the width of the material removed during the cutting process) widths and extensive HAZ (heat-affected zones) (Eltawahni *et al.* 2010). Specifically, controlling parameters, such as laser power, cutting speed, and beam focus, is paramount to achieving optimal cut quality, characterized by minimal KERF and reduced thermal damage (Kubovský *et al.* 2020; Açık 2023). The precise interplay of these variables directly influences the geometric characteristics of the cut, such as the KERF width, and the extent of thermal degradation, including charring and discoloration (Dolumbia *et al.* 2022). This necessitates a detailed investigation into how varying diode laser cutting parameters influence the resultant KERF dimensions and the morphological properties of the HAZ in specific wood species such as oak and walnut. Optimal process efficiency and cut quality in laser wood cutting are achieved through a judicious

combination of parameters, as variations in laser power, focal plane position, traverse speed, gas pressure, and the number of passes significantly affect the cutting characteristics (Hernández-Castañeda *et al.* 2009b). For instance, higher laser power typically increases cutting depth and KERF width, while an optimal focal position on the material surface tends to minimize KERF dimensions (Sim and Jung 1997). Conversely, excessively high power settings or slow feed speeds can lead to increased thermal degradation, manifesting as charring and a wider HAZ, thereby compromising the aesthetic and structural integrity of the material. This is particularly relevant for diverse wood species, as their unique anatomical structures and densities necessitate tailored parameter optimization for efficient and high-quality processing (Rużiak *et al.* 2025). Understanding the intricate relationship between these parameters and their impact on KERF width and HAZ is crucial for developing predictive models that can optimize laser cutting processes for various wood types (Klement *et al.* 2023).

Numerous studies have explored the impact of laser parameters on cut quality in wood processing, including investigations into the influence of laser power, cutting speed, and shielding gas on various wood types (Corleto *et al.* 2024; İlçe and Çiftçi 2025). Studies have established mathematical relationships between laser parameters and wood surface roughness (Gurău and Petru 2018; Liu *et al.* 2020; Doumbia *et al.* 2021; Li *et al.* 2022). Others have optimized these parameters for specific materials such as medium-density fiberboard (Eltawahni *et al.* 2010) and micro-thin wood veneers (Doumbia *et al.* 2021). Despite these advancements, the complex and non-linear relationship between laser parameters and KERF width in CO₂ laser cutting of polymethyl methacrylate underscores the necessity for sophisticated predictive models to forecast outcomes under diverse conditions (Vasileska *et al.* 2024). In the context of wood, studies have demonstrated that laser power, cutting speed, and annual ring count significantly influence KERF and HAZ properties (Rużiak *et al.* 2024). Moreover, research indicates that higher processing speeds and optimal laser power contribute to reduced KERF widths and improved surface quality, while factors such as the number of cuts can profoundly impact cutting depth (Deng and Hsia 2016; Adamčík *et al.* 2025). Conversely, lower cutting speeds and higher laser power typically result in increased charring and a more pronounced HAZ (Domadia *et al.* 2024; Moradi *et al.* 2020).

This intricate interplay of variables necessitates a comprehensive investigation into the specific responses of diverse wood species, such as oak and walnut, to varying diode laser cutting parameters to establish optimized processing windows for enhanced material integrity and aesthetic outcomes. This study aimed to address this gap by systematically evaluating the influence of diode laser power and cutting speed on the resultant KERF width and the extent of the HAZ in oak and walnut, two commonly utilized hardwoods with distinct anatomical structures. This research will contribute to the development of predictive models for diode laser processing of hardwoods, enabling more precise control over cutting quality and minimizing post-processing requirements.

The application of laser technology in wood processing has garnered increasing attention due to its advantages over conventional methods, particularly in achieving intricate geometries and cleaner cuts without tool wear or sawdust generation (Ferraz 2013). The precision and versatility of laser cutting allow for diverse applications, from fine artistic detailing to industrial-scale manufacturing (Gurău *et al.* 2017). However, the thermal nature of laser cutting introduces challenges, primarily the formation of a HAZ and KERF, which can compromise the aesthetic and structural integrity of the wood (Maciak *et al.* 2024). Researchers have extensively investigated various laser types,

including CO₂ and fiber lasers, for their suitability in processing different wood species (Aniszewska *et al.* 2020). A systematic review highlighted that despite the growing adoption of laser engraving for hardwood, inconsistencies in thermal interaction, surface finish, and dimensional precision persist due to variable wood characteristics and parameter settings (Muhammad *et al.* 2025). Specifically, the impact of CO₂ laser power and scanning speed on wood surface roughness has been shown to exhibit linear and logarithmic correlations, respectively, with higher power and lower speeds leading to more pronounced ablation and surface ridges (Gurău and Petru 2018). Furthermore, the thermal modification of wood, prior to laser processing, significantly influences cutting widths and removal depths, with thermally modified veneers often exhibiting larger KERF dimensions and altered material removal characteristics due to changes in wood's physical and chemical properties (Doğan *et al.* 2024). This pre-treatment effect, for instance, has been observed in aspen Thermowood, where higher pre-treatment temperatures resulted in deeper engraving lines during infrared CO₂ laser processing (Rāviņš *et al.* 2023). Such modifications alter the wood's inherent properties, including its density, moisture content, and chemical composition, all of which are critical factors influencing the interaction dynamics with laser irradiation (Jurek and Wagnerová 2021). For example, research on poplar wood has indicated that increased laser power often leads to a rougher surface, whereas higher feed speed and path spacing can result in a smoother finish due to variations in total heat absorption (Li *et al.* 2022). Moreover, intrinsic wood properties, such as density, moisture content, and anatomical structure, critically influence the quality of laser cuts, with denser latewood exhibiting higher CO₂ laser absorption compared to earlywood tissues (Corleto *et al.* 2024).

EXPERIMENTAL

This section describes the experimental setup, materials, and procedures employed to systematically investigate the influence of diode laser cutting parameters on KERF and HAZ in oak and walnut. The methodology encompasses the precise characterization of both raw materials and post-processed samples, ensuring a rigorous analysis of the effects of varying laser power and cutting speed.

The raw wood logs were procured from North Macedonia by Sancaklı A.Ş. To optimize the mechanical properties for processing, the logs were submerged in water-filled vats for 15 days. Subsequently, they were processed into 2.5-mm-thick veneers using a rotary peeling technique at the manufacturing facility. Following the peeling process, the veneers were dried in a fully automatic hot-air circulation veneer dryer within the same facility to achieve a target moisture content of $8 \pm 2\%$. For the experimental study, randomly selected veneer sheets were sectioned into 10 cm × 10 cm dimensions. To prevent any moisture fluctuation prior to testing, these specimens were immediately sealed in airtight zip-lock bags and transported to the Wood Materials Testing Laboratory at Düzce University Vocational School. Upon arrival at the laboratory, the experimental specimens were removed from the zip-locked bags and conditioned in a climate chamber at $65 \pm 3\%$ relative humidity and 20 ± 2 °C until reaching a constant mass. Following this standardization of environmental conditions, the air-dry densities of the veneers were determined in accordance with the TS ISO 13061-2 (2021) standard. The calculated air-dry densities for this specific batch of specimens were determined as 684 kg/m³ for the oak veneers and 642 kg/m³ for the walnut veneers. These standardized conditions and material

properties are crucial for ensuring the reproducibility and comparability of the experimental results.

A diode laser with a wavelength of 445 ± 5 nm, a focal length of 50 mm, a working area of $400 \text{ mm} \times 400 \text{ mm}$, and a maximum feed rate of 12,000 mm/min was employed to cut the wood samples under varying parameters (Fig. 1). The specific parameters used in the cutting process are presented in Fig. 1. These parameters were determined through preliminary trials based on the diode laser machine's feed rates. In these trials, 2.5-mm-thick walnut and oak veneers were successfully cut at the lowest power level of 1.67 W—the minimum level required to achieve complete cutting at the slowest feed rate. Through systematically varying both power and feed rate thereafter, full penetration was attained across all parameter combinations.

The experimental setup was designed to investigate the influence of fiber orientation angle on kerf width, heat-affected zone (HAZ), and edge quality. In this context, the procedure commenced with the specimen being aligned along its natural grain axis and fixed to the machine bed, followed by the initial cut performed parallel to the fibers (0°). Subsequently, a transverse cut was executed perpendicular to the grain orientation and the 0° reference cut (90°), thereby representing the cross-sectional direction. Finally, taking the 0° reference axis as the baseline, precise angular laser cuts were carried out at intermediate orientations of 30° , 45° , and 60° . This systematic approach was implemented to reveal the transitional behavior of the material under varying fiber orientations and to evaluate the corresponding effects on cutting parameters (Fig. 2).

Each parameter combination (three feed rates $\times$ three power levels $\times$ five cutting angles; 45 combinations per species) was tested on three independent veneer specimens, yielding a total of 135 specimens per wood species. For each specimen, three HAZ measurements were taken at different positions along the same cut, and the average value was reported. Experimental variability was calculated from the independent specimen replicates, while repeated measurements within a specimen were used to minimize local heterogeneity.

The heat-affected zone (HAZ) and KERF boundaries were imaged using a Dino-Lite AM4113T digital microscope, with measurements performed in DinoCapture 2.0 software. Magnification levels of $\times 170$ – 200 were employed, yielding an image resolution of 2592×1944 pixels. Calibration was carried out using a certified calibration slide to ensure dimensional accuracy. HAZ boundaries were defined based on clear visual criteria, specifically the carbonization line, color change, and contrast differences observed in the micrographs. Each measurement was repeated three times per specimen, and the average values were reported. The standard deviation was calculated, resulting in a measurement uncertainty of approximately ± 0.005 mm. The system's pixel resolution and calibration procedure allow reliable detection of HAZ values as small as 0.01 mm. All measurements were performed by an experienced operator, and while every effort was made to minimize error, the possibility of minor oversights is acknowledged as part of scientific transparency. This meticulous approach ensured robust data collection for subsequent statistical analysis, facilitating the development of predictive models for optimal laser cutting performance.

The comprehensive dataset generated from these measurements was subjected to rigorous statistical analysis, including independent samples t-tests, analysis of variance (ANOVA), and *post-hoc* analyses using SPSS software (IBM SPSS Statistics 23, Duzce University), to elucidate the quantitative relationships between diode laser power, cutting speed, and the resultant KERF width and HAZ dimensions in both oak and walnut veneers.

To determine HAZ width, three regions were selected on each side of the cut line, and the average width was adopted as the characterized HAZ value. The oak and walnut samples following the cutting operations are illustrated in Fig. 1. This visual representation serves to qualitatively demonstrate the macroscopic effects of the varied laser parameters on the wood substrates, complementing the quantitative measurements of KERF and HAZ.

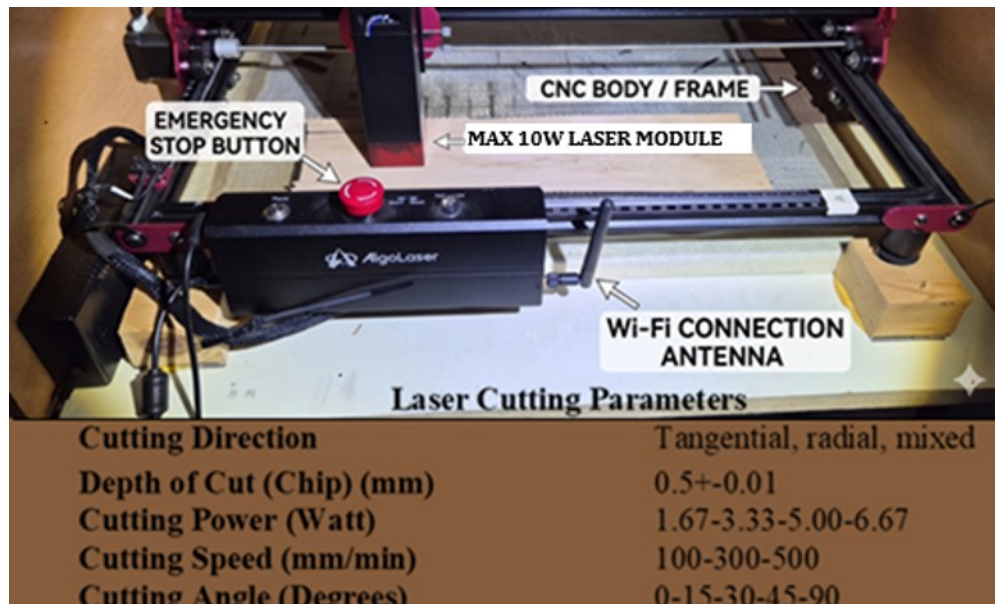


Fig. 1. Laser cutting process of wood veneers

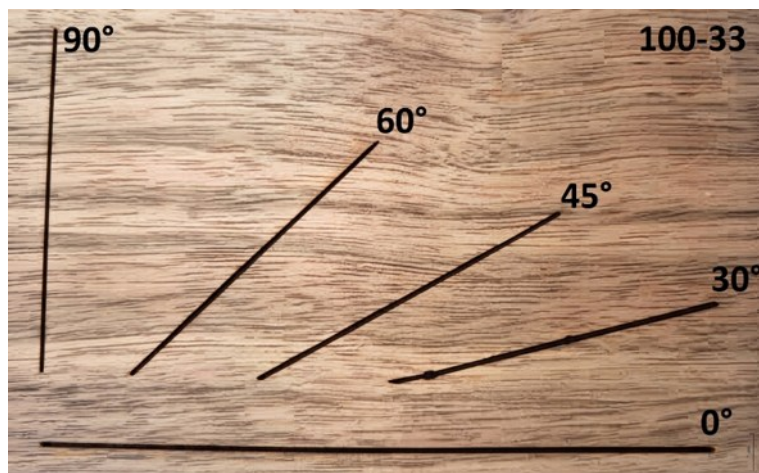


Fig. 2. Fiber orientation angles applied in laser cutting experiments

The specimens were securely fixed to the machine table to prevent movement and vibration during cutting. Cuts were performed by directing the laser beam perpendicularly and obliquely to the wood fibers, in both radial and tangential directions. The results of these experiments, along with the parameter combinations, are summarized in Fig. 1. This meticulous approach to parameter selection and specimen preparation provides a robust foundation for analyzing the intricate relationships between laser cutting variables and the resulting KERF and HAZ characteristics in oak and walnut veneers. The deliberate choice of a diode laser—unlike the more common CO₂ lasers used in woodworking, enabled

investigation of its shorter wavelength and distinct energy absorption characteristics on the wood matrix.

RESULTS AND DISCUSSION

The empirical findings from the laser cutting experiments are presented below, including measured KERF widths and HAZ dimensions across various parameter sets for oak and walnut veneers (Table 1).

The dataset displayed strong homogeneity and adhered to a normal distribution, as confirmed by both Kolmogorov–Smirnov and Shapiro–Wilk tests ($p > 0.05$). (Table 2). The close alignment between the arithmetic means and medians justified the implementation of parametric multifactorial analyses. Consequently, a series of variance analyses were conducted to systematically evaluate the individual and interactive effects of diode laser power, feed rate, and cutting direction on the resultant KERF width and HAZ dimensions.

Table 1. Descriptive Statistics of KERF and HAZ Values for Oak and Walnut

Number of Specimens (N = 135)	Mean	Median	Minimum	Maximum	Std. Dev.
Oak KERF	0.201	0.204	0.113	0.297	0.042
Walnut KERF	0.174	0.176	0.028	0.287	0.046
Oak Haz	0.084	0.078	0.010	0.160	0.037
Walnut Haz	0.095	0.099	0.010	0.200	0.045

Table 2. Normality Tests of KERF and HAZ Values for Oak and Walnut

Number of Specimens (N = 135)	Skewness	Kurtosis	Kolmogorov–Smirnov P	Shapiro–Wilk P
Oak KERF	−0.073	−0.500	0.200	0.768
Walnut KERF	−0.292	1.452	0.200	0.463
Oak Haz	0.232	−0.651	0.081	0.397
Walnut Haz	0.332	−0.533	0.042*	0.243

* $p < 0.05$

The HAZ variables exhibited means of 0.084 mm (oak) and 0.095 mm (walnut) closely aligning with medians, while ranges spanned 0.01 to 0.16 mm and 0.01 to 0.20 mm, respectively (Table 1). Positive skewness and negative kurtosis indicated right-skewed, platykurtic distributions. Although the Kolmogorov–Smirnov test rejected normality for walnut HAZ, Shapiro–Wilk tests yielded $p > 0.05$ for both variables, thereby supporting approximate normality (Table 2). This comprehensive statistical overview establishes a robust basis for further analysis into the specific effects of laser parameters on these critical cut quality metrics.

The KERF variables exhibited strong normality, while HAZ variables showed approximate normality. The close alignment of means, medians, and standard deviations indicated balanced data, supporting parametric statistical tests. These multifactorial analyses evaluated the effects of laser power, cutting speed, and direction on KERF width and HAZ, quantifying their individual and interactive impacts on cut quality (Hernández-Castañeda *et al.* 2009; Yang *et al.* 2018; Kechagias *et al.* 2022). The KERF variables

showed robust normality, while HAZ variables exhibited marginal adherence. The close alignment of means, medians, and standard deviations confirmed data balance, justifying subsequent parametric statistical analyses. These analyses included a series of multifactorial experiments designed to systematically evaluate the influence of laser power, cutting speed, and cutting direction on the KERF width and HAZ dimensions, thereby elucidating the complex interplay of these parameters on the resultant cut quality (Hernández-Castañeda *et al.* 2009; Yang *et al.* 2018; Kechagias *et al.* 2022). Specifically, the analysis sought to quantify the individual and interactive effects of these cutting parameters, such as laser performance and cutting speed, on the resultant KERF width and HAZ, which are critical indicators of cutting efficiency and quality (Rużiak *et al.* 2022).

Table 3 presents the factorial ANOVA outcomes for kerf width, revealing that all investigated parameters—material type, feed rate, laser power, and cutting angle—exerted statistically significant influences ($p < 0.001$). Among the main effects, cutting angle ($F = 5270.921$, $\eta^2 = 0.992$) and material type ($F = 5474.730$, $\eta^2 = 0.968$) emerged as the most dominant factors, indicating that kerf formation is highly sensitive to geometric orientation and intrinsic material properties. Laser power ($F = 697.134$, $\eta^2 = 0.886$) and feed rate ($F = 363.006$, $\eta^2 = 0.801$) also contributed significantly, though with comparatively smaller effect sizes.

Interaction effects were equally pronounced. The material $\times$ feed rate ($F = 1901.372$, $\eta^2 = 0.955$) and laser power $\times$ angle ($F = 712.045$, $\eta^2 = 0.969$) interactions highlight that kerf behavior is not uniform across species but varies depending on operational settings. Three-way and four-way interactions were consistently significant, with partial η^2 values exceeding 0.94, underscoring the multifactorial nature of kerf formation. These findings confirm that kerf width is governed by complex interdependencies rather than isolated parameters.

Table 3. Factorial ANOVA Results for KERF (N = 270)

Source	df	Mean Square	F	Sig.	Partial η^2
Materials	1	0.050	5474.730	0.000	0.968
Feed rate	2	0.003	363.006	0.000	0.801
Laser power	2	0.006	697.134	0.000	0.886
Angle deg	4	0.048	5270.921	0.000	0.992
Materials $\times$ Feed rate	2	0.017	1901.372	0.000	0.955
Materials $\times$ Laser power	2	0.003	356.907	0.000	0.799
Materials $\times$ Angle deg	4	0.002	260.090	0.000	0.853
Feed rate $\times$ Laser power	4	0.001	119.009	0.000	0.726
Feed rate $\times$ Angle deg	8	0.003	347.256	0.000	0.939
Laser power $\times$ Angle deg	8	0.007	712.045	0.000	0.969
Materials $\times$ Feed rate $\times$ Laser power	4	0.011	1192.325	0.000	0.964
Materials $\times$ Feed rate $\times$ Angle deg	8	0.004	382.138	0.000	0.944
Materials $\times$ Laser power $\times$ Angle deg	8	0.003	351.374	0.000	0.940
Feed rate $\times$ Laser power $\times$ Angle deg	16	0.003	286.734	0.000	0.962
Materials $\times$ Feed_rate $\times$ Laser_power $\times$ Angle_deg	16	0.003	295.035	0.000	0.963

The model demonstrated exceptional explanatory power ($R^2 = 0.997$; Adjusted $R^2 = 0.996$), accounting for nearly all variance in kerf width. This high level of fit validates the robustness of the factorial design and emphasizes that the combined effects of material characteristics and processing parameters must be considered when optimizing laser

cutting performance. In practical terms, the results suggest that fine adjustments in feed rate and laser power are insufficient unless cutting angle and material type are simultaneously optimized, thereby reinforcing the necessity of integrated parameter control in industrial applications.

Table 4 summarizes the post-hoc Tukey HSD comparisons for feed rate, laser power, and cutting angle with respect to kerf width. The results confirm that kerf values differed significantly across all factor levels ($p < 0.001$). For feed rate, specimens processed at 167 mm/min exhibited the widest kerf (mean = 0.1936 mm), which was significantly greater than those cut at 333 mm/min (mean = 0.1882 mm) and 500 mm/min (mean = 0.1814 mm). This trend indicates that higher feed rates reduce kerf width, which is likely due to shorter laser–material interaction times.

Laser power comparisons revealed that intermediate power (667 W) produced the largest kerf (mean = 0.1972 mm), significantly exceeding both low (333 W, mean = 0.1848 mm) and high (1000 W, mean = 0.1811 mm) power levels. This non-linear response suggests that excessive power may cause localized burning and material ejection, narrowing the effective cut width.

Cutting angle exerted the strongest influence, with kerf increasing progressively from 0° (mean = 0.1427 mm) to 30° (0.1717 mm), 60° (0.2021 mm), and reaching maximum values at 45° (0.2103 mm) and 90° (0.2119 mm). The differences between 45° and 90° were not statistically significant, indicating a plateau effect at steep angles. These findings highlight that kerf formation is highly sensitive to geometric orientation, with oblique angles amplifying thermal penetration and widening the cut.

Overall, the post-hoc analysis reinforces the factorial ANOVA results by identifying specific group contrasts. The data demonstrate that kerf width is minimized at high feed rates and extreme laser power, while maximized at intermediate power and steep cutting angles. These insights provide practical guidance for optimizing laser cutting parameters, emphasizing that balanced settings are required to achieve precise kerf control across different materials.

Table 4. Tukey HSD Post-hoc Comparisons for KERF

Factor	Group Comparison	Mean Difference	Sig. (p)	Interpretation
Feed rate	167 vs 333	+0.0054	<0.001	167 > 333
	167 vs 500	+0.0121	<0.001	167 > 500
Laser power	667 vs 333	+0.0124	<0.001	667 > 333
	667 vs 1000	+0.0161	<0.001	667 > 1000
Angle	0° vs 30°	-0.0289	<0.001	30° > 0°
	0° vs 90°	-0.0692	<0.001	90° > 0°

Table 5 shows that laser power was the most influential factor on HAZ expansion ($F = 6198.397$, $\eta^2 = 0.986$), followed by feed rate ($F = 1834.038$, $\eta^2 = 0.953$), and cutting angle ($F = 989.514$, $\eta^2 = 0.957$). Material type also had a significant but comparatively smaller effect ($F = 659.822$, $\eta^2 = 0.786$).

Interaction effects were highly significant, particularly material $\times$ laser power ($F = 985.414$, $\eta^2 = 0.916$) and feed rate $\times$ laser power ($F = 603.747$, $\eta^2 = 0.931$), indicating that HAZ behavior was strongly dependent on combined parameter settings. Higher-order interactions (three-way and four-way) also reached significance ($\eta^2 > 0.65$), underscoring the multifactorial nature of thermal damage.

Table 5. Factorial ANOVA Results for HAZ (N = 270)

Source	df	Mean Square	F	Sig.	Partial η^2
Materials	1	0.009	659.822	0.000	0.786
Feed_rate	2	0.025	1834.038	0.000	0.953
Laser_power	2	0.085	6198.397	0.000	0.986
Angle_deg	4	0.014	989.514	0.000	0.957
Materials × Feed_rate	2	0.000	31.510	0.000	0.259
Materials × Laser_power	2	0.013	985.414	0.000	0.916
Materials × Angle_deg	4	0.001	67.722	0.000	0.601
Feed_rate × Laser_power	4	0.008	603.747	0.000	0.931
Feed_rate × Angle_deg	8	0.002	157.645	0.000	0.875
Laser_power × Angle_deg	8	0.004	277.827	0.000	0.925
Materials × Feed_rate × Laser_power	4	0.001	83.804	0.000	0.651
Materials × Feed_rate × Angle_deg	8	0.001	82.603	0.000	0.786
Materials × Laser_power × Angle_deg	8	0.002	133.585	0.000	0.856
Feed_rate × Laser_power × Angle_deg	16	0.001	101.301	0.000	0.900
Materials × Feed_rate × Laser_power × Angle_deg	16	0.001	109.313	0.000	0.907

The corrected model explained 99.5% of the variance ($R^2 = 0.995$; Adjusted $R^2 = 0.992$), confirming the robustness of the factorial design. These findings demonstrate that HAZ formation was primarily governed by energy input and processing speed, with geometric orientation and material properties exerting secondary but meaningful influences. In practice, minimizing HAZ requires careful balancing of feed rate and laser power, particularly when cutting at oblique angles.

Table 6. Tukey HSD Post-hoc Comparisons for HAZ (N = 270)

Feed Rate Comparison	Mean Difference	Sig. (p)	Interpretation
167 vs 333	-0.0150	<0.001	333 > 167
167 vs 500	-0.0333	<0.001	500 > 167
333 vs 500	-0.0184	<0.001	500 > 333

Table 6 illustrates the post-hoc Tukey HSD comparisons for HAZ. Feed rate exerted a clear monotonic effect: HAZ increased significantly from 0.0737 mm at 167 mm/min to 0.0887 mm at 333 mm/min and 0.1070 mm at 500 mm/min ($p < 0.001$). This confirms that higher feed rates intensified thermal damage by reducing cooling intervals and prolonging heat accumulation.

Cutting angle comparisons revealed a progressive widening of HAZ as the angle increased from 90° (0.0656 mm) to 0° (0.1088 mm). The differences between 30° and 45° were not statistically significant ($p = 0.122$), suggesting partial overlap in thermal behavior at intermediate angles. However, all other contrasts were highly significant ($p < 0.001$), highlighting that geometric orientation strongly modulated heat conduction and diffusion.

Overall, the post-hoc analysis reinforces the ANOVA findings by identifying specific group contrasts. HAZ expansion was minimized at low feed rates and steep angles, while maximized at high feed rates and perpendicular cutting. These results emphasize the need for balanced parameter selection to reduce thermal damage and optimize cut quality.

Microscopic analysis of laser-cut surfaces in Fig. 3 clearly demonstrated significant morphological differences in the KERF and HAZ among the selected hardwood species. The Kerf represents the central void generated by the complete ablation and vaporization

of the lignocellulosic matrix. This void is immediately flanked by the HAZ—a region characterized by severe thermal degradation, carbonization (charring), and visible discoloration extending into the unaffected wood fibers. In the lighter-toned, ring-porous anatomical structure of oak, the thermal gradient of the HAZ is distinctly pronounced. This visual evidence corroborates the statistical findings that thermal damage in oak is highly sensitive to variations in energy input, specifically laser power and feed rate.

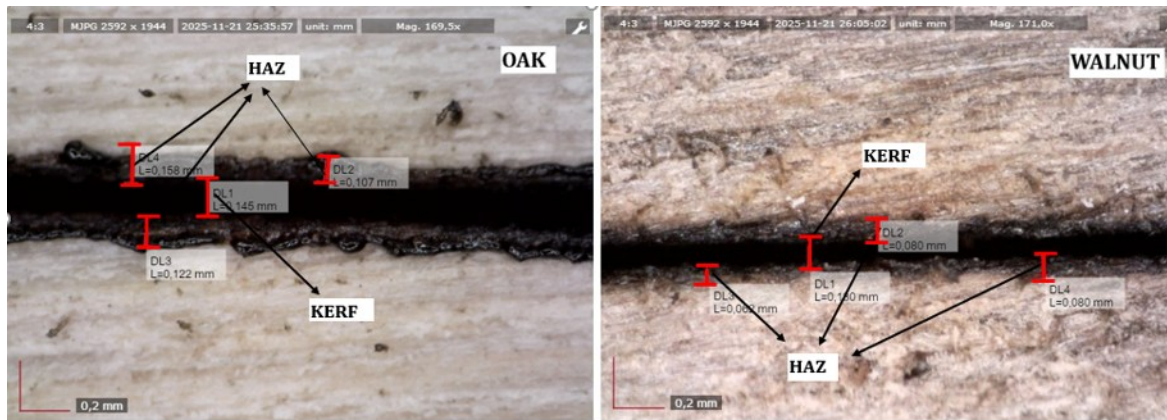


Fig. 3. Kerf and HAZ microscopic result

The present findings on kerf and HAZ formation in hardwoods, supported by ANOVA and Tukey HSD analyses (Tables 3, 5, and 6), are consistent with earlier reports emphasizing the multifactorial nature of thermal damage in laser cutting. Visual evidence from microscopic analysis (Fig. 3) corroborates that oak's ring-porous anatomy amplifies thermal gradients, while walnut's diffuse-porous structure restrains heat diffusion, in line with Açıık (2023). Similar to recent microstructural investigations demonstrating how structural heterogeneity governs localized mechanical damage and micro-crack evolution on wood surfaces (Kaçamer 2026), the present SEM analyses revealed that the inherent anatomical properties of the wood strictly dictate the extent of localized thermal degradation. The findings are further supported by Doumbia *et al.* (2022), who observed substantial kerf variations across different wood species (such as Korean pine and Northeast China ash), as well as Hernández-Castañeda *et al.* (2009a), who emphasized the structural dependence of thermal degradation on grain orientation and moisture content.

Following the initial comparison across material types, subsequent analyses were conducted separately within each material group to evaluate the effects of processing parameters. This stratified approach controls for material heterogeneity, isolating the contributions of operational variables and ensuring that observed differences can be reliably attributed to process-related factors rather than inherent material properties. This methodological choice is crucial for accurately discerning how variations in laser power, cutting speed, and cutting direction individually and interactively influence the resultant kerf width and HAZ within oak and walnut (Der *et al.* 2023).

Comparable findings were reported in recent experimental studies (Der 2026), which confirmed that feed rate, laser power, and cutting angle are dominant parameters influencing kerf width and HAZ expansion. Complementary optimization approaches using artificial neural networks have also been reported (Rużiak *et al.* 2026), achieving predictive accuracy above 97% for kerf geometry in beech plywood and HDF, thereby highlighting the potential of computational modeling to complement experimental results.

Furthermore, polymer-based investigations (Der 2025) extended this perspective by integrating machine learning models (LSTM-GRU, XGBoost) to predict kerf and HAZ outcomes in FFF-printed ABS thermoplastics, again identifying cutting speed and laser power as critical factors. Taken together, these studies reinforce the robustness of the present results and situate them within a broader research context that spans both traditional ANOVA-based analyses and advanced predictive modeling across different material systems.

Beyond the immediate scope of wood processing, broader methodological and sustainability frameworks also provide valuable context. Statistical and computational techniques in manufacturing (Davim 2012) and design of experiments in production engineering offer rigorous approaches for analyzing multifactorial interactions, directly supporting the factorial ANOVA design employed here. The role of lasers in manufacturing (Davim 2016) situates the present findings within the wider industrial application of laser technologies. Moreover, sustainability-oriented perspectives such as Industry 5.0 (Davim 2025a), intelligent manufacturing aligned with the 2030 Agenda (Davim 2024), and bibliometric analyses of Sustainable Development Goals (Davim 2025b) underscore the relevance of minimizing thermal damage and optimizing process parameters not only for technical performance but also for environmental responsibility.

Overall, feed rate had no significant effect on either kerf or HAZ in walnut; cutting angle dominated kerf, laser power dominated HAZ, reflecting material stability to feed rate. This material-specific response highlights the complex interplay between processing parameters and wood properties, particularly how inherent stability to heat transfer mechanisms within walnut may modulate thermal damage irrespective of feed rate variations, distinguishing it from other wood types where feed rate can be a dominant factor (Sobri *et al.* 2025a). The present study provides novel insights into the differential impacts of diode laser cutting parameters on kerf width and HAZ in oak and walnut, two distinct hardwood species. Specifically, the investigation elucidates the nuanced responses of these wood types to variations in feed rate, laser power, and cutting angle, thereby advancing the understanding of laser-material interaction in heterogeneous biological matrices.

The current study's findings underscore that while certain parameters, such as cutting angle, predominantly influence the geometric aspects of the kerf, others, including laser power and feed rate, exert a more significant control over thermal damage, consistent with observations in other lignocellulosic materials (Rajko *et al.* 2021; İlçe and Çiftçi 2025; Sobri *et al.* 2025b). For instance, the observed increase in HAZ with higher laser power and lower cutting speeds aligns with previous research demonstrating enhanced thermal degradation under elevated energy densities and prolonged exposure times (Kechagias *et al.* 2021). The absence of a statistically significant effect of feed rate on HAZ in walnut, despite its pronounced influence in oak, suggests species-specific thermal absorption and dissipation characteristics, potentially linked to variations in density, moisture content, or cellular structure. Furthermore, the observation that kerf width in oak was significantly affected by cutting angle but not by feed rate or laser power suggests a complex interaction between beam geometry and anisotropic wood structure, corroborating findings from studies on CO₂ laser cutting of various wood species where grain direction played a critical role in cut quality (Lee 1996). This anisotropic behavior can lead to variations in heat transfer and material removal rates depending on the orientation of the wood fibers relative to the laser beam (Leone *et al.* 2022). Consequently, understanding these directional dependencies is crucial for optimizing laser processing parameters to minimize kerf and

HAZ, especially in hardwoods with complex anatomical structures (Gurău *et al.* 2022 2024).

In this study, the effects of diode laser cutting parameters—feed rate, laser power, and cutting angle—on kerf width and HAZ were systematically evaluated in two hardwood species: oak and walnut. The findings demonstrate that material type plays a pivotal role in determining cutting behavior, with inter-species variations in sensitivity to these parameters, highlighting the need for tailored optimization strategies in laser processing of lignocellulosic materials (Rajko *et al.* 2021; Sobri *et al.* 2025c). In oak wood, kerf measurements exhibited the strongest dependence on cutting angle, with means progressively increasing from 0.153 mm at 0° to 0.226 mm at 60° ($p < 0.05$ *via* Tukey HSD), while showing insensitivity to feed rate and laser power. Conversely, HAZ was significantly influenced by feed rate (decreasing from 0.104 mm at high speeds to lower values) and laser power (increasing to 0.104 mm at 10 W). This indicates that in oak, the kerf's geometric characteristics were primarily dictated by the interaction of the laser beam's angle with the wood's structural anisotropy, while thermal damage was predominantly governed by the energy input rate. This divergence implies that for oak, optimization strategies should independently address geometric fidelity through angle adjustments and thermal integrity through feed rate and power modulation. In contrast, walnut wood displayed remarkable stability to feed rate variations, with no significant effects on either kerf or HAZ ($p > 0.05$ across ANOVA and Tukey tests), despite weak trends toward narrower kerf at higher speeds.

Overall, these results reveal a clear dichotomy: kerf is predominantly governed by geometric factors such as cutting angle, which alter beam penetration and material removal efficiency (Lee 1996; Gurău *et al.* 2022, 2024), while HAZ responds to thermal energy deposition *via* laser power and feed rate (Kechagias *et al.* 2021). This mechanistic distinction emphasizes the importance of integrating material-specific properties with process parameters to mitigate defects in laser cutting. Taken together, these studies reinforce the robustness of our results and situate them within a broader research context that spans traditional ANOVA-based analyses, advanced predictive modeling, and sustainability-driven manufacturing paradigms. This integrated perspective highlights both the scientific and practical significance of parameter optimization in laser cutting of hardwoods. Future research should prioritize the development of adaptive laser cutting systems that dynamically adjust parameters based on real-time material characterization. These systems could integrate *in situ* optical sensors for monitoring the HAZ or machine learning algorithms trained on comprehensive material property datasets, thereby maximizing process quality while minimizing thermal damage. The findings of this study provide a substantial contribution to developing material-specific optimization strategies for industrial applications. Notably, the precise selection of critical parameters—such as cutting angle and laser power—for distinct wood species like oak and walnut can markedly enhance cut quality and effectively control thermal effects.

CONCLUSIONS

1. The interaction between diode laser cutting parameters and wood anatomy revealed a mechanistic dichotomy: geometric fidelity of the cut (kerf width) was predominantly governed by cutting angle, whereas thermal degradation (HAZ) was dictated by energy input variables—laser power and feed rate.

2. In ring-porous oak, kerf width progressively increased with cutting angle from 0° to 60°, while remaining statistically unaffected by feed rate and power. In contrast, HAZ expansion was strongly dependent on energy deposition, enlarging significantly under higher power and slower feed rates.
3. Semi-ring-porous walnut demonstrated pronounced thermal stability against feed rate fluctuations. Kerf width remains strictly dependent on cutting angle, while HAZ expansion was exclusively correlated with laser power, underscoring species-specific thermo-mechanical behavior.
4. The inherent anatomical properties of hardwoods fundamentally dictate their laser processing responses. Optimization strategies must therefore be material-specific, decoupling geometric corrections (*via* angle adjustment) from thermal management (via power and speed modulation).
5. The observed increase in kerf width at oblique cutting angles arises not only from anisotropic wood structure but also from geometric projection effects related to beam–fiber orientation. This combined influence highlights the necessity of precisely defining cutting angle relative to grain direction and beam axis in laser–wood interaction studies.
6. By contrasting these findings with recent CO₂ laser cutting studies on polymers and composites, this work demonstrates that hardwood anatomy introduces unique anisotropy effects absent in synthetic materials. This distinction establishes the need for predictive models tailored to lignocellulosic substrates.
7. From an industrial perspective, the results provide actionable guidance for veneer cutting in furniture and wood product manufacturing, enabling improved dimensional accuracy while minimizing thermal damage.
8. In alignment with sustainable and intelligent manufacturing paradigms (Industry 5.0), the study contributes to energy-efficient, material-specific laser processing strategies that reduce waste, enhance product quality, and support the 2030 Agenda for Sustainable Development.

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Conflicts of Interest

The author declares no conflicts of interest.

Declaration of Generative AI Use

The author declares that the generative AI tool Jenni AI (<https://app.jenni.ai/>) was used solely to assist with the literature search during the preparation of this manuscript. All information, cited references, and generated outputs were carefully verified and evaluated by the author against the original sources before being incorporated into the manuscript. No generative AI tools were used for data analysis, interpretation of results, generation of figures, or drawing scientific conclusions. The author takes full responsibility for the accuracy, originality, and integrity of the manuscript.

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