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ENERGY DOSE AND SPECIFIC CUTTING ENERGY IN CO_2 LASER CUTTING OF SOLID AND ENGINEERED WOOD MATERIALS

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ABSTRACT

The energy requirements of CO_2 laser cutting for three solid wood species (spruce, oak, and beech) and three engineered wood-based materials (pine plywood, beech plywood, and high-density fiberboard) are examined in this study. Energy dose (*Ed*) and specific cutting energy (*Ec*) were calculated for each material under selected laser power and feed rate combinations. The goal was to achieve a kerf width of 300 µm, consistent with the geometric tolerances of ISO 9013:2017. Results show that *Ed* increases with material density, while *Ec* reveals additional influences, including anatomical structure and bonding in engineered products. Oak exhibited the lowest *Ec* despite a relatively high density, while HDF and beech plywood showed the highest values. These findings suggest that material density can inform initial laser parameter selection, but cutting efficiency also depends on how energy interacts with structure and composition. The observed relationships between density and *Ed*, and between *Ed* and *Ec*, provide a framework for refining processing settings based on material characteristics.

Keywords: CO_2 laser; laser cutting; dimensional tolerances; energy dose; specific energy.

INTRODUCTION

Laser cutting of wood has become a standard process in industries ranging from woodworking and cabinetry to model making. Particularly, CO_2 lasers are frequently used in the woodworking industry due to their high precision and minimal material waste (Naresh 2021; Mushtaq *et al.*, 2020).

Historically, in conventional woodworking, the width of a cut, commonly referred to as the kerf, has been determined by the physical thickness of the cutting tool, such as a saw blade (Menschel *et al.*, 2021). Mechanical cutting tools introduce precise, predictable kerf dimensions defined by their geometry, which is an essential factor for dimensional planning and material optimization. By contrast, in laser cutting, the kerf is governed not by a physical blade, but by the diameter of the focused laser beam interacting with the material (Martínez-Conde *et al.*, 2017). In the context of precision laser woodworking, the beam focus size effectively plays the same role as the saw thickness did in mechanical cutting, controlling the minimum achievable kerf width. In this study, a beam focus width of approximately 300 µm serves as the reference for achieving high-dimensional precision, drawing a direct operational parallel to mechanical processes but under new, thermally driven conditions.

The focus is on achieving kerf widths of around 300 µm, corresponding to the nominal diameter of the laser beam focus, to meet ISO 9013:2017 Class I dimensional tolerances for 6 mm-thick material. Although ISO 9013 defines tolerances based on deviations from the intended contour rather than kerf width directly, a kerf width of ~ 300 µm ensures that each side remains within ±150 µm of the intended boundary and thus stays within Class I limits without template modification, toolpath compensation, or kerf offset adjustment.

Ensuring the quality of wood cuts is essential, yet there is no wood-specific international standard for evaluating laser-cut quality. In practice and research, the metal-focused ISO 9013 standard (initially developed for thermal cutting of metals) can be applied to assess the quality of laser-cut wood (Barcikowski *et al.,* 2004b; ISO 9013:2017).

However, wood's organic nature introduces challenges not fully addressed by metal-focused metrics, variations due to moisture content, potential for surface charring, and structural anisotropy. CO_2 laser interaction with lignocellulosic material induces complex thermal, morphological, and chemical changes (Kúdela *et al.,* 2023), further complicating attempts to standardize quality using metal-based tolerancing systems.

While ISO 9013 provides useful dimensional reference, the standard does not account for the effects of grain direction, internal structure, or the thermal response of adhesives in engineered products. Incorporating a correction factor based on anatomical or structural features may help extend ISO 9013's applicability to wood and wood-based materials more reliably.

Natural woods vary in structure due to grain direction and growth characteristics, leading to inconsistent cutting behavior (Açık 2023a). In contrast, engineered wood products, such as plywood and high-density fiberboard (HDF), typically yield more predictable cutting outcomes due to their uniform structure and controlled manufacturing processes (Magaznieks and Narica 2018).

Recent advancements have increasingly shifted laser processing of wood and wood composites toward systematic, data-driven approaches (Ružiak *et al.,* 2024; Naresh *et al.,* 2024). However, further refinement is needed to establish reproducible, material-specific methodologies that match the level of standardization seen in metal and polymer laser cutting (Hernández-Castañeda and Li 2011). Comparative work by Gochev also demonstrated that the specific energy required for laser cutting wood depends strongly on wood species and density, establishing a theoretical and experimental foundation for future research (Gochev 2016).

Knowing how much energy is required to cut various materials to tight tolerances is essential not only for quality control but also for improving production efficiency, reducing costs, and guiding material-specific cutting strategy (Sobolewska and Ciecińska 2021).

The goal of this study is to evaluate and compare the specific energy and energy dose required for CO_2 laser cutting of selected wood species and engineered wood-based materials to achieve a kerf width of 300 µm, corresponding to ISO 9013:2017 Class I tolerances, and determine how material density and structure influence energy dose and specific cutting energy.

MATERIALS AND METHODS

Six materials were selected for this research, consisting of three natural woods: beech wood (*Fagus sylvatica* L.), oak wood (*Quercus petraea*), and spruce wood (*Picea abies* L.), and three engineered wood-based products: beech plywood, pine plywood, and high-density fiberboard (HDF). Sample dimensions were 500 mm × 70 mm × 6 mm. All materials were acclimatized under controlled conditions to maintain moisture content between 8% and 10% before cutting.

A CO_2 laser operating at a wavelength of 10.6 μm with a maximum power output of 135 W was used. Samples were processed at different power outputs (40%, 60%, 80%, and 100%, corresponding to 54 W, 81 W, 108 W, and 135 W, respectively) and at varying cutting speeds (5, 10, 15, and 20 mm·s^{-1}). The laser system uses a focusing lens with a focal length of 50.8 mm, a beam radius of 0.3 mm, and compressed air at 0.35 bar as the assist gas. The laser cuts were made tangentially on the radial surface, parallel to the grain.

Kerf widths resulting from each combination of power and speed were measured using a high-resolution Keyence VHX 7000 digital microscope. Combinations of speed and power were identified for each material that yielded kerf widths as close as possible to the target width of 300 μm on both the top and bottom sides of the kerf, complying with Class I dimensional tolerances specified by ISO 9013:2017 for a 6mm thick material.

To determine a suitable combination of laser cutting speed and power for each material, the goal was to achieve an average kerf width as close as possible to 300 μm, in line with Class I dimensional tolerances according to ISO 9013:2017. For each tested setting, the measured kerf widths at the top and bottom sides of the samples were compared to the target value. The differences were calculated individually for the top and bottom and then summed to represent the total deviation from 300 μm. The setting with the smallest total deviation was selected as the most appropriate. This method allowed both the entrance and exit kerf widths to be considered, minimizing the influence of tapering on the results. Where multiple settings had similar deviations, preference was given to the combination with the lower deviation from the 300 μm target kerf width.

Specific energy (*Ec*) and energy dose (*Ed*) were calculated using equations 1 (Orech and Juza 1987) and 2 to quantify the energy efficiency and energy requirements for the desired kerf width under power and speed combinations. Density measurements for all materials were carried out (at w ≈ 8%) for the calculation of specific energy E_c.

$$E_c = \frac{P}{\rho \times v \times e \times s} \quad [\mathrm{J} \cdot \mathrm{kg}^{-1}] \tag{1}$$

$$E_d = \frac{P}{d \times v} \quad [\mathrm{J} \cdot \mathrm{m}^{-2}] \tag{2}$$

Where: P – power output of laser [W];
ρ – density of sample [kg · m^{-3}];
v – cutting speed [m · s^{-1}];
e – depth of cut [m];
s – kerf width [m];
d – beam diameter [m].

RESULTS AND DISCUSSION

Table 1 presents the optimized experimental settings and the corresponding kerf widths closest to the target value of 300 μm, along with calculated values of energy dose (E_d) and specific cutting energy (E_c) across three wood species (spruce, beech, oak) and three engineered wood-based materials (beech plywood, pine plywood, HDF).

Tab. 1 Laser cutting parameters, kerf widths, and energy characteristics of selected wood species and wood-based materials.

Material	ρ_w [kg·m^{-3}]	speed [mm·s^{-1}]	power [W]	Kerf width top [µm]	Kerf width bottom [µm]	Avg width [µm]	E_d [J·m^{-2}]	E_c [J·kg^{-1}]
BeechPlywood	740.1	15	108	387.56	297.27	342.41	2.40E+07	4.98E+06
PinePlywood	558.3	15	54	323.11	289.11	306.11	1.20E+07	3.56E+06
HDF	884.7	5	54	394.79	307.16	350.98	3.60E+07	5.78E+06
Spruce wood	332.3	20	54	367.87	251.28	309.57	9.00E+06	4.30E+06
Beech wood	728.0	15	81	408.24	232.96	320.60	1.80E+07	3.92E+06
Oak wood	747.1	20	81	375.99	207.94	291.96	1.35E+07	3.12E+06

The average kerf width varied narrowly around the desired target (291.96 µm to 350.98 µm), demonstrating the suitability of the selected laser settings in achieving class I dimensional tolerances according to ISO 9013:2017. However, noticeable variations were observed among materials, reflecting differences in their anatomical and physical structures and densities. Our E_c value for spruce wood 4.3×10^6·kg^{-1} is consistent with the findings of Kubovský *et al.,* who reported E_c values for *Picea abies* L. between 4.1×10^6 to 7.4×10^6 J·kg^{-1} depending on laser power, feed rate, and focal position (Kubovský *et al.,*2012).

Influence of Material Density

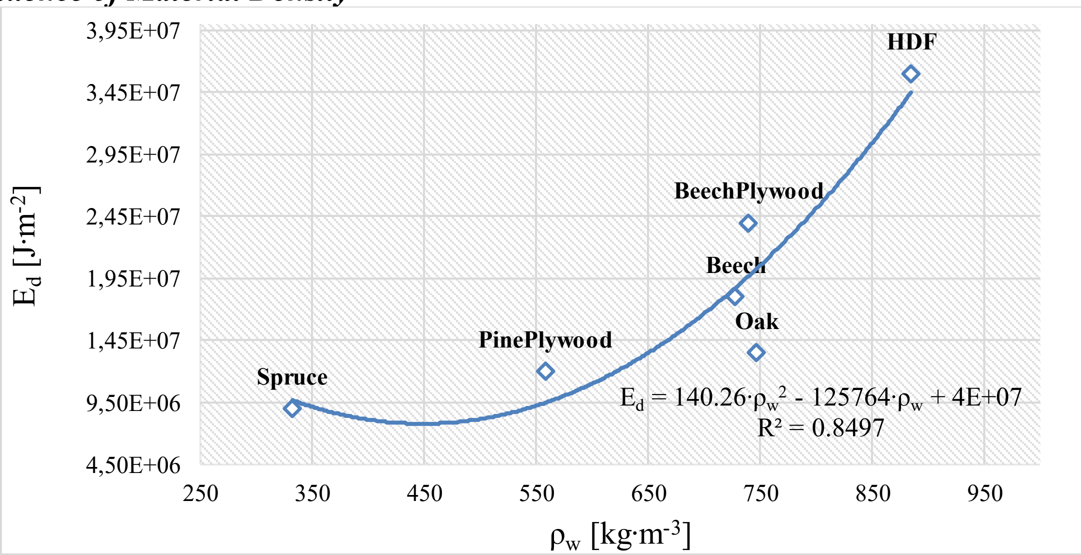

Fig. 1 Relation between material density and energy dose (E_d) in CO_2 laser cutting.

Figure 1 illustrates the relationship between material density (ρ_w) and the energy dose (E_d) required to achieve a kerf width of 300 µm. It shows a consistent trend across the six materials tested. Spruce, with the lowest density (ρ_w = 332.2 kg·m^{-3}), required the lowest energy dose (E_d = 9.00×10^6 J·m^{-2}), while HDF, the densest sample ($\rho_w \approx$ 885 kg·m^{-3}), required the highest energy (E_d = 3.6×10^7 J·m^{-2}). A second-degree polynomial regression fitted to the data $\mathbf{E_d = 140.26 \cdot \rho_w^2 - 125764 \cdot \rho_w + 4 \times 10^7}$ yielded a coefficient of determination $\mathbf{R^2 = 0.8497}$, indicating that approximately 85% of the variation in energy dose required can be explained by differences in material density. This suggests a strong, though not exclusive, dependence of energy dose on density.

The results show that E_d increases rapidly with density above 700 kg·m⁻³, suggesting that denser materials require more energy per unit area to reach the target kerf width. Beech, oak, and beech plywood are all close in density (around 740 kg·m⁻³), yet their required energy doses differ. Oak requires less energy than beech, despite similar density. This may be related to anatomical structure: oak is ring-porous, with large earlywood vessels that create internal variation in how heat is conducted and absorbed. Beech, as a diffuse-porous species, has a more uniform vessel distribution, which may lead to more stable heating but slower material degradation. This suggests that while density plays a major role as well as other factors like wood anatomy and adhesive content in plywood also influence the energy required for laser cutting.

This interpretation is consistent with Guedes et al. (2020), who reported higher energy requirements in denser woods during mechanical processing, as well as Andrade et al. (2022), who found that wood density has a moderate positive correlation with specific cutting energy, though other factors like anatomical structure also play a role, and Açık (2023)b, who observed greater kerf widths and thermal effects in denser species during CO_2 laser cutting. Given the limited sample size (n = 6), further testing is needed to confirm the general applicability of these findings.

Energy Dose (E_d) and Specific energy (E_c)

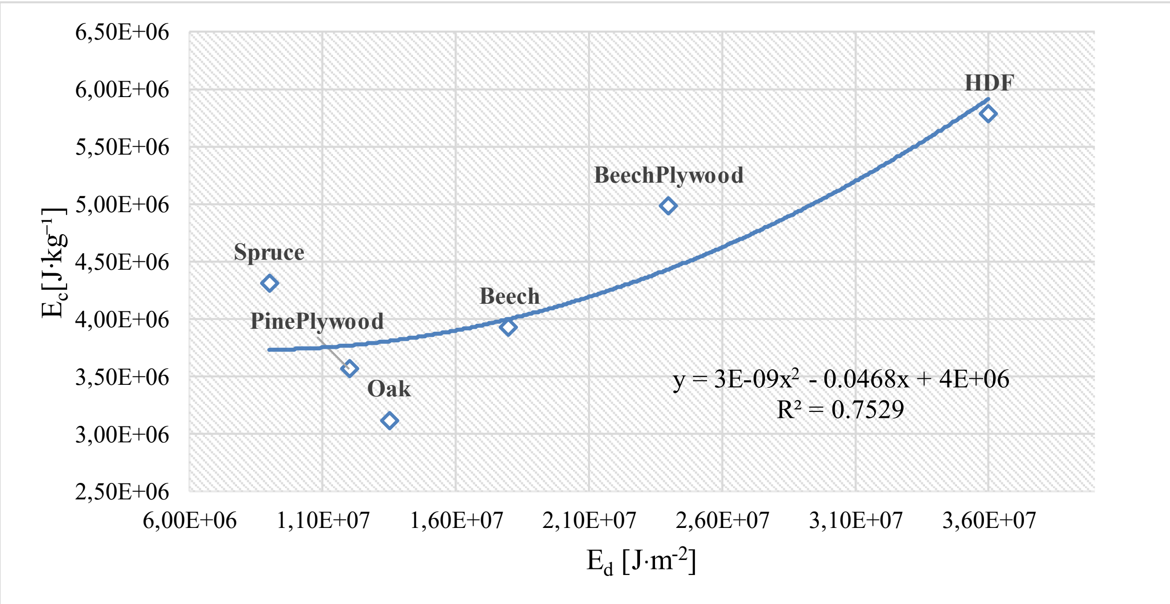

Fig. 2 Relation between energy dose delivered (*Ed*) and specific energy needed (*Ec*) in CO_2 laser cutting.

Figure 2 presents the relationship between the energy dose required to achieve a kerf width of 300 µm (E_d) and the corresponding cutting energy needed to remove 1kg for the six tested materials (E_c). The data show a positive nonlinear correlation, with E_c generally increasing alongside E_d. A fitted second-order polynomial regression $\mathbf{E_c = 3E\text{-}09 \cdot E_d^2 - 0.0468 \cdot E_d + 4E{+}06}$ describes this relationship with a coefficient of determination $\mathbf{R^2=0.7529}$, suggesting that roughly 75% of variability in E_c can be explained by changes in the applied energy dose. Materials at the lower range of energy dose (spruce, pine plywood, oak) exhibit relatively lower E_c values (around 3.0–4.5×10⁶ J·kg⁻¹). At higher E_d values, notably for beech plywood and HDF, E_c values rise as well, peaking above 6.0×10⁶ J·kg⁻¹ for HDF. This indicates that higher-density materials receiving larger energy doses require disproportionately more energy per unit mass to achieve the target kerf width. The deviation observed between materials at similar E_d levels, for example, beech versus beech plywood, indicates that additional factors beyond applied surface energy and density influence cutting efficiency. Such factors could include differences in internal structure, anatomical features, or the presence of adhesives in composite materials, all affecting heat absorption, transfer, and material removal rates.

However, while E_d quantifies the intensity of the laser energy applied to a material surface, E_c assesses how efficiently this energy translates into removing a mass of material. Comparing these metrics provides insights into the effectiveness of laser cutting conditions, looking into whether increased energy exposure yields proportionally efficient material removal.

A key comparison in this study is between beech wood and beech plywood, materials of nearly identical densities (728.0 vs. 740.1 $kg \cdot m^{-3}$; a difference of only 1.7%). Despite this similarity, beech plywood required approximately 27% higher specific cutting energy (E_c), indicating that density alone cannot fully account for differences in energy demand. Additionally, the average kerf width in beech plywood was 6.8% greater. These observations suggest that engineered structures, specifically the alternating grain orientations and adhesive layers in plywood, create barriers to heat penetration and result in less uniform thermal distribution. Consequently, more energy is dissipated within the plywood structure, reducing the efficiency of material removal.

Gochev described how such structures of accumulated thermal degradation residues, such as carbonized lignin in the kerf, which may contribute to reduced cutting efficiency and elevated specific energy requirements E_c (Gochev 2016). This behavior aligns with previous observations in peripheral mechanical processing, where wood species with complex grain structure or bonding agents required higher cutting energy (Carolina et al., 2022; Guedes et al., 2020).

Oak, despite having similar density to beech, required the lowest specific energy ($E_c = 3.12 \times 10^6\ J \cdot kg^{-1}$). This suggests that anatomical differences and possibly enhanced thermal conductivity along the grain direction positively influence cutting efficiency. Similar observations were reported by Açık (2023)b, who noted improved laser processing characteristics in anisotropic materials, such as bamboo, due to aligned fiber structures.

In contrast, HDF showed the highest energy demand in terms of both energy dose ($Ed = 3.60 \times 10^7\ J \cdot m^{-2}$) and cutting energy per unit mass ($E_c = 5.78 \times 10^6\ J \cdot kg^{-1}$). This result reflects significant energy losses likely stemming from the material's high density and adhesive-rich fiber matrix. Such characteristics were previously identified by Barcikowski et al. (2004) as key factors elevating energy requirements during laser cutting.

For engineered wood products like beech plywood, energy behavior during laser processing depends significantly on layered structure, alternating grain orientations, and glue-line interactions. Differences in thermal conductivity between wood layers and adhesive lines influence local heating, charring, and the efficiency of material removal. Adjusting processing parameters, cutting speed, and power output can improve energy utilization.

While laser power and feed rate are often used as the main parameters in kerf width adjustment, the actual cut geometry is determined by the geometry of the focused beam, its actual spot diameter, depth of focus, and where that focus lies relative to the material surface, as well as assist gas pressure and other factors. Gochev (2023) showed that placing the focal plane at the surface gives the best results in 6 mm-thick material, whereas for thicker workpieces, moving the focus point below the surface or deeper into the material yields a narrower kerf and straighter cut walls.

The relationship between density, energy dose (E_d), and specific cutting energy (E_c) shows how energy demand in laser cutting is influenced by material properties. Density influences the energy dose (E_d), which in turn reflects on E_c, the energy needed to remove mass. These relationships do not imply direct dependence but show a pattern that can be useful when selecting cutting conditions. Density can be used as a starting value when estimating suitable power and speed, while *Ed* helps refine expectations of cutting efficiency. This chain, density to E_d to $E_{c,}$ offers a basis for more informed adjustments to processing settings in future work.

CONCLUSION

CO_2 laser cutting of three wood species and three engineered materials using energy dose (*Ed*) and specific cutting energy (*Ec*) to evaluate cutting performance were examined in this work. *Ed* showed a strong connection to material density, while *Ec* revealed how structure and composition affect material removal. Engineered products such as HDF and beech plywood had the highest *Ec* values, which may be due to their resin content and layered construction. Oak, with a similar density to beech, showed the lowest *Ec*, suggesting that internal structure plays a role in how materials respond to laser exposure.

The observed relations between density, *Ed*, and *Ec* suggest that density could help guide the choice of laser settings, with Ed providing additional information on the energy applied and its effectiveness. Although the sample group is limited, these outcomes support further testing aimed at improving laser cutting efficiency based on measurable material properties.

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