CZECH UNIVERSITY OF LIFE SCIENCES IN PRAGUE
FACULTY OF FORESTRY AND WOOD SCIENCE

"EFFECT OF WOOD PROPERTIES AND CUTTING PARAMETERS ON THE QUALITY OF LASER CUT SURFACE"

"Vliv vlastností dřeva a řezných parametrů na kvalitu laserem řezaného povrchu"

DISSERTATION THESIS

Study program:	Forestry Engineering
Department (department/institute):	Department of Wood Processing and Biomaterials
Dissertation supervisor:	Ing. Miroslav Sedlecký, PhD.

Prague 2026 **Ing. Roberto Corleto**

Assignment

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CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Forestry and Wood Sciences

Ph.D. THESIS ASSIGNMENT

Roberto Corleto

Forestry Engineering
Wood Processing and Forest Machinery

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE
Faculty of Forestry and Wood Sciences

DISSERTATION THESIS TOPIC

Author of thesis:	Roberto Corleto
Study programme:	Forestry Engineering
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Thesis supervisor:	Ing. Miroslav Sedlecký, Ph.D.

Supervising department: Department of Wood Processing and Biomaterials
anguage of a thesis: English

Thesis title: **The influence of wood properties and cutting parameters on the quality of laser-cut surfaces**

Objectives of thesis: The work should evaluate the basic options for setting the CO_2 laser when cutting beech wood and the effect of the settings on the resulting quality of the machined surface and the change of selected physical properties.

- Setting the laser cutting in terms of cutting speed, gas pressure and power.

- Determination of the effect of moisture content on the cutting process.

- Optimization of cutting beech wood with a CO_2 laser.

Methodology: 1. Analysis of publications on CO_2 laser wood cutting.
2. Designing the optimization process, creating samples and determining their physical properties.
3. Control of samples and creation of test sets - subsequent measurement of individual properties.
4. Processing of results using standard statistical methods:
  - determining the distribution of the data,
  - exclusion of outliers,
  - data testing.
5. Description of the results and their evaluation.
6. Discussion, summary, and conclusions.

The proposed extent of the thesis: min. 100 pages

Keywords: CO_2 Laser; Beech wood; Laser power; Gas pressure; Focal point

Recommended information sources:

1. BADONIYA, P. CO2 laser cutting of different materials—A review. Int. Res. J. Eng. Technol, 2018, 5.6: 1-12.
2. ELTAWAHNI, H. A., et al. Evaluation and optimization of laser cutting parameters for plywood materials. Optics and lasers in engineering, 2013, 51.9: 1029-1043.
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I declare that I have written a dissertation on the topic of the effect of wood properties and cutting parameters on the quality of laser cut surfaces, with the use of literature and based on consultations and supervisor recommendations. I agree to the publishing of the dissertation pursuant to Act no. 111/1998 Coll., on schools, as amended, regardless of the outcome of its defense.

In Prague on…………. Ing. Roberto Corleto

Abstract

In recent years, CO_2 laser technology has been increasingly applied in wood processing due to its precision, non-contact cutting, elimination of tool wear, and absence of kerf width limitations. This study investigates the performance and quality of beech wood (*Fagus sylvatica* L.) processed with a CO_2 laser, comparing it to traditional saw cutting and evaluating the effects of varying moisture content (0%, 8%, 12%, and 18%). Key laser parameters, including cutting speed, laser power, gas pressure, and focal point, were monitored, while surface quality was assessed through profile deviation (*Ra*), waviness (*Wa*), color difference (ΔE), chemical changes, water vapor emission, and Brinell hardness. Results indicate that laser focus mainly influenced surface quality**.** Lower moisture slightly increased color changes**,** chemical modifications reduced hemicellulose and lignin, and surface hardness was slightly lower than saw-cut samples. Non-contact measurements provided more accurate surface quality**,** and overall, laser cutting delivered superior precision and smoother surfaces compared to circular saw cutting. The findings of this study enhance the understanding of CO_2 laser cutting's impact on wood and demonstrate that, compared to traditional circular saw cutting, laser cutting offers superior performance in terms of precision and surface quality. However, further optimization is required to improve energy efficiency and reduce operational costs, making this method even more viable for widespread industrial use.

Keywords: CO_2 laser technology, beech wood, Surface quality, Colour difference, Moisture content, Laser process parameters.

Abstrakt

V posledních letech se technologie, CO_2 laseru stále častěji uplatňuje při zpracování dřeva díky své přesnosti, bezkontaktnímu řezání, eliminaci opotřebení nástrojů a absenci omezení šířky zářezu. Tato studie zkoumá výkonnost a kvalitu buku (*Fagus sylvatica* L.) zpracovaného CO_2 laserem, přičemž je srovnávána s tradičním řezáním pilou a hodnotí se vliv různých obsahů vlhkosti (0 %, 8 %, 12 % a 18 %). Byly sledovány klíčové parametry laseru, včetně rychlosti řezání, výkonu laseru, tlaku plynu a ohniska, zatímco kvalita povrchu byla hodnocena pomocí odchylky profilu (*Ra*), vlnitosti (*Wa*), barevného rozdílu (ΔE), chemických změn, emisí vodní páry a Brinellovy tvrdosti. Výsledky ukazují, že hlavní vliv na kvalitu povrchu měl fokus laseru. Nižší vlhkost mírně zvýšila barevné změny, chemické úpravy snížily obsah hemicelulózy a ligninu a tvrdost povrchu byla mírně nižší než u vzorků řezaných pilou. Bezkontaktní měření poskytla přesnější hodnocení povrchu**,** a celkově laserové řezání zajistilo vyšší přesnost a hladší povrchy ve srovnání s kruhovou pilou. Zjištění této studie zlepšují porozumění vlivu CO_2 laserového řezání na dřevo a ukazují, že oproti tradičnímu řezání kruhovou pilou nabízí laserové řezání lepší přesnost a kvalitu povrchu. Další optimalizace je však potřebná ke zvýšení energetické účinnosti a snížení provozních nákladů, což činí tuto metodu vhodnější pro širší průmyslové využití.

Klíčová slova: technologie CO_2 laseru, bukové dřevo, kvalita povrchu, barevný rozdíl, obsah vlhkosti, procesní parametry laseru.

Hypothesis and Objectives

Goal

The primary objective of this thesis is to analyze the effects of CO_2 laser cutting on wood to optimize the quality of the laser cut-surface. Although this technology remains relatively unexplored in the context of wood processing, it presents significant opportunities for improving outcomes compared to traditional techniques. The research includes a comprehensive comparison of the advantages and limitations of conventional methods versus laser cutting, providing guidance for the industry in selecting the most suitable approach based on specific materials and products. The analysis is grounded in experiments conducted on beech wood samples (*Fagus sylvatica L.*) with varying moisture levels. The aim is to assess how moisture content (MC %) influences the quality of laser cutting. Optimizing the machining process is essential for enhancing both the yield and quality of the final product.

Hypothesis

1. The moisture content of wood (0%, initial (8%), 12%, and 18%) significantly affects the surface quality after CO_2 laser cutting.
2. CO_2 laser processing parameters, such as cutting speed, focal point, power, and gas pressure, have a measurable effect on cutting performance and surface quality.
3. There is a measurable difference in the surface profile of laser-cut wood when evaluated using non-contact methods compared to contact methods.
4. The elevated temperatures generated during laser cutting induce measurable chemical changes and alter the cell wall structure of the wood surface.
5. CO_2 laser cutting produces a superior surface quality compared to conventional cutting methods in wood processing.
6. Laser cutting impacts the diffusion and hardness properties of wood, influencing the overall performance of the processed material.

Research Objectives

- To systematically assess the surface quality of laser-cut specimens by measuring surface waviness, roughness, and color change, while examining the effects of varying wood moisture contents (0%, 8%, 12%, and 18%) and key laser cutting parameters, including cutting speed, focal point position, and gas pressure.
- To critically compare the effectiveness of contact and non-contact measurement techniques in evaluating the surface quality of laser-cut specimens, identifying their respective advantages and limitations in capturing precise surface characteristics.
- To conduct a comprehensive comparative analysis of surface quality between specimens produced through conventional sawing methods and those cuts using CO_2 laser technology.
- To investigate the chemical composition of laser-cut specimens using Fourier-transform infrared spectroscopy (FTIR), and to examine the anatomical structure (cell wall structure) of the wood surface using scanning electron microscopy (SEM), aiming to elucidate both the chemical and microstructural alterations induced by the laser cutting process.
- To evaluate the impact of laser cutting on the diffusion properties and hardness of wood by conducting diffusion and hardness tests on laser-cut samples, assessing changes in material properties resulting from the thermal effects of the laser, and quantifying any alterations caused by heat exposure.

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1. **Corleto, R**. Gaff, M. Niemz, P. Sethy, A. K. Todaro, L. Ditommaso, G. Rezaei, F. Sikora, A. Kaplan, L. Das, S. Kamboj, G., et al. (2020). Effect of thermal modification on properties and milling behaviour of african Padauk (*Petrocarpus soyauxii Taub*) wood. Journal of Materials Research and Technology 9(4): 9315-9327. DOI: 10.1016/j.jmrt.2020.06.018

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INTRODUCTION

Wood has been a fundamental material since ancient times, serving both structural and energetic purposes. Today, its sustainable use in traditional and innovative applications contributes significantly to carbon sequestration (Islam et al. 2023). However, wood is a living and highly variable material whose properties depend on species-specific characteristics and growth conditions. This natural heterogeneity, particularly evident in temperate hardwoods, often affected by knots and density variations makes standardization challenging. In this context, reliable non-destructive evaluation methods, including laser-based techniques, are essential to characterize and enhance the value of wood resources, especially those of secondary or variable quality (Boivin et al. 2024). In recent years, global demand for wood and environmentally friendly products has increased, partly due to changing consumer aesthetic preferences and the adoption of new technologies. Advances in furniture and building decoration production have leveraged technologies such as laser cutting to meet modern design demands and reduce costs (Kaplan et al. 2018; Eltawahni et al. 2013; Fukuta et al. 2016). Traditional mechanical cutting affects mainly physical properties (Kilic et al. 2006), whereas laser cutting induces structural, chemical, and physical changes (Haller et al. 2001; Kačík-Kubovský 2011; Kubovský-Kačík 2013). Compared to saws and milling tools, laser cutting is faster, more precise, produces less waste, reduces thermal stress, and can lower costs by up to 30 % (Li et al. 2018; Kubovský et al. 2020; Islam et al. 2023). Laser-cut wood is hydrophobic, unlike hydrophilic saw-cut wood, affecting adhesion (Maciak et al. 2024). Investments in laser technology aim to achieve superior surface quality at competitive costs (Stewart et al. 1980). Originally used for packaging molds, laser cutting now applies to automotive, furniture, marking, and sculpture industries (Powell 1998; Barcikowski et al. 2006; Yusoff et al. 2008). Cutting methods include mechanical, physical, chemical, or biological approaches (Reinprecht et al. 2021). Optimizing surface quality improves hardness, color, gloss, shape, and resistance to environmental and biological factors, reducing defects and production time while enhancing bonding, painting, and coating (Očkajová et al. 2016; Gaff et al. 2020; Aydın-Çolakoğlu 2003; Cebrail-Tutus 2020; Petutschnigg et al. 2013; Kúdela et al. 2020). Laser cutting is contactless, requiring minimal clamping, and avoids oxidation of cutting edges, producing smoother, more uniform surfaces compared to conventional methods (Yusoff, 2008; Barnekov 1986; Crafer et al. 1993). Laser cutting causes thermal decomposition, altering the chemical and anatomical surface structure, affecting color and hydrophilic/hydrophobic properties (Kúdela et al. 2019). Laser technology can economically optimize the cutting of hardwood boards to produce furniture or other articles. Since hardwood boards often have irregular shapes, such as tapering or curvature, it is essential to use an optimal cutting map, created by specialized software and integrated with trade orders. The intrinsic properties of the wood influence the surface quality of processed wood, the tools used and the processing parameters (Hazır-Koç 2018). Surface quality depends on moisture, extractives, species anatomy, and beam power density (McMillin-Harry 1971; Barnekov et al. 1986). Optimization of laser cutting parameters is crucial to achieve superior surface quality compared to traditional sawing methods (Brémaud et al. 2011). Laser treatment is crucial for optimizing wood surface characteristics such as shape, roughness, hardness, color, gloss and resistance to various agents (water, sun, fire, fungi and other biological agents) in the furniture industry and decoration (Fukuta et al. 2016; Očkajová et al. 2016; Gaff et al. 2020). Improved surface quality is essential for efficient gluing, finishing, sanding, and coating operations in furniture manufacturing. Surface roughness, which is strongly influenced by wood anatomy, density, and processing method, directly affects the accuracy and performance of adhesives and surface treatments. Excessive roughness often requires additional sanding, leading to increased material losses and longer production times. Therefore, systematic roughness assessment is a key component of quality control, contributing to reduced costs and improved efficiency in wood processing (Aydın-Çolakoğlu 2003; Açık-Tutuş 2020). Microscopic investigations indicate that laser treatment locally softens the wood surface by inducing partial fusion of cell walls within the outer micrometer-scale layer, without causing direct carbonization (Haller et al. 2014; Dolan 2014; Wang-Piao 2011). As a result, laser-cut surfaces are generally smoother than those produced by conventional sawing. This thermally induced surface modification also alters wood wettability, a critical factor for effective adhesive bonding and surface finishing (Dolan et al. 2014; Wang-Piao 2011; Petrič-Oven 2015; Hernandez-Castaneda et al. 2011). The anatomical characteristics of wood species, including vessel and lumen dimensions, significantly influence surface roughness during laser cutting (Fujiwara et al. 2003). Laser–wood interaction often results in curvilinear cut profiles and surface irregularities, arising from the combined effects of wood cellular structure and laser processing conditions (Adamčík et al. 2023). In solid wood, inherent surface variability is further governed by anatomical heterogeneity such as growth ring patterns, earlywood–latewood ratios, and density variations (Forest Products Laboratory 1987; Barcikowski et al. 2006; Korkut-Donertas 2007; Brémaud et al. 2011). In laser-cut wood, surface roughness (*Ra*) is mainly influenced by laser power, whereas in conventional saw cutting it depends on tool wear (Martinez-Conde et al. 2017). Laser-cut surfaces often require post-processing to remove thermally affected layers. Surface quality is affected by cutting parameters, wood anatomy, moisture, density, and fiber characteristics, measured using light sectioning, confocal microscopy, tactile devices, glossmeters, or laser methods (Barcikowski et al. 2006; Forest Products Laboratory 1987). Roughness increases with laser frequency and air pressure, and decreases with scanning speed and laser power. In beech, laser power and nozzle feed rate are critical (Eltawahni et al. 2011; Kubovsky 2020; Gurau et al. 2017), while higher assist gas pressure reduces combustion and roughness (Gurau-Petru 2018). Laser cutting performance is strongly governed by processing parameters. Higher cutting speeds reduce combustion, production costs, and cycle time, while increasing wood thickness requires lower feed rates when using high-power lasers (Peters 1975; Peters-Banas 1977). Laser power is the dominant factor controlling surface quality: increasing power generally increases surface roughness (*Ra*) and total color difference (ΔE), whereas higher scanning speeds tend to mitigate these effects. Excessive CO_2 laser power can induce carbonization and lignin degradation (Hattori et al. 1991; Naderi et al. 1999). In addition, surface roughness is influenced by assist gas pressure, laser frequency, and focal point position, with optimized gas pressure and centered focal positioning promoting smoother surfaces through more uniform energy distribution (Lin et al. 2008; Gurau-Petru 2018; Huber et al. 1989). CO_2 laser cutting of species like spruce, beech, oak, pine, larch, maple, and poplar produces anatomical undulations, especially in cuts perpendicular to the grain, due to differing ablation of earlywood and latewood. Surface quality assessment should consider both roughness (*Ra*, *Rz*, *RSm*) and morphological features. High powers (e.g., 45 W at 6 mm/s) can induce carbonization and microfractures, while lower settings reveal anatomical changes without major *Ra* variation. Cutting orientation affects earlywood, creating cavities and highlighting pores, with partial fusion or carbonization more common in beech than maple. Beech wood (*Fagus Sylvatica* L.) also exhibits denser roughness profiles, reflecting its higher pore frequency. These results emphasize that species, fiber orientation, and processing parameters critically influence wood microstructure and laser response, underscoring the need for species-specific strategies for lower-grade wood valorization (Adamčík et al. 2025; Gurau et al. 2024). The optimal feed rate for laser cutting is lower than for conventional cutting, as in the case of plywood, to ensure high-quality cuts. Increasing the cutting speed improves productivity through shorter cycle times, while optimizing the shielding gas speed increases performance (Mukherjee et al. 1990; Khan et al. 1992). When processing bamboo wood with laser cutting, it has been observed that the width and depth of the cut decrease with increasing cutting speed and increase with increasing laser power (Guo et al. 2021). The CO_2 laser, with a wavelength of 10.6 μm, is almost completely absorbed by wood and is the cheapest and most widely available type of laser, which is why much of the research focuses on it rather than on Nd fiber or disk lasers (Grad 1998; Yusoff 2006; Khan et al. 1992). CO_2 laser cutting induces heating, oxidation, and the formation of a carbon layer, altering the chemical composition of wood (Naderi et al. 1999; Hattori et al. 1991). Wood, composed mainly of cellulose, hemicellulose, and lignin, exhibits chemical changes detectable via Fourier Transform Infrared Spectroscopy (FTIR), a key method for studying heat and photodegradation effects (Chuchala et al. 2023). In beech wood (*Fagus Sylvatica* L.), CO_2 laser cutting increases O–H band intensity due to decomposition of oxygen-containing groups and cleavage of aliphatic hydroxyls, suggesting possible hemicellulose deacetylation, accompanied by a slight bending and absence of the C=O band (Rezaei et al. 2023). Studies on MDF confirm that higher feed rates increase surface roughness, highlighting the critical roles of laser power, cutting speed, shielding gas, nozzle design, and gas velocity in optimizing cut quality for both hard and soft woods (Lum et al. 2000; Eltawahni et al. 2011; Khan et al. 1992; Mukherjee et al. 1990). During CO_2 laser cutting of wood, with a power of 1 kW and a pulse duration of 300 ms, thermal decomposition of the cell wall is observed (Barcikowski et al. 2006; Wang et al. 2011). Late wood, with a higher density, a higher absorption of laser radiation by the cellular tissues is observed, while cells of early woody tissue show a lower absorption (Nath 2020). Wood moisture content (MC %) significantly affects laser-cut surface quality. Optimal moisture content (MC %) reduces charring and improves surface finish compared to dry wood (Lagaňa et al. 2021; Papp-Csiha 2017). Wet wood absorbs laser energy through water molecules, causing heating, boiling, pyrolysis, carbonization, and evaporation, which lowers cutting depth and increases energy consumption (McMillin-Harry 1971; Hernandez-Castaneda et al. 2011; Peters-Banas 1977; Bilanski-Ferraz 1991). Higher MC % decreases cutting efficiency by reducing feed rate and increasing thermal conductivity, limiting energy in the heating zone (McMillin-Harry 1971; Hernandez-Castaneda et al. 2011). Thin specimens are primarily cut by direct evaporation, whereas thicker ones require combined action of laser and heated gas jet. Increased MC % raises surface roughness (*Rq*, *Rz*) with species-dependent effects, necessitating slower feed rates (Rami Benkreif & Csilla Csiha 2022; Piili et al. 2009). In high moisture content (MC %) wood, much laser energy vaporizes water, reducing combustion efficiency (McMillin-Harry 1971; Hernandez-Castaneda et al. 2011). High MC can improve surface quality and reduce charring at high feed rates (Guo et al. 2021), while lower MC % favors smoother surfaces (Rezaei et al. 2022). For beech wood (*Fagus sylvatica* L.), increasing laser irradiation from 7.8 to 75 J/cm² elevates carbonization and decreases brightness (Kubovský-Kačík 2013; Sernek 2015; Vidholdová et al. 2017). Key parameters influencing wood colour change include feed rate, scan width, focus position, and laser power (Li et al. 2021). Higher laser dose, power, and transport speed uniformly reduce brightness (ΔL^*) and total colour difference (ΔE^*) (Kubovský-Kačík 2013), while increased power also raises surface roughness (*Ra*) and ΔE (Gurau et al. 2017). Despite the extensive body of research on laser–wood interaction, a comprehensive understanding of how moisture content influences surface quality, chemical modification, diffusion behavior, and hardness in laser-cut hardwoods remains limited. In particular, systematic studies that simultaneously evaluate surface roughness, waviness, color change, chemical alterations, and physical properties under controlled laser processing conditions are still scarce, especially for European beech (*Fagus sylvatica* L.). Although laser woodworking is classified as one of the non-traditional processing methods, there is extensive use and literature on the interaction of lasers with metals, polymers, ceramics, and textiles, but little on the interaction between lasers and wood. Therefore, studies on laser technology remain elusive, and the wood industry is particularly interested in providing quality products at a lower cost and in shorter production times.

This research utilized beech wood (*Fagus sylvatica* L.), a hardwood species. The material used in this study was sourced from woodstore.cz, a commercial supplier located in the Czech Republic.

2.1 Beech (*Fagus Sylvatica* L.)

Beech (*Fagus sylvatica* L.) is an ecologically and economically essential hardwood species commonly used in Europe. Characterized by medium density, a light color, and exceptional impact resistance, it is widely used in a variety of applications, including furniture, plywood, floors, toys, musical instruments and construction materials (Bulušek et al. 2016; Štefančík et al. 2018, Gašparík et al. 2016). This tree typically reaches heights of 30-40 meters and features silvery-grey bark, often covered with epiphytic algae, along with alternate, ovate or elliptical leaves (Packham et al. 2012). Native to Europe, the European beech is particularly widespread in Central Europe, with a notable presence in the forests of the Czech Republic (Fig. 1). It covers 7.2% of the total forest area in the country, compared to the 40.2% expected in potential natural vegetation (Chytrý et al., 2012; Machar et al., 2017).

Ecologically, beech (*Fagus Sylvatica* L.) is one of Europe's most important deciduous trees, playing a key role in the transition and adaptation strategies of European forests (Saltré et al. 2015; Liu et al. 2005; Straže et al. 2022). Its robust growth and positive response to rising CO_2 levels, increased precipitation, and warmer temperatures enhance its competitive ability (Rezaie et al. 2018; Šimůnek et al. 2021). Beech wood (*Fagus Sylvatica* L.) is one of the most widely utilized hardwoods in Europe, favored for its medium density and light color. It is commonly used for producing furniture, plywood, decorative veneers, parquet, and various other products (Pladias: Database of the Czech Flora and Vegetation, Gryc et al. 2008). When processing beech wood using CO_2 laser cutting, it is crucial to account for factors such as density and composition, as these elements significantly influence both the cutting speed and the final quality of the cut.

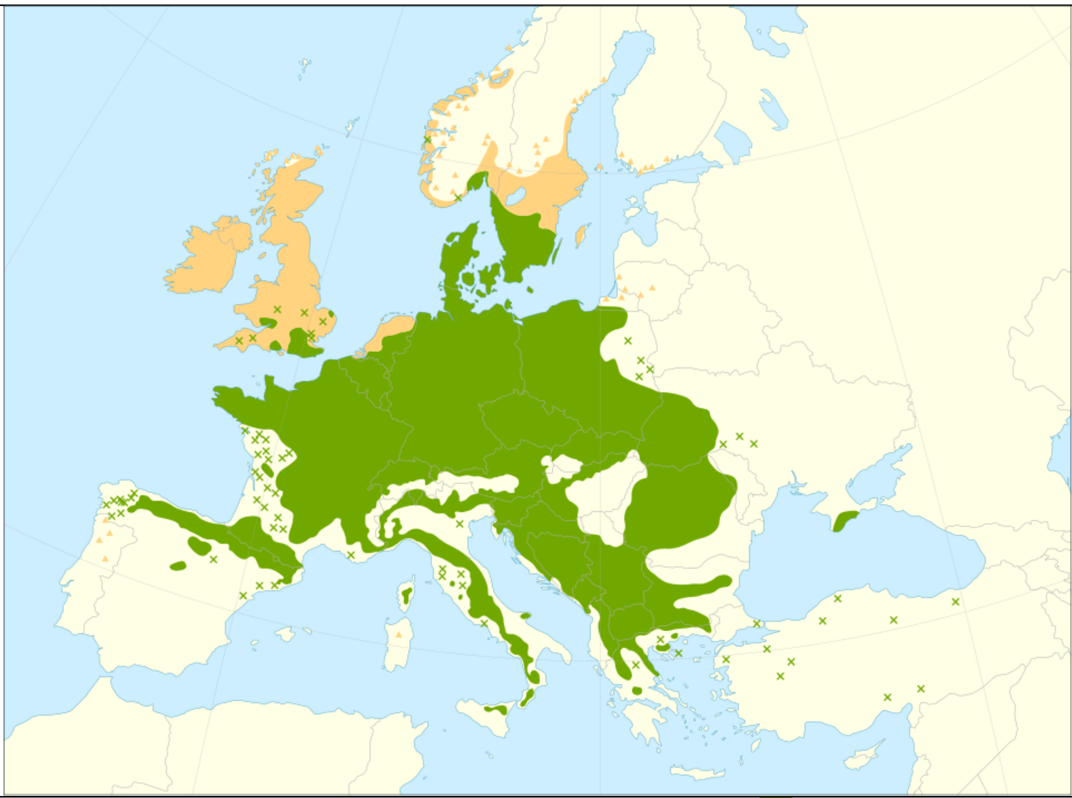

Figure 1. Distribution map of European beecn (*Fagus sylvatica* L.). ■ ✕ Native continuous range and isolated population ■ ▲ Introduced and naturalized (synanthropic) continuous range and isolated population authored by Caudullo et al. 2017.

3.1 History of laser

Marking and cutting materials were among the earliest forms of human artistic expression. The first evidence of marking dates to the Paleolithic period, with carvings on caves and bones. Later, around 3000 years ago, the Sumerians began using carvings on cylindrical stones. The technique of marking and cutting metal developed in the 5th century B.C. and became popular in Greece in the following centuries. In Egypt and Babylonia, as well as by the Romans, the cutting and marking of wood was done with primitive tools. The Japanese pioneered the creation of authenticated prints by cutting blocks of wood, while in the 15th and 16th century Europe, cutting and marking were mainly used for religious decorations (Margry 2012)

The theoretical basis for laser technology was laid by Albert Einstein in 1917 with his energy equation (Equation 1).

$$E = hv \tag{1}$$

Where:

1. E = is the energy of the photon.
2. h = is Planck's constant (6.626×10^{-34} Js).
3. v = is the frequency of electromagnetic radiation.

In 1950, Alfred Kastler contributed to developing the first devices capable of amplifying radiation by stimulated emission. However, it was in 1951 that Purcell and Pound first demonstrated the population inversion between nuclear magnetic energy levels. The first amplifier that used stimulated emission was the MASER (Microwave Amplification by Stimulated Emission of Radiation), developed in 1953 by Brasov, Towers and Veber (Yusoff 2006). Subsequently, several lasers were developed, including the CO_2 laser invented by Kumar Patel at Bell Labs in 1964, a molecular gas laser that emits radiation in the IR region of the spectrum, IR lasers being the most efficient with wavelength bands around 9.4 and 10.6 pm, and the highest power continuous wave (CW) lasers currently available (Yusoff 2006)

The first industrial CO_2 laser was created in 1966 by engineers at Coherent Radiation Laboratories. The use of lasers for wood cutting began in the early 1970s to produce dies in the packaging industry, remaining at the forefront of cutting technologies for over five decades and, replacing more conventional techniques such as mechanical sawing (Guo et al. 2021; Alejandro Martínez-Conde et al. 2017).

The CO_2 laser is the most widespread and most potent source in the world, operates in the infrared spectral range (wavelength 10.6 µm), has good absorption in organic materials and is well suited to woodworking. It reaches continuous powers of around 80 kW and, with its high efficiency of 15-20%, offers numerous possibilities for industrial applications (Steen-Mazumder 2010).

The use of lasers in woodworking is extensive across many areas of wood science, as illustrated in Fig. 2, including cutting, drilling, welding, coating, hardening, ablation, surface treatments, marking, engraving, micromachining, and modification of metallic and non-metallic materials.

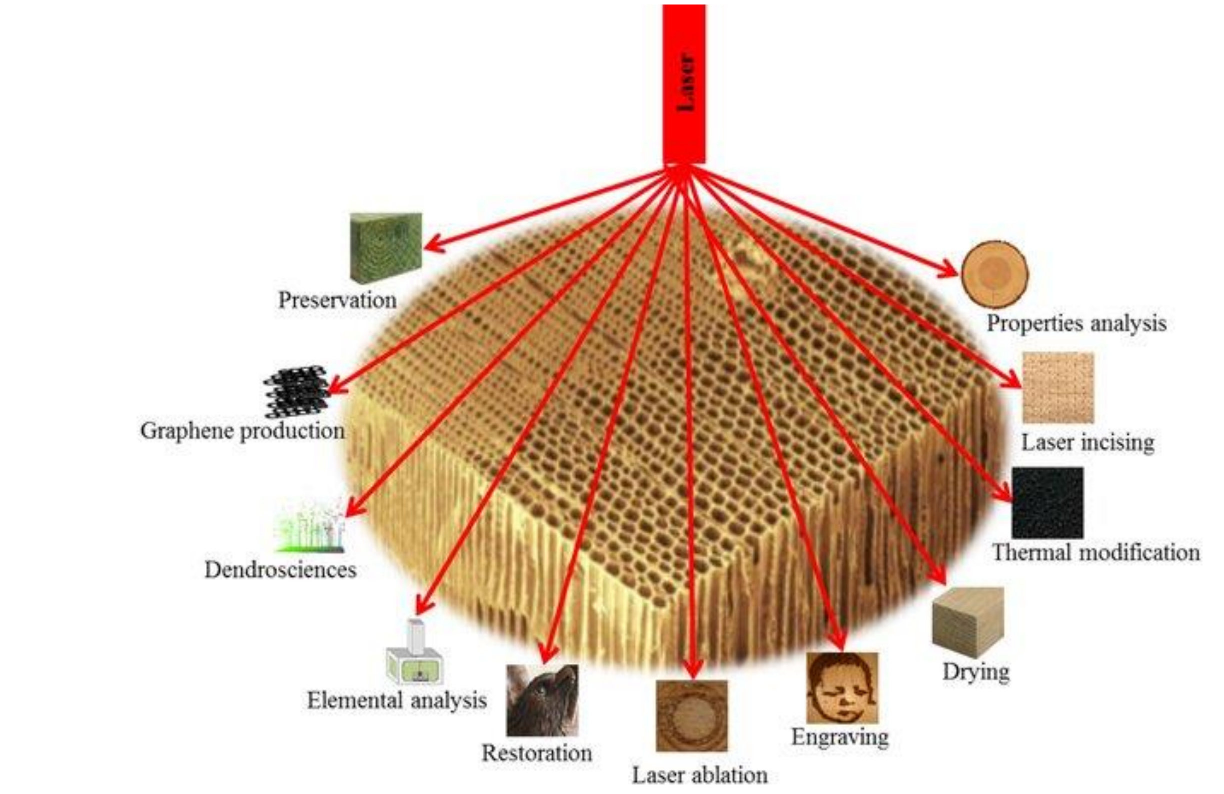

Figure 2. Laser applications in wood science range from determining the properties of wood to the production of advanced materials (By Islam et al. 2023)

Modern laser technology can precisely control the energy delivered to the material surface by adjusting parameters such as laser beam power, laser head movement speed, focal distance, and raster density. These parameters enable optimal results for different purposes and materials, including organic materials such as wood (Kudela et al. 2020; Gurau et al. 2018).

3.2 Laser Technology

Laser stands for Light Amplified by Stimulated Emission of Radiation and is defined as '...a device that produces a powerful, narrow beam of light that can be used as a tool, e.g. to cut various materials, perform medical operations, etc.' (Cambridge University Press 2014). The laser device is used when a resting atom is excited with energy; its electrons rise to a higher layer and, when they return to their resting state, release the energy obtained from the photons (Fig. 3) (Thesis: 'Quality systems and productivity' by: Carlos Joaquin Guzman Garcia 2004).

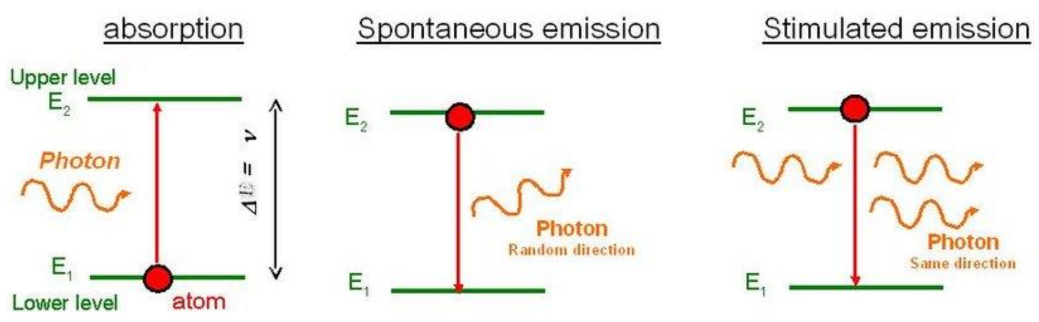

Figure 3. Principle of stimulated laser emission by De Matos 2017.

The laser beam is projected through a lens and focused on the surface of the material and, due to the high temperature, the volumetric zone concerned heats up, melts and vaporises rapidly.

Laser technology consists of three main components (Fig. 4)

- An active liquid, gaseous or plasma medium from which light is generated and amplified.
- An energy source.
- Resonators with optical feedback.

A certain number of light escapes from one of the two reflectors, as it is not 100% reflective, allowing the formation of a laser beam. The resonator is also responsible for the monochromaticity and unidirectionality of the beam (Steen-Mazum der 2010, 12-13).

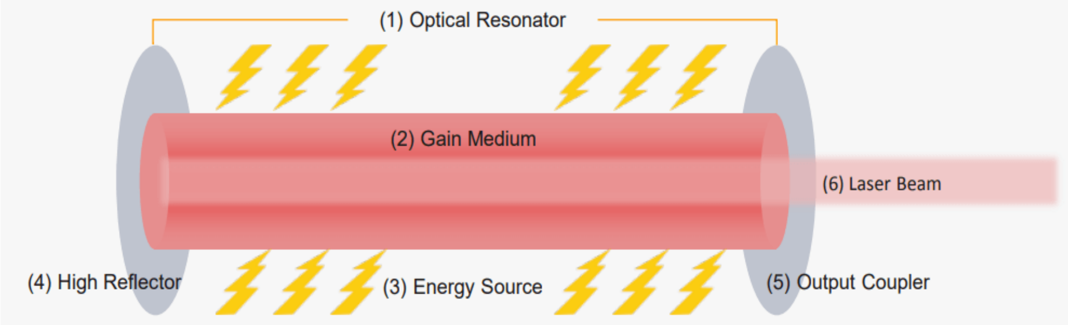

Figure 4. Laser. @2024 Messer Cutting Systems Inc.

The laser thus represents a source of energy that can be directed at desired objects by controlling the power and intensity, enabling the cutting of a wide variety of materials, from metal to textiles (Ondogan et al. 2005).

Laser cutting is a widely used process in many industries, where metallic and non-metallic materials are cut, welded and surface-treated, and is currently the most promising physical method for surface modification and wood cutting (Žigon et al. 2018; Zhiu et al. 2004).

3.3 Processing Wood with Laser Technology

Laser technology for wood cutting has numerous advantages over competing technologies and conventional methods that have ensured the growth of this industry, further improving the quality of wood products for the following reasons:

- Minimum cutting width (0.1-0.3 mm).
- Greater cutting precision (0.1-0.5 mm).
- High cutting precision on flexible or fragile materials that do not deform during cutting, as would occur if they were cut using mechanical methods.
- Reduced stress during workpiece processing.
- High cutting speed compared to conventional methods.
- Greater positioning flexibility and cutting interruption at any point on the workpiece.

- Achievement of high-quality edges and reduced production costs by using high productivity organic materials.

- Reduced labour requirements.

- Extremely quiet process compared to other techniques, which improves the working environment and efficiency of operating personnel.

- No tool wear due to the lack of direct contact with material.

In addition, the laser process reduces dust production, normally collected pneumatically, which is a very expensive process and is estimated to account for around 30% of total production costs (Yosuff et al. 2006; Seeger-To¨nsing 1999).

The energy of the laser beam is focused into a small area (0.1 to 0.8 mm^2), with the advantages of narrow, parallel cutting edges, a small thermally modified surface, reduced thermal distortions and the possibility of working on complex profiles with minimal radii of curvature (even sharp edges).

Among the most prominent disadvantages of laser cutting are:

- The carbonizing effect during combustion leads to a reduction in the surface quality of the wood (Naderi 1999).

- The generation of smoke and gaseous by-products during the laser cutting of wood, which may affect surface quality and requires efficient extraction and filtration systems.

- The difficulty of cutting highly reflective and conductive materials such as gold, copper, and silver.

- The difficulty of accurately cutting blind slits, pockets, holes or thin materials.

- Relatively high initial capital cost (Eltawahni et al. 2011).

The laser's ability to cut any material generally involves light absorption, transforming light energy into heat, distribution, heat transfer rate and vaporization in the heated area. Two fundamental optical properties of wood are significant: absorbance and transmissivity, in addition to processing variables and equipment (Barnekov et al. 1986; Yusoff 2006).

The CO_2 laser is a gas laser that emits radiation with a wavelength of 10.6 μm. This type of laser is particularly advantageous for woodworking compared to other laser types, such as the Nd laser, due to its excellent absorption of radiation by organic materials and relatively lower cost. Furthermore, the CO_2 laser offers high beam quality, higher power and a reasonable cost per watt (Fukuta et al. 2016; Nath et al. 2020; Martínez-Conde et al. 2017; Jiang et al. 2021).

The operating principle of the CO_2 laser is based on the excitation of CO_2 molecules using high voltage and high frequency in a laser resonator. This resonator contains fully reflective mirrors at both ends and a partially reflective mirror, which allows the coherent laser beam to pass through. The laser produces an infrared beam with a wavelength of 10.6 μm, which is focused on the surface of the material through a lens (Fukuta et al. 2016; Nath et al. 2020; Martínez-Conde et al. 2017; Jiang et al. 2021).

The cutting mechanism of the CO_2 laser can be described as follows:

- Beam emission: The high-intensity infrared light beam generated by the laser is focused on the material's surface through a lens.

- Heating and Melting: The focused beam heats the material locally, causing the surface to melt in a very narrow area (less than 0.5 mm depth).

- Material Removal: The melted material is ejected from the cutting zone by a pressurized gas jet, coaxial to the laser beam.

- Movement of the Cut: The material removal zone moves across the surface of the workpiece, thus creating the cut. This movement is achieved by manipulating the focused laser spot.

The efficiency of CO_2 laser cutting, and the quality of the cut surface are influenced by several parameters, including:

- Laser power.
- Focal Length.
- Focal Point Position.
- Type and Pressure of Assist Gas.
- Feed Rate.

- Material characteristics (type of wood or composite, density, moisture content).

Studies have documented the impact of these parameters on cutting quality and process efficiency (McMillin-Harry 1971; Peters-Banas 1977; Barnekov et al. 1986; Piili et al. 2009). CO_2 lasers are widely used in industry due to their ability to cut a wide range of materials with precision. The most common models use a mixture of CO_2, N_2 (nitrogen) and He (helium) and operate at a wavelength of 10.6 µm. These lasers can have an efficiency of up to 30% and produce an output power generally ranging between 25 and 1000 W (Silfvast 2003; Steen 2003). Helium (He), being a good co-conductor, acts on the cooling of the system as it keeps the CO_2 at a low temperature (below 200 °C), a necessary condition for laser operation (Hitz at al. 2001).

Peters and Marshall (1975) conducted studies on using the CO_2 laser for cutting different wood materials, including wood panels, plywood, cardboard, and paper. This work demonstrated the effectiveness of the CO_2 laser in precisely cutting wood materials (Martínez-Conde et al. 2017). Eltawahni et al. (2011) examined how various CO_2 laser parameters, such as cutting speed, focus and power, affect the cutting quality on medium-density fiberboard (MDF) panels of different thicknesses. Their results showed that these parameters strongly influence the cutting width and surface roughness (Eltawahni et al. 2011).

When cutting wood with CO_2 lasers (Fig. 5), it has been observed that using high powers can cause the material to melt and carbon to form on the surface, resulting in the thermal decomposition of lignin in the wood cell wall. This phenomenon has been documented in previous studies (Hattori et al. 1991; Naderi et al. 1999).

Lum et al. (2000) studied the effect of laser cutting on medium-density fiberboard (MDF), identifying the cutting process as a form of thermochemical decomposition (TCD). Their results showed that the average width of the cut decreases with increasing cutting speed. Although they did not find a significant reduction in shear width by varying the type or pressure of the shielding gas, they observed that increasing the gas pressure did not improve surface roughness (*Ra*) values. Furthermore, they concluded that the surface roughness (*Ra)* increased with increasing cutting speed and that the maximum cutting speed for each thickness did not depend significantly on the pressure or type of gas. Therefore, it was suggested that using compressed air may be more economical than nitrogen for laser cutting of MDF (Lum et al. 2000).

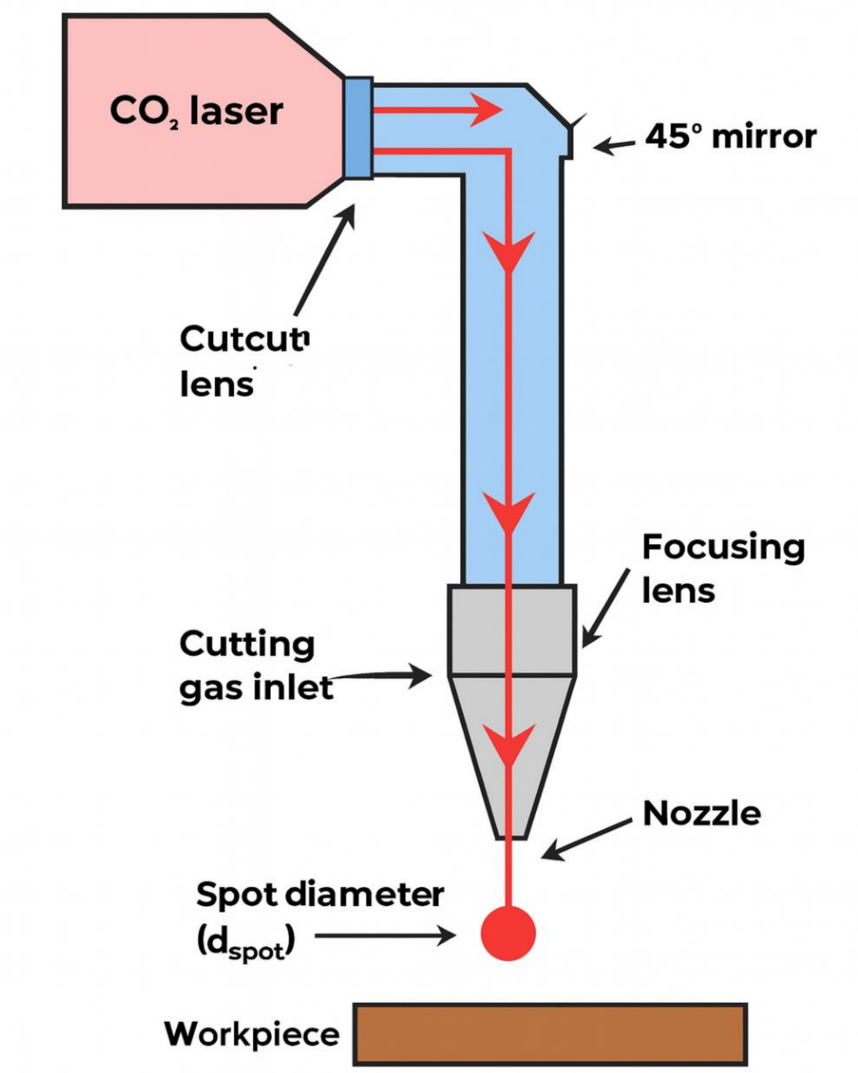

Figure 5. The CO_2 laser cutting process on wood (L – longitudinal, R – radial and T- tangential direction content available from Wood Science and Technology.

The laser beam's energy acts to break chemical bonds and thus destroy the integrity of the material. Furthermore, the importance of parameters such as laser power, specific energy, cutting speed and protective gas determine the quality of cutting hard, soft, and resinous woods such as Picea abies, Abies alba and Pinus Nigran (Yusoff et al. 2008).

When investigating the laser cutting of green or wet wood, Peters, and Banas (1977) observed that high moisture content reduces the efficiency of the cutting process compared to dry wood. However, high moisture content helps improve the cut surface's quality, as it reduces carbonization and limits the formation of carbon residues on the surface. Malachowski (1984) confirmed the feasibility of cutting green wood using a CO_2 laser, focusing on green branches, and demonstrating that the process is also feasible for moist materials. Several studies have examined the optimization of CO_2 laser cutting for wood, using theoretical and experimental models to improve the quality of the cut. Zhou and Mahdavian (2004) and Hernandez-Castaneda (2011) analyzed the cutting parameters, while Kubovský et al. (2020) and McMillin et al. (1971) studied how cutting speed, assist gas pressure, laser power, focal point, and physical properties of the wood influence the surface quality during cutting. Piili et al. (2009) confirmed that these parameters are critical to achieving a high-quality finish. According to Nath et al. (2020), various parameters influence the hole size when cutting beech (*Fagus sylvatica* L.) wood, including laser power, focal point position and pulse duration. The direction of the cut, such as cutting parallel to the tracheids (fibers) of the wood, can improve the quality of the cut.

CO_2 lasers have been successfully used in wood processing, including fresh wood with high moisture content and branches up to 2-3 cm in diameter. Operating at relatively low powers, these lasers offer adequate cutting speeds, suggesting their use in pruning fruit trees and some forest plantations.

The cellulose and lignin in wood absorb radiation in the 493 cm^{-1} band, converting the laser energy into heat. Since wood conducts heat inefficiently, the heat accumulates on the surface, causing localized combustion and carbonization. Heat transfer capability depends on various factors, including laser power, feed rate and wood density (Maciak et al. 2024).

3.4 Classification of lasers

Lasers are classified according to their medium into three main categories: semiconductor diode, gas, liquid and solid. Each operates in one of two-time modes: continuous wave (CW) or pulsed. In CW mode, the laser beam is emitted continuously throughout the entire cutting process. In contrast, in pulsed mode, the beam is emitted periodically in short time intervals for each cutting pulse (Chryssolouris 1991).

The laser diode uses a light-emitting diode (LED) with an optical cavity made of solid material to amplify light from the forbidden semiconductor band. Its wavelength can be varied by adjusting the current, temperature or magnetic field. The output can be continuous (CW) or pulsed.

Solid lasers such as ruby, neodymium, glass and Nd-YAG (aluminum yttrium garnet) with a wavelength of 1.06 microns have replaced other types due to their high efficiency and ability to maintain high power for extended periods. Liquid lasers operate with an electron beam passing through an optical cavity in an external coil-like magnetic field, causing photons to be emitted. This type of laser can generate wavelengths ranging from the microwave to the X-ray region.

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The most common gas lasers are carbon dioxide (CO_2) lasers, known for their effectiveness in large-scale production due to their 10.6-micron wavelength (Steen 2003). Other types of industrial laser systems include the carbon monoxide (CO_2) laser and the excimer laser (Steen 2003). These lasers use a gas-filled tube as an optical cavity. An external pumping source applies a voltage to excite the atoms in the gas, causing a population inversion in which the electrons move from a lower to a higher energy state and then return. The generated photons bounce between the mirrors at the ends of the cavity, accumulating in an oscillating action. The light emitted by these lasers is typically continuous (CW).

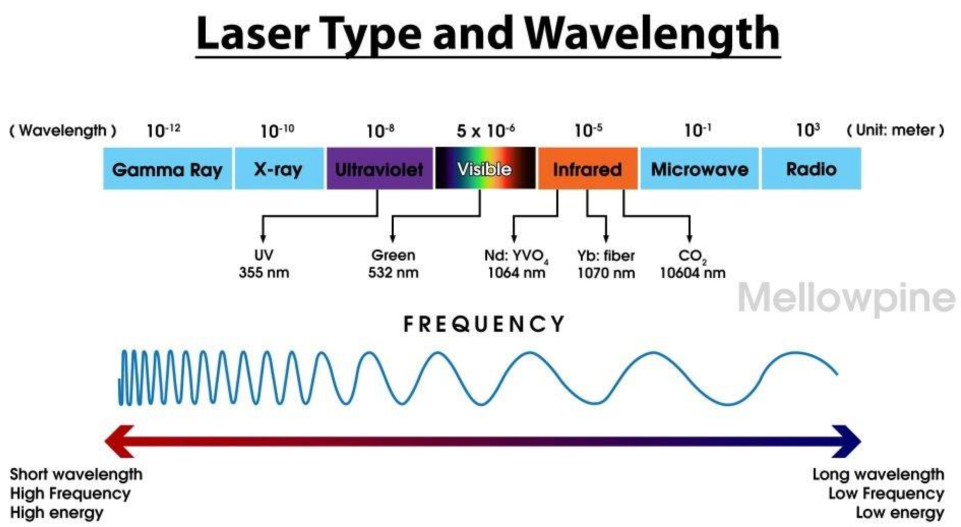

Figure 6. The wavelength of different lasers in the electromagnetic spectrum (John 2023).

Lasers operate through advanced principles of quantum physics and materials science, using different wavelengths (Fig. 7) determined by the type of laser and the excitation process. The main parameters include the emission wavelength, power, diameter, and beam divergence. Other essential factors are the type of emission (pulsed or continuous), efficiency, output beam profile, pulse duration and usability of the device.

LASER TYPE	WAVELENGTH (Nanometers)
Argon Fluoride	193
Xenon Chloride	308 and 459
Xenon Fluoride	353 and 459
Helium Cadmium	325 - 442
Rhodamine 6G	450 - 650
Copper Vapor	511 and 578
Argon	457 - 528 (514.5 and 488 most used)
Frequency doubled Nd:YAG	532
Helium Neon	543, 594, 612, and 632.8
Krypton	337.5 - 799.3 (647.1 - 676.4 most used)
Ruby	694.3
Laser Diodes	630 - 950
Ti:Sapphire	690 - 960
Alexandrite	720 - 780
Nd:YAG	1064
Hydgrogen Fluoride	2600 - 3000
Erbium:Glass	1540
Carbon Monoxide	5000 - 6000
Carbon Dioxide	10600

Figure 7. A summary of the various laser types shows the specific wavelength of light produced by each type of laser, highlighting the fundamental differences between different laser materials (Copyright © 1995-2024, DigiKey).

3.5 CO_2 Laser parameters

This chapter provides a general overview of the parameters of the laser machine used in the cutting process.

3.5.1 Cutting speed

The cutting speed in the laser cutting process is closely related to the thickness of the material to be processed. When working with thicker materials, the cutting speed must be reduced to allow adequate penetration and acceptable cut quality. Conversely, for thinner materials, the cutting speed can be increased.

This balance is crucial to achieve optimal cutting results and prevent problems such as carbonization or insufficient laser penetration (Jon 2005; Moposita 2018).

The cutting speed must be adjusted according to the material thickness to optimize cutting quality and economic efficiency. An increase in cutting speed reduces the cycle time and, consequently, the unit cost of the process. However, if the cutting speed exceeds the maximum recommended value for a specific thickness, the laser may not penetrate the material completely, resulting in incomplete cuts. Conversely, a cutting speed that is too low may cause burning or charring of the edges, compromising the quality of the final cut. The attached figure (Fig. 8, 9) illustrates the maximum recommended speeds for different material thicknesses, highlighting the importance of keeping cutting parameters within the limits to avoid quality problems (Martinez-Conde et al. 2017). The feeding speed significantly affects the surface roughness of the material. Studies have shown that a lower cutting speed can improve surface quality by smoothing the surface. However, burning can occur if the speed is too low, especially in woody materials. To obtain high-quality surfaces, it is often advisable to use low-speed vertical or conventional cutting instead of high-speed laser cutting (Barnekov et al. 1989; Eltawahni et al. 2011).

In industrial projects where surface quality is a priority, opting for woods such as solid poplar, which offers relatively even surfaces, is preferable. However, coniferous woods such as Scots pine and cedar may have a smoother cut surface on average, due to their large trachea structure and the marked distinction between spring and summer wood. In general, to minimize roughness, it is advisable to use high-density woods, which tend to provide smoother and less rough surfaces (Kubovský et al. 2020, McMillin et al. 1971, Piili et al. 2009).

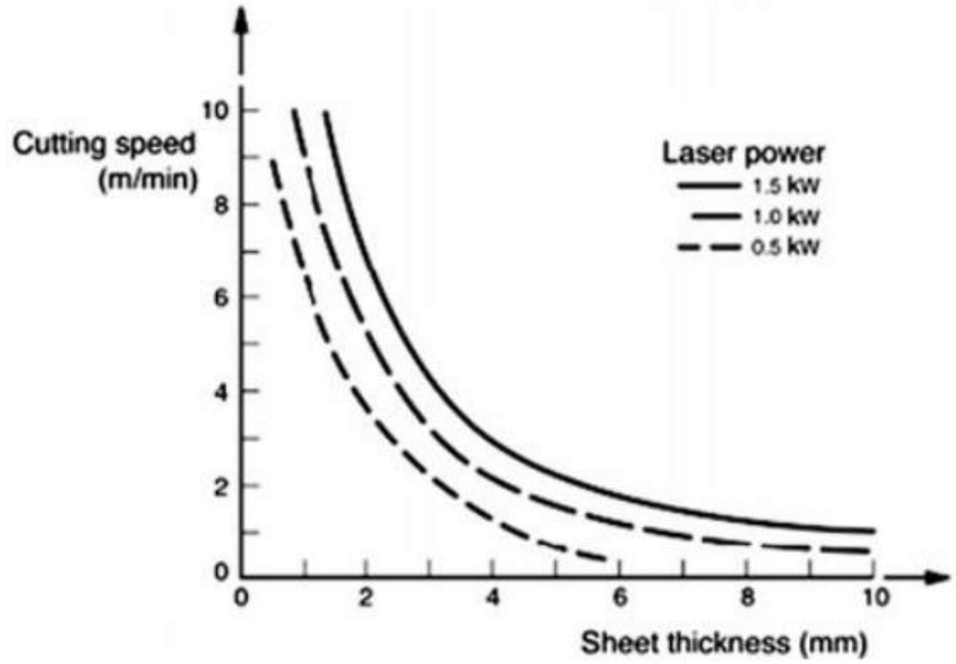

Figure 8. Variation of cutting speed with workpiece thickness (adapted from Ion 2005).

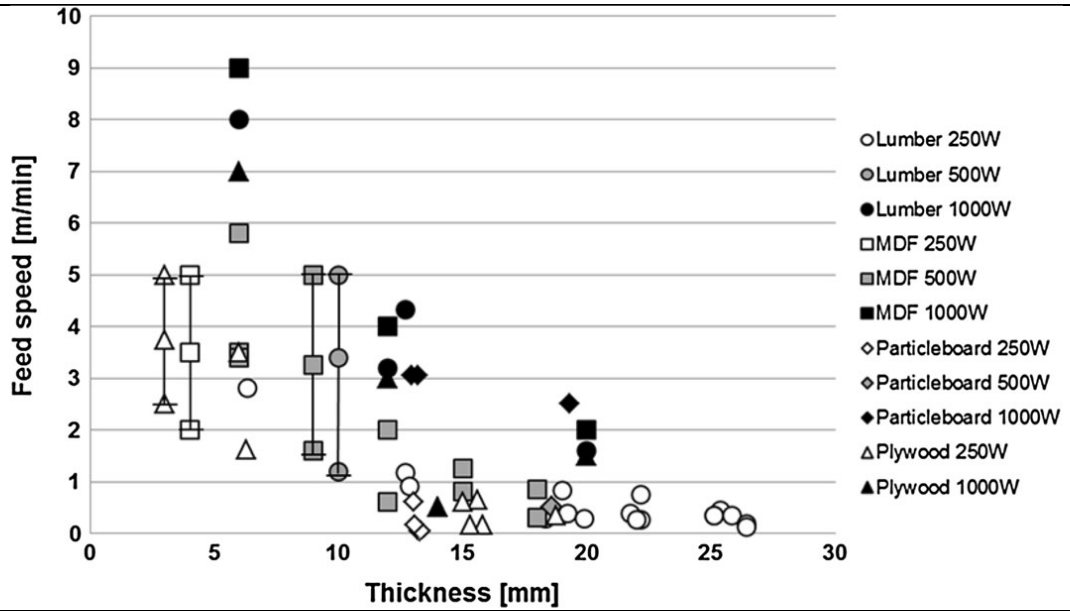

Figure 9. shows the relation between feed speed and material thickness for different wood types (lumber, MDF, particleboard, plywood) at various CO_2 laser powers. The dots indicate minimum, median, and maximum feed speeds (Martinez-Conde et al. 2017).

The cutting speed, expressed in meters per second, is a fundamental parameter in laser processing, as it directly affects both productivity and cutting quality. Increasing the speed accelerates the process but may reduce precision and compromise surface finish, especially when working with thick materials or those with complex thermal properties. Conversely, lower speeds improve edge definition and surface quality, albeit at the cost of longer processing times.

In general, low speeds (0.1–1 m/s) are suitable for complex geometries or heat-sensitive materials, producing smooth surfaces and fine details; moderate speeds (1–10 m/s) provide a good balance between quality and productivity, while high speeds (>10 m/s) favor processing efficiency, making them ideal for large-scale production.

Several studies have shown that the feed rate significantly influences surface roughness: reducing it results in smoother and more homogeneous surfaces but increases the risk of burning, particularly in wood. For high-quality finishes, moderate speeds and vertical cuts are preferred. The material's nature also plays a crucial role: for example, poplar offers good uniformity but may be rougher than softer woods such as pine or cedar, while dense hardwoods are preferred when surface finish is critical.

Laser cutting can produce wavy or carbonized surfaces due to the combustion of lignin and cellulose; however, the use of pulsed lasers helps mitigate these effects, improving uniformity and reducing roughness. Additionally, laser-cut surfaces show a lower water absorption capacity, which limits pathogen attack and reduces the need for chemical treatments (Acik-Tutus 2020; Maciak 2024; Accurl 2025).

3.5.2 Focal point position

Focal length, depth of focus and focal point position influence the energy concentration and geometry of the laser beam in the cut. Studies show that the position of the focal point relative to the cut material is crucial for cutting efficiency (Barnekov et al. 1986; Peters-Marshall 1975). When the focal point is above the material's surface, the energy density decreases, leading to a greater width of cut and carbonization of the surface. If the focal point is on the surface, the energy density is maximum but decreases with increasing wood thickness. The ideal position of the focal point is slightly above the centre of the workpiece to achieve a uniform energy density, a narrower cutting width and a less charred surface (Fig. 10).

For cutting wood, particle board, fiber board and plywood, the optimal focal length is between 75 and 150 mm (Eltawahni et al. 2011; Peters-Marshall 1975). A focal length of 190.5 mm is recommended for phenolic resin boards, while for cardboard, it is between 63.5 and 127 mm (Powell 1998; Martinez-Conde et al. 2017; Malmberg et al. 2006).

A greater cutting width and more evident carbonization are observed when the focal point is slightly above the surface. If the focal point is on the surface or slightly above the centre of the workpiece, the cut is smoother, with less carbonization and a smoother surface (Barnekov et al. 1989).

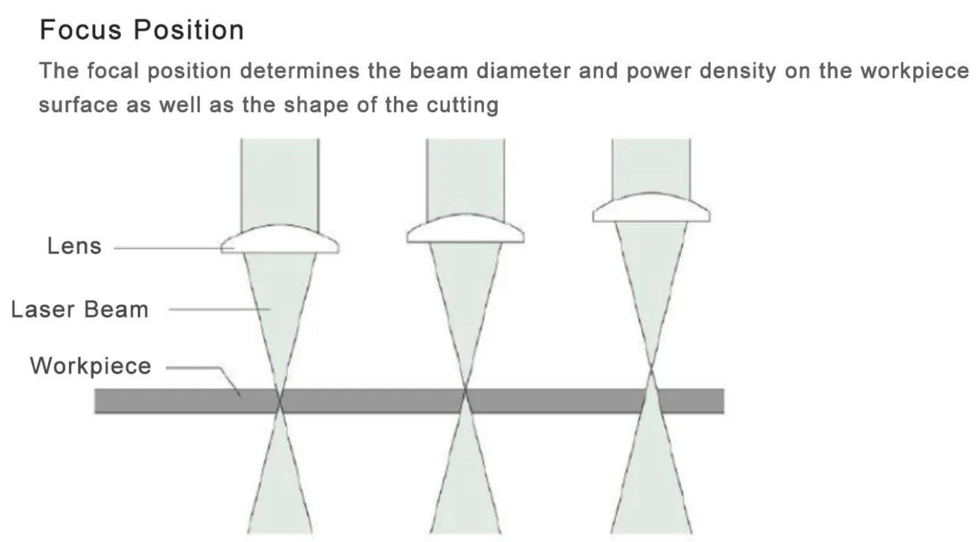

Figure 10. Variation of focal point position on the workpiece (Copyright@1987-2022 Nanjing BLMA Machinery Co., Ltd.).

The optimal focal point position during CO_2 laser cutting on hardwood should be at a position Z/2 (Z is the focal length) below the surface, with an average laser power density (Eltawahni et al. 2011).

When the focal point is positioned below the surface, the energy density is more uniform throughout the thickness and below the surface, resulting in a deeper cut with a smaller *kerf*. For cutting thin materials, the position of the focal point is not very important; however, for cutting hard and thick wood, it is important to know the position of the focal point to achieve the most efficient cuts.

According to Barnekov (1986), the position of the focal point relative to the workpiece also influences the efficiency of the cut, as well as accuracy and quality (Barnekov 1986).

The top of the focal column should touch the surface to achieve the highest average laser power density. This position of the focal point relative to the workpiece surface maximizes the average power density of the laser in the kerf, including the entire focused beam column within the kerf and exploiting the self-focusing of the beam (Yusoff 2006; Khan-Cherif 1992)

A smooth surface with less charring was obtained when the focal point was positioned at or slightly above the centre of the workpiece. According to

Barkenov (1986), the three main areas that influence the interaction between the laser beam and the wood are 1) the characteristics of the laser beam, 2) the variables of the equipment and processing, and 3) the properties of the working materials. To date, no information defines the optimal focal length for cutting wood thicker than 50.8 mm (2 inches). The position of the focal point relative to the workpiece also influences the efficiency of the cut, whereby the energy density is uniform across the thickness, and the width of the cut is smaller and more uniform; the cutting surface has less charring and is smoother and deeper (Barnekov et al. 1986; Gaff et al. 2020).

3.5.3 Laser Power

Laser power, measured in watts, is one of the most influential parameters in laser cutting processes, as it directly affects the feed rate, cutting quality, and the extent of the heat-affected zone. Increasing laser power enhances the material removal rate and allows deeper cuts, enabling the processing of thicker materials. However, excessive power can cause corner burning, slag formation, and thermal distortion due to heat accumulation, which can compromise both precision and surface finish (Steen 2003). The selection of the appropriate power range must therefore be carefully calibrated according to the material type and its thickness. In general, low power levels (10–500 W) are suitable for thin or heat-sensitive materials such as light plastics, fabrics, and metal foils, ensuring minimal thermal impact. Medium power levels (500–2,000 W) are ideal for materials of intermediate thickness, providing a balance between accuracy and productivity. At high power levels (above 2,000 W), laser cutting is applied to dense or thick materials such as stainless steels and special alloys commonly used in the automotive and aerospace industries where precise heat management is essential to prevent deformation or surface damage (Copyright ©2025 Accurl).

High power levels increase cutting depth almost linearly, while feed rate has a nonlinear influence, reducing penetration when excessively high (Maciak et al., 2024). Conversely, insufficient power may result in incomplete cuts or localized melting, with variations depending on the material. Similarly, excessively high cutting speeds shorten the interaction time between the laser beam and the material surface, hindering penetration and leading to discontinuous cuts (Barnekov et al. 1986; Lum et al. 2000; McMillin-Harry, 1971; Malmberg et al. 2006). In summary, a controlled increase in laser power allows for deeper and more complete cuts, but it requires a careful balance with feed rate and the thermal characteristics of the material to ensure precision, efficiency, and high-quality cutting results (Moposita 2018).

3.5.4 Gas pressure

To achieve effective laser cutting, the use of an auxiliary gas (Fig. 11) is crucial and performs four main functions:

- Ejection of melted material: Removes melted material and reduces slag formation.
- Protection: Protects the laser lens from splashes and prevents oxidation of the cutting zone.
- Cooling: Cools the cutting edge and can produce additional heat due to the exothermic reaction, depending on the gas used.

The gas pressure, which can vary from low (~1-6 bar with oxygen) to high (up to 20 bar with inert gases), and the nozzle condition have significant dynamic effects during cutting. Increased gas pressure reduces the carbonization layer on the wood surface without affecting the cutting width and speed (Quintero et al. 2011). An active gas such as O_2 generates oxide on the surface after cutting, which requires cleaning processes. While using inert gas or nitrogen does not produce rust on the surface, it can reduce cutting speed. The gas purity is also a factor in cutting performance, as even a small amount of impurities reduces cutting speed or can increase slag after cutting (Moposita 2018).

The role of oxygen on the depth of cut was also investigated by replacing the cover gas with air. It was noted that when air was used instead of nitrogen as cover gas, the depth of cut was relatively higher.

In contrast, by introducing low-flow oxygen into the cut through an auxiliary nozzle, it was found that the combustion process was enhanced and the cutting performance improved (Yusoff 2006; Khan-Cherif 1992).

Smoke from wood combustion must be expelled by means of a gas jet to protect and control excessive combustion (Huber et al. 1989). The type of gas and its pressure also significantly influence the penetration depth and quality of the cut.

Studies show that different jet configurations can significantly improve the cutting process, and for various classes of materials or wood species, specially designed jet systems may be required to reduce beam diffraction and maintain the desired energy level with less surface carbon (Huber et al. 1989).

In addition, gas type and pressure affect penetration depth, feed rate and wood quality (Peters-Marshall 1975, Powell 1998, Lum et al. 2000).

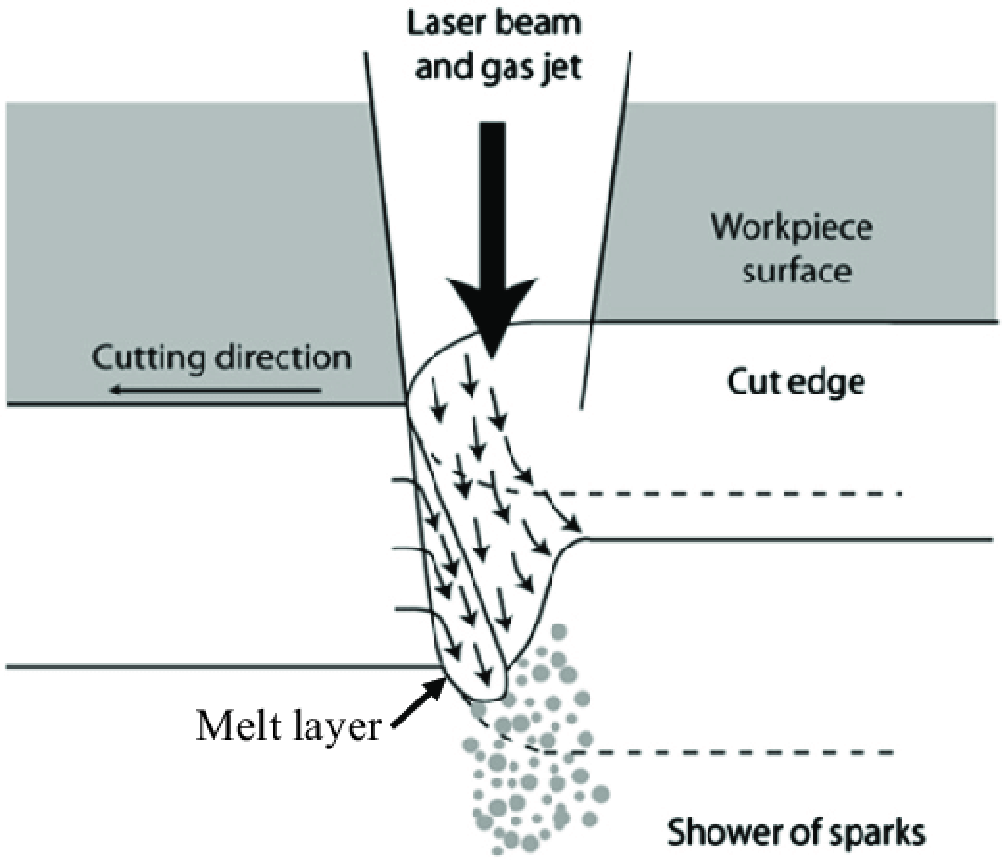

Figure 11. Schematic diagram illustrating laser cutting process (Source: CO_2 Laser Cutting; Powell John 1993).

Optimizing gas pressure is crucial: too low a pressure compromises the effective removal of debris and gas, increasing the risk of burning or material build-up on the cutting edge. On the other hand, pressure that is too high can cause dispersion of the laser beam, compromising cutting accuracy and potentially increasing surface roughness.

3.5.5 Heat-affected Zone (HAZ)

The Heat-Affected Zone (HAZ) in wood (Fig. 12), created by the heat of the laser beam during cutting, is significantly influenced by:

- Growth rings: The density changes caused by growth rings.
- Fibre orientation: The arrangement of the fibres in the wood.

- Laser power: The intensity of the laser beam used.
- Material thickness: The thickness of the wood to be cut.

These factors are crucial for the formation and quality of the Heat-Affected Zone (HAZ) (Powell-Kaplan 2004, Rezaei et al. 2022; Barnekov et al. 1986). The quality of the cut can be optimized by reducing the temperature of the workpiece, thus promoting low-temperature laser processing. In a study that examined the cutting of a unidirectional carbon/epoxy laminated composite both perpendicular and parallel to the fibers, a cold nitrogen jet was used to limit damage and analyze the growth of the Heat-Affected Zone (HAZ) (Pan-Hocheng 2001).

The Heat-Affected Zone (HAZ) range is estimated from the matrix isotherm and the carbon temperature. Heat conduction is maximized along the carbon fibers, and the shape of the Heat-Affected Zone (HAZ) is influenced by the scanning direction of the laser beam concerning fiber orientation. An unexpected amount of heat is confined near the laser, resulting in a narrower Heat-Affected Zone (HAZ). By increasing the cutting speed, heat diffusion from the cutting zone decreases, temperature gradients in the *kerf* increase, and local oxidation is reduced (Yusoff 2006; Pan-Hocheng 2001).

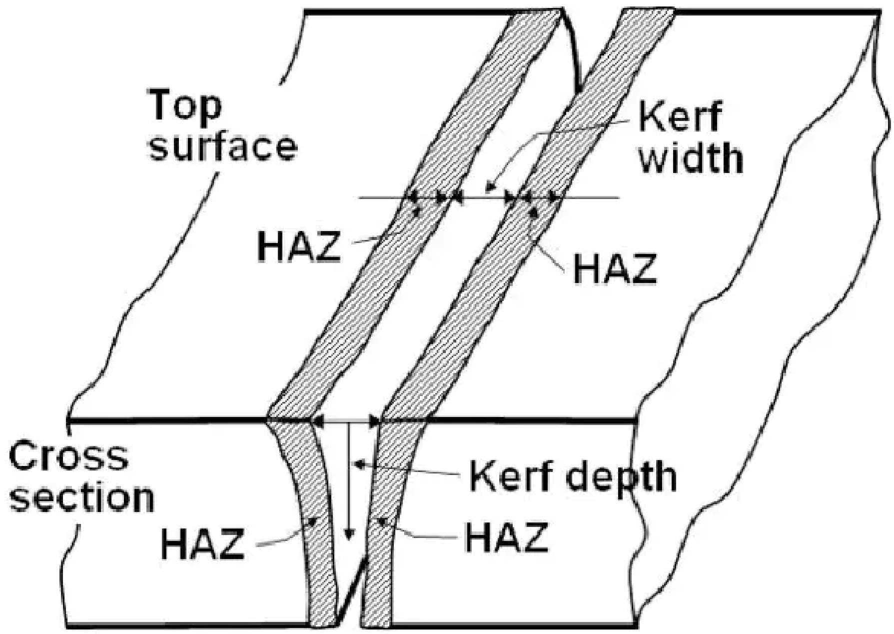

Figure 12. Laser Heat-Affected Zone (HAZ) (Image source: SemanticScholar.org, Copyright © 2021 Weldingpros.net).

In the laser cutting process, the beam, characterized by a Gaussian distribution, has a very small focal point (Fig. 13). The power density and depth of focus of the laser beam allow a reduction in beam width and an increase in cutting speed, enabling the cutting of thicker materials (Steen 2003).

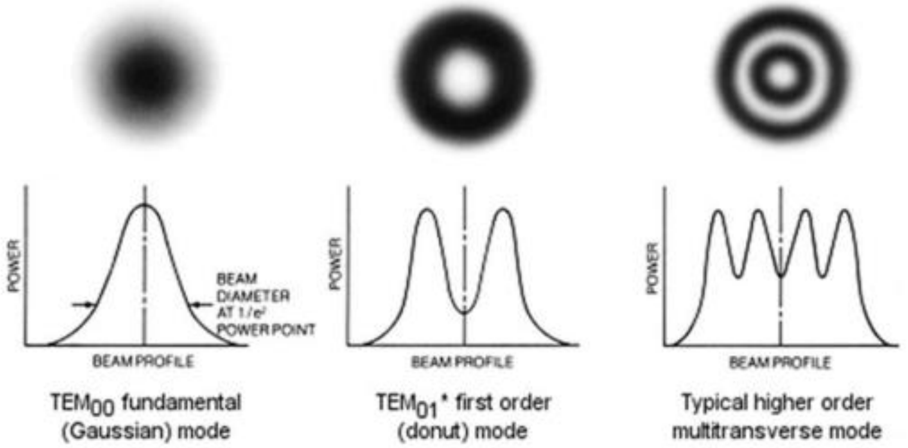

Figure 13. Types of laser beams. Fuente: Laser Material Processing (Steen 2003).

The Heat-Affected Zone (HAZ) plays a crucial role in determining the surface characteristics of laser-cut wood. Its effects can be evaluated by analyzing surface roughness (*Ra*) and waviness (*Wa*), which reflect the degree of thermal influence and the material's response to localized heating. During laser cutting, the laser beam inevitably produces a charred surface layer due to the pyrolytic degradation of wood components. The Heat-Affected Zone (HAZ) represents the thermally affected region, whose extent and morphology are influenced by factors such as the varying density of wood growth rings, fiber orientation, laser power, and material thickness (Gurau et al. 2024; Barnekov et al. 1986; Powell & Kaplan 2004).

In wood materials, the size of the Heat-Affected Zone (HAZ) is further affected by the transition between earlywood and latewood, the anatomical characteristics of the species, and the cutting direction relative to the grain. It is typically defined as the distance between the melted or charred zone and the surrounding unaffected material. These variables cause the heat to propagate unevenly through the wood structure, resulting in differences in surface texture, color, and microstructural composition. The surface quality within the Heat-Affected Zone (HAZ) is therefore clearly distinguishable from that produced by conventional sawing processes: while mechanical cutting generates fibrous, unaltered edges, laser cutting produces a smoother but thermally modified surface, often darkened by partial carbonization (Barnekov et al. 1986; Powell & Kaplan 2004).

3.5.6 Nozzle shape and diameter

The nozzle diameter directly influences the maximum gas pressure and flow rate, which is crucial for the economic efficiency of cutting, especially when using nitrogen. The optimal distance between the nozzle and the material is crucial for achieving a quality cut. For non-metallic materials, this distance generally varies between 1.5 and 4.0 mm, while for metals, it is between 0.5 and 1.0 mm. This distance allows adequate penetration and facilitates material burning (Yusoff 2006).

The design of the orifice and nozzle (Fig. 14) determines the shape of the gas jet, influencing the quality of the cut. During the laser cutting process, the nozzle directs the gas coaxially to the laser, reduces pressure across the lens and minimizes lens movement and misalignment. It also helps reduce turbulence in the melt, maintaining a stable pressure on the surface of the cut material (Moposita 2018).

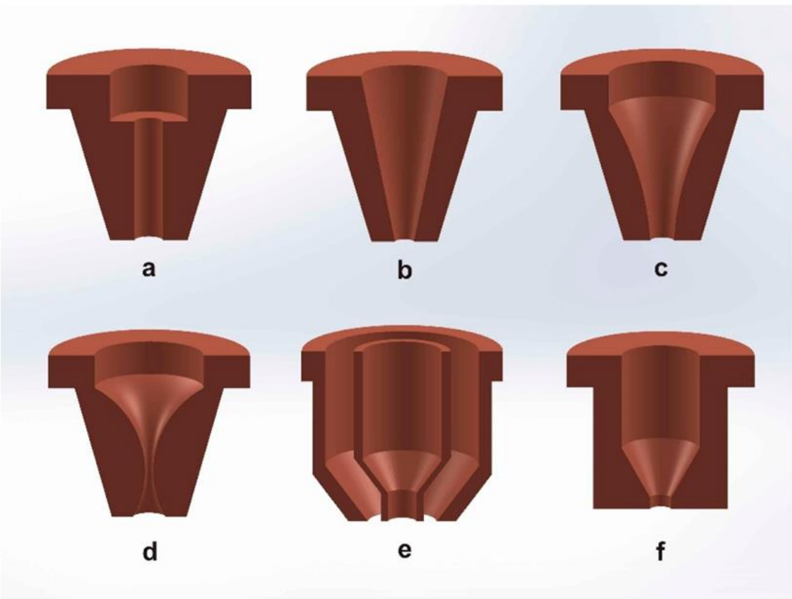

Figure 14. Nozzle geometries commonly used for laser fusion cutting: (**a**) parallel, (**b**) conical, (**c**) converging, (**d**) converging-diverging, (**e**) annular, and (**f**) flat tipped (reprinted with permission from Riveiro et al. 2019).

3.5.7 Cutting Kerf Width in Laser Processing

In laser cutting, material removal occurs through combustion or vaporization induced by the beam's energy. The width of the cut, known as the *kerf*, represents the amount of material removed during processing and typically ranges between 0.08 mm and 1 mm, depending on operating conditions and material properties. This value is determined by several parameters, including laser power—which tends to widen the *kerf* as energy increases beam geometry (diameter and focal length), feed rate, assist gas pressure and composition, as well as the nature and density of the material being processed. Softer materials, such as wood and polymers, generally produce wider *kerfs* due to their lower thermal conductivity and rapid surface heating, whereas metals and ceramics, characterized by higher thermal resistance, tend to form narrower and more precise cuts. Surface coatings or treatments can also significantly affect *kerf* width by altering the material's reflectivity and laser energy absorption (© 2025 Fabworks).

The interaction between the laser beam and wood is inherently non-uniform: radiation absorption varies locally due to the heterogeneous structure of the material, leading to multiple and diffuse reflections within the cutting groove. Numerous studies describe the *kerf* as having a typical conical V-shaped profile, with a wider opening at the surface that gradually narrows with depth. This geometry is attributed to the focal point of the laser being positioned on the material surface, where the energy density is highest. However, part of the incident energy is dispersed due to the generation of fumes, partial melting, and reflections along the groove walls, which reduces the beam's effectiveness in deeper regions. The *kerf* width is also influenced by the anatomical anisotropy of wood: it tends to be wider in *earlywood* the softer, low-density spring growth—and narrower in *latewood*, which is denser and more resistant, thus requiring higher energy for vaporization.

According to recent studies, an increase in CO_2 laser power leads to a proportional widening of the *kerf* (fig. 15), resulting from higher energy concentration and faster material evaporation. Conversely, increasing the cutting speed reduces exposure time, producing a narrower and more uniform *kerf*. When both power and speed increase simultaneously, the upper portion of the cut tends to widen, while the lower section remains narrower due to progressive energy absorption along the inner walls of the groove (Guo 2021; © 2025 Fabworks)

These considerations highlight that the cutting width is not merely a geometric parameter but plays a crucial role in determining the overall efficiency of the manufacturing process. Optimizing the *kerf* width during laser cutting makes it possible to minimize material losses, thereby improving yield and enhancing the overall sustainability of production.

Minimizing material loss has become one of the main challenges in today's wood industry. The optimization of manufacturing processes and the development of innovative technologies are essential to reduce both production costs and waste. Material losses often result from overestimated machining allowances or from non-optimized cutting parameters. In sectors such as engineered flooring, for instance, the cost of the top veneer layer can exceed 80% of the total production cost, emphasizing the importance of precise control over the kerf width and associated material removal during processing (Żywicki et al. 2021)

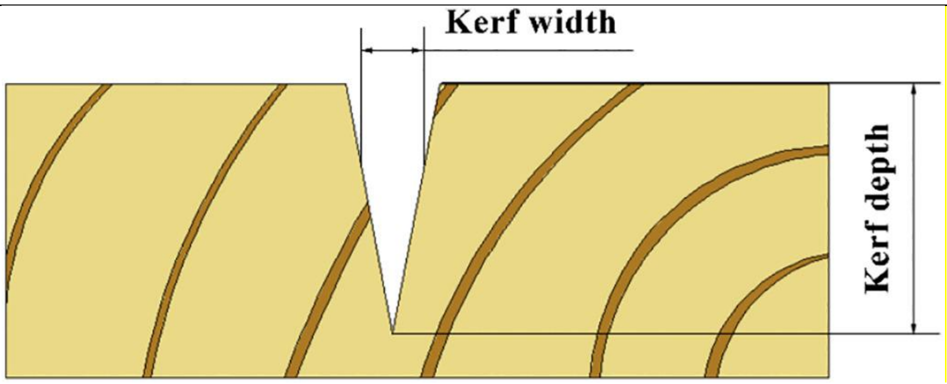

Figure 15. Kerf morphology on wood after CO_2 laser cutting (Guo et al. 2021).

4 Properties of wood Relevant to Laser Processing

Listed and explained below are the wood properties that influence the wood cutting process.

4.1 Cellular structure and chemical composition

The cellular structure of wood, including fiber direction and growth rings, significantly affects both the quality of the laser-cut surface and the formation of the Heat-Affected Zone (HAZ). A cut parallel to the fibers typically produces a smoother and more uniform surface than a perpendicular cut, as the laser beam interacts more evenly with fibers oriented in the same direction, minimizing edge defects. Growth rings, whose density and composition vary, influence the absorption and dissipation of laser-generated heat (Powell & Kaplan 2004; Yusoff 2006).

Wood is primarily composed of cellulose (40–50%), hemicellulose (20–30%), and lignin (20–30%), with minor components including extractives, essential oils, resins, and minerals. These constituents significantly influence the quality of the laser cut. Lignin efficiently absorbs the laser beam's energy, enhancing cutting performance. Laser power and exposure time affect energy absorption, inducing degradation of hemicelluloses and amorphous regions of cellulose, thereby reducing the polysaccharide content in wood (Forest Products Laboratory 2010; Powell & Kaplan 2004; Yusoff 2006; Barnekov et al. 1986; Kačík & Kubovský 2011; Rezaei et al. 2022). Numerous studies highlight that earlywood (spring wood) undergoes more rapid combustion during laser cutting compared to latewood. Earlywood cells, with large lumens and thin walls, are more easily vaporized by the laser beam, while latewood, characterized by smaller lumens and thicker cell walls, tends to melt rather than vaporize due to lignin's thermal resistance. This melting can partially fill the lumens, temporarily creating a smoother appearance but also contributing to surface irregularities. The use of a CO_2 laser further intensifies lignin combustion and cellulose carbonization, increasing the surface roughness of the processed wood (Adamčík et al. 2025; Gurau et al. 2024).

Chemical changes in wood exposed to laser treatment have been widely documented. In beech wood (*Fagus Sylvatica* L.), higher laser energy induces significant alterations in polysaccharide structures, including hemicellulose degradation, deacetylation, and lignin bond cleavage. Similar effects have been observed across multiple species, including lime, maple, oak, and fir. The chemical response to laser treatment is highly species dependent. Structural and compositional changes are often analyzed using FTIR spectroscopy, which detects modifications in functional groups by measuring infrared absorption variations linked to vibrational modes of chemical bonds (Kubovský & Kačík 2011; Gurau et al. 2024). In summary, the interplay of wood anatomy, chemical composition, and laser parameters governs the Heat-Affected Zone (HAZ) formation, surface morphology, and chemical alterations. Understanding these interactions is critical for optimizing CO_2 laser cutting processes, ensuring high-quality cuts, and minimizing undesirable thermal effects.

4.2 Moisture content

Wood is a hygroscopic material, capable of exchanging water vapor with the surrounding air and reaching an equilibrium moisture content. Water influences the structural use of wood by altering its mechanical properties (such as stiffness, strength, and deformation), as well as the material's dimensions, while also affecting surface roughness parameters (Lagaňa et al. 2021; Papp-Csiha 2017; Gurau-Csiha 2015, Thybring et al. 2022). Wood's moisture content (MC%)

is defined as the weight of water expressed as a percentage of the kiln-dry (OD) weight, i.e., the amount of water present in the wood (Thybring et al. 2022).

During drying, the free water in the lumens exits at a rate that also depends on the presence of air or gas, while the water in the cell walls remains and depends on the drying process. When the liquid water in the lumen escapes completely, and the cell wall is still intact, this is called the saturation point (FSP). Below this critical level, the properties of the wood are altered (Panigrahi et al. 2018).

There are two methods to increase the moisture content of artificially dried wood samples: one consists of air-conditioning them in a chamber with fixed temperature and increasing air humidity while measuring the moisture content (MC%) of the wood samples in a humidification chamber.

The other method consists of soaking the samples in water and subjecting them to a drying procedure, while measuring the moisture content (MC%) of the wood samples in a drying process (Benkreif et al. 2021).

The moisture content of wood greatly influences the laser cutting process. High moisture content (especially its change under FSP) causes shrinkage and swelling of the surface, affecting cutting performance and radiation absorption. The higher the moisture content, the higher the thermal conductivity of the wood and the lower the concentration of energy in the cutting zone, as energy is also used to boil and evaporate moisture. This reduces accuracy, depth of cut and surface quality (McMillin-Harry 1971; Hernandez-Castaneda et al. 2011).

With increased moisture content, the feed rate must be reduced to allow sufficient energy for evaporation and combustion of the material. Wet wood generally has a lower process yield than dry wood but can improve cutting quality by reducing charring. Although wet wood requires higher energy input per unit volume due to water evaporation, it may result in shallower grooves and a more uniform cut, as reported in previous studies (Powell 1998; McMillin-Harry 1971; Barnekov et al. 1986; Peters-Marshall 1975). High wood moisture can also result in a rougher surface and affect the amount of finishing material used, bond strength and overall joint quality (Zhong et al. 2013). Regarding wetting, i.e. the ability of the liquid to wet the surface of a solid material, which is important for glueing wood, laser cutting affects this by taking the contact angle as a reference (Wang and Piao 2011; Petriˇc-Oven 2015). A study by Rami Benkreif and Csilla Csiha (2022) showed that an increase in wood moisture content leads to an increase in surface roughness, as measured by the parameters *Rq* and *Rz*. The roughness response to moisture changes depends on the wood species, with tangential surfaces generally being more sensitive to moisture changes than radial surfaces, except for some species such as maple, alder and beech. All wood species show an increase in roughness from a moisture content of 18% (Rami Benkreif-Csilla Csiha 2022).

Guo et al. (2021) found that cutting wet wood improves accuracy by significantly reducing the cut width compared to dry wood. In the case of pine wood, cutting wet wood reduces the cut width by 48.1% in the perpendicular direction and 46.5% in the parallel direction. This effect is due to the higher thermal conductivity of wet wood, which disperses more thermal energy and reduces the energy available for laser cutting. However, in perpendicular cutting, the change in cut width due to moisture content (MC%) is more significant (65.2%) than in parallel cutting (Guo et al. 2021).

When processing thicker materials, it is necessary to increase the laser power to maintain a constant cutting speed. Instantaneous vaporization, where the gas from the nozzle mixes with the vapours, heating and cutting the rest of the workpiece, is ideal for cutting the top layer while the rest of the material is cut by burning. In the furniture industry, cutting occurs on thicknesses above 40 mm, although thicknesses up to 30 mm have been used in experiments (Powell 1998; Yusoff 2006).

4.3 Wood Wettability

Wood wettability is the ability of the material to absorb and retain water, strongly influenced by its cellular structure, porosity, and chemical composition, particularly lignin and cellulose. Woody cells, such as tracheids and fibers, determine water retention: the higher the porosity, the greater the wettability. Lignin is generally more water-resistant than cellulose, and surface treatments such as oils and varnishes can reduce wettability, affecting durability in wet environments and susceptibility to deterioration and infestation (Forest Products Laboratory 1987; Zhang & Morrell 2000).

Wettability depends on intermolecular forces between liquids and solid surfaces and can be classified as reactive or non-reactive. Reactive wettability involves interactions that change the contact angle, while factors such as longitudinal elasticity, surface roughness, and inhomogeneity influence this angle, which serves as a quantitative measure of wood wettability. Higher contact angles indicate low (hydrophobic) wettability, while lower angles indicate high (hydrophilic) wettability. Contact angles also provide insight into surface free energy and adhesion properties (Amziane & Collet 2017; Maciak et al. 2024).

Closely related to wettability, wood permeability governs the ability of wood to absorb and retain preservatives or other treatments. Many species, particularly heartwood portions, are naturally impermeable. To enhance treatment effectiveness, various industrial techniques are used to improve penetration, including mechanical or laser incisions, vaporization, solvent or critical point drying, and biological treatments. Among these, mechanical incision is the most widely employed for increasing lateral permeability, as it creates millimetric holes or fissures that allow partial preservative penetration. However, its effectiveness is limited by the difficulty of producing very small or complex geometries and the shallow depth of penetration, which often results in surface-only treatment (Nath et al. 2020).

The interplay between wettability and permeability is critical in determining how wood interacts with water and chemical treatments. High moisture content generally increases wettability, while surface treatments or natural extractives can reduce it. Similarly, microstructural features, such as cell wall thickness and lumen size, affect both water absorption and the ability to retain preservatives. Understanding these properties is essential for optimizing wood processing, finishing, and preservation (Forest Products Laboratory 1987; Amziane & Collet, 2017; Zhang & Morrell 2000; Maciak et al. 2024).

4.4 Transport of water in Wood

Water in wood moves through several mechanisms: vapor diffusion, diffusion through the cell walls, and capillary transport. Diffusion refers to the random motion of molecules occurring both in vapor and within the cell walls. At a constant temperature, water transport can be described in terms of potential gradients, such as relative humidity, vapor pressure, and osmotic pressure (Thybring et al. 2022; Siau 1984).

The diffusion flux can be described by (Equation 2) Fick's law:

$$J = -D\frac{d\varphi}{dx}, \tag{2}$$

Where:

J represents the diffusion flux, with units of amount of substance per unit area per unit time. It indicates the quantity of substance passing through a specific area over a given time interval.

D is the diffusion coefficient, or diffusivity, with units of area per unit time.

$\frac{d\varphi}{dx}$ represents the concentration gradient.

φ (for ideal mixtures) denotes the concentration, with units of amount of substance per unit volume.

x is the spatial position, with units of length.

(Thybring et al. 2022; Siau 1984; Fick 1855)

The transport of liquid water in wood is described by Darcy's law (Equation 3), which is similar in form to Fick's law under steady-state conditions.

$$J = (\rho\_w \; * \; k \; / \; \mu) * (\Delta p \; / \; \Delta x) \tag{3}$$

Where:

J (kg m^{-2} s^{-1}) represents the water flux,

x (m) is the distance along the flow direction,

p (Pa) denotes the pressure,

k (m^2) is the permeability of the material,

ρ_w (kg m^{-3}) is the density of water,

μ (Pa·s) is the dynamic viscosity of liquid water.

Water molecules are in constant motion even in the absence of gradients, but no net migration occurs. When a temperature gradient is established, water transport becomes more complex and can be described by considering multiple potentials (Thybring et al. 2022; Janssen et al. 2011). In such cases, vapor pressure is often a sufficient indicator of the driving potential for flow in porous materials.

In summary, water transport in wood depends both on vapor diffusion through the cell walls and on the capillary flow of liquid water along the vessels and tracheids. The combination of these mechanisms is influenced by the wood's microstructure, moisture content, and environmental conditions, playing a crucial role in processes such as drying, thermal treatment and laser machining (Darcy 1856; Fick 1855; Siau 1984; Thybring et al. 2022).

4.5 Water Vapor Diffusion

Water vapor diffusion in still air depends on the velocity of molecular motion and the mean free path between collisions of water molecules with other gas molecules such as oxygen and nitrogen. This distance increases as air pressure decreases. At a constant temperature, diffusion increases with rising temperature because the molecules move faster.

Wood exhibits a porous structure that facilitates the transport of water vapor through diffusion and of liquid water by capillarity (Fig. 16). Water within the cell walls moves by diffusion, with a continuous exchange of water molecules between the walls and the macroscopic cavities, as illustrated by the interaction between vapor and bound water in the walls themselves (Thybring et al. 2022).

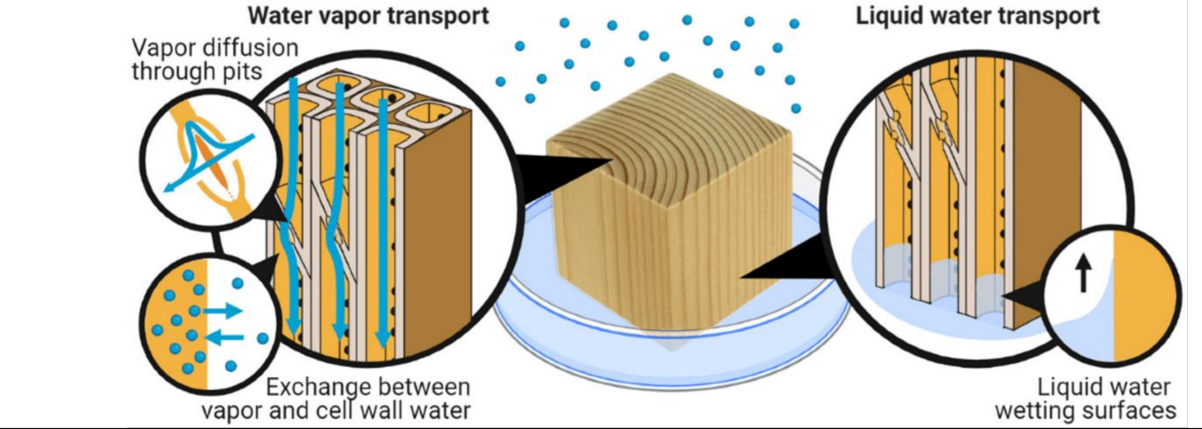

Figure 16. Mechanism of water transport in wood (Thybring at al. 2022).

In softwoods, the main cells are axial tracheids, which contain longitudinally oriented voids, whereas in hardwoods the structure is dominated by vessels and fibrous tracheids. These voids, being much longer than wide, promote faster water vapor diffusion along the longitudinal direction. Smaller, radially oriented ray cells also contribute to diffusion.

Vapor diffusion is further influenced by the connectivity of the voids. The bordered pits connecting tracheid cells in softwoods are the most significant structures for fluid transport. In unaspirated pits, water molecules diffuse between the microfibrils, while in aspirated pits, the torus blocks direct vapor flow, increasing transport resistance. To pass through, water molecules must adsorb, diffuse, and desorb (Zelinka et al. 2016; Choong et al. 1968; Petty et al. 1970; Thybring et al. 2022).

Molecular dynamics simulations of absorbed water in polymer models—such as amorphous cellulose, amorphous hemicellulose, and an ordered cellulose–hemicellulose composite show that water diffusion coefficients increase exponentially with moisture content. In these systems, water molecules are either immobile, binding to hydroxyl groups of the polymers, or mobile. As moisture increases, water mobility rises due to polymer expansion, which enhances porosity, reduces tortuosity, and improves the connectivity between water molecules. Moreover, the energy required to break hydrogen bonds at adsorption sites decreases. These findings are consistent with observations that water softens the polymers in wood cell walls and that water–polymer interactions weaken as moisture increases (Stamm 1959; Stamm 1960; Keplinger et al. 2015).

Measuring water diffusion within wood cell walls is complex due to the interaction between vapor and capillary water. Stamm (1956) attempted to isolate this process by filling the voids with a low–melting point metal alloy, although it is unclear whether the measurements reflected only wall-bound water, since the alloy did not completely fill the voids and may have restricted wall swelling. Thybring and Fredriksson (2021) later proposed the use of flexible, hydrophobic polymers chemically bound to the surface of cell walls. Despite the uncertainties in Stamm's data, his reported diffusion coefficients increased with moisture content, consistent with molecular simulations and NMR measurements. Diffusion coefficients were higher in the longitudinal direction and varied linearly with inverse temperature, indicating that energy is required to overcome an activation barrier, as in Arrhenius kinetics. Stamm also observed similar behavior for water diffusion in thin regenerated cellulose films.

In the over-hygroscopic range, liquid water in wood moves under a capillary pressure gradient, although this phenomenon is relatively limited. The flow of liquid water is faster along the longitudinal direction, with variations between and within species. Bordered pits in softwoods and tyloses in hardwood vessels affect permeability. Water imbibition in wood is generally nonlinear, with higher moisture content within the cell walls preceding capillary flow (Thybring et al. 2022).

4.6 Material thickness

The thickness of the wood material to be cut with the laser affects the sharpness rate of the cut with a drastic reduction (McMillin-Harry 1971; Peters-Marshall 1975; Lum et al. 2000, Peters-Banas 1977).

In thicker materials, it is necessary to increase the laser power to maintain a constant cutting speed (Lum et al. 2000). Instantaneous vaporization, in which the gas from the nozzle mixes with the vapours and heats the rest of the workpiece, is ideal for cutting the top layer while the rest of the material is cut by combustion.

In the furniture industry, cutting takes place on thicknesses of more than 40 mm (Powell 1998). Although laser cutting of wood can reach thicknesses of up to 40 mm, thicker sections are possible. However, for experimental purposes, only wood pieces with a thickness of 30 mm have been used (Yusoff 2006).

4.7 Density

It is a property of all materials, solid, liquid, and gaseous, which determines the amount of material that is compressed in each space (Moposita 2018), defined by the following equation (Equation 4):

$$\boldsymbol{\rho} = \boldsymbol{m}\ \boldsymbol{v} \tag{4}$$

Where:

- ρ = density (kg/m^3)
- m = Mass (kg)
- v = Volume (m^3)

The density of wood, which varies with moisture content, is a crucial physical property that influences almost all its strength characteristics. This density is mainly determined by the amount of wood substance per unit volume and the moisture content, while extractives and minerals have lesser effects. Wood density generally varies between 320 and 720 kg/m^3 but can range from 160 kg/m^3 for balsa to over 1040 kg/m^3 for some tropical woods.

High-density wood is more robust and stiffer than low-density wood with the same moisture cont. However, it tends to shrink and swell more with changes in humidity. During laser cutting, the density of the wood affects the feed rate: higher density slows down the process, as the laser takes longer to vaporize and fight the material, especially in the knots, which are denser than uniform wood (Yusoff 2006; McMillin-Harry, 1971; Peters-Marshall 1975; Li-Mazumder 1991; Powell 1998; Piili et al. 2009).

In the furniture industry, cutting usually takes place on thicknesses greater than 40 mm, requiring more laser power so that the cutting speed is constant (Lum et al. 2000; Zhou-Mahdavian 2004; Martínez-Conde et al. 2017).

The density of early and hard wood (between 400 and 730 kg/m^3) combined with a CO_2 laser engraving in the radial and tangential face has an essential effect on the cut, altering the number of rings crossed during the cut and the depth (Nath et al. 2020).

Furthermore, it was observed that during laser cutting, a decrease in laser beam degradation occurs in the annual ring due to the different density transitions between earlywood and latewood (Petutschnigg et al. 2013; Kubovský et al. 2020).

Wood species with high density and low porosity can produce smoother machined surfaces (Sütçü et al. 2013).

4.8 Roughness surface on the wood

The quality of machined wood surfaces is determined by the accuracy with respect to the dimensions specified by the designer and influences subsequent processes such as finishing and adhesion. Surface characteristics, including roughness, waviness, and shape, define the result of the work.

Surface roughness (*Ra*) represents the finest surface irregularities, often caused by the machining process or the condition of the material itself (Gurau 2017; Magoss 2008). This type of surface finish manifests itself as micro-irregularities, which may be noticeable depending on the precision of the cutting process. A surface is considered rough if these deviations are large and smooth if the irregularities are minimal.

Theoretically, the roughness of a surface produced by machining can be seen as the combination of two components: ideal roughness, resulting from the process design, and natural roughness, due to the inherent imperfections of the material (Sütçü 2013).

The surface roughness of wood is influenced by several factors, including annual ring variation, density, cell structure and the ratio of early to late wood.

In porous species, such as oak, surface quality is particularly critical. These woods may require the application of filler or coatings to achieve a smoother surface, thus increasing production costs. Conversely, less porous or soft species, while not presenting this problem, still require an additional sanding process to even out the surface (Zhong et al. 2013; Benkreif et al. 2020).

Surface roughness can be measured using various methods, both contact and non-contact. The main techniques include the stylus, optical profiler, image analysis, pneumatic method, microscopy, and ultrasound (Kilic et al. 2006). Average roughness (*Ra*), maximum profile height (*Rz*), and mean square deviation (*Rq*) maximum profile height (*Rz*) are the roughness parameters used to assess the quality of the machined surface (Sütçü 2013; Sedlecký et al. 2018).

4.9 Color change

Color is an important characteristic of wood, influencing and defining the aesthetic qualities of wood products. The color of a coated wood surface plays a key role in determining its visual appeal. Laser processing offers a potential technique to modify the natural tone of light-colored woods, producing darker shades that resemble those of more valuable species. Surface gloss, on the other hand, represents a physical property that quantifies how effectively a material reflects light under specific geometric conditions (Li et al. 2022).

Wood color changes, expressed through the CIE Lab system, are commonly used to monitor the variations that occur during various processing operations, such as drying, steaming, or thermal and chemical modification (Chuchala 2023). When using laser technology, increasing irradiation and transport speed cause a uniform decrease in brightness (ΔL^*) and overall color difference (ΔE^*) (Kubovský and Kacik, 2013). The color of wood is strongly influenced by the chemical changes of its main components: cellulose, hemicellulose, and lignin. Lignin absorbs light of specific wavelengths and alters the chromophoric structures of the wood through chromophoric, hydrolytic, and oxidative reactions. These changes depend on the irradiation dose and feed rate during laser cutting (Kubovský et al. 2011; Kubovský et al. 2016; Li et al. 2018; Sernek, 2015).

During laser irradiation, the wood color changes due to heating, oxidation, and carbonization, which modify the chemical composition of the surface. Furthermore, heat treatment induces color variations through the formation of highly colored intermediate compounds such as lignin derivatives, quinones, and quinone methides (Sernek 2015; Li et al. 2018). Increased surface carbonization and reduced brightness in beech wood (*Fagus sylvatica* L.) occur as irradiance increases from 7.8 to 75 J/cm² and laser power from 70.92 to 29.72 (Vidholdová et al. 2017). The color difference also rises at high irradiation doses (8–29 J/cm²) (Li et al. 2021; Kubovský and Kacik 2013). The brightness of beech wood (*Fagus Sylvatica* L.) decreases significantly with increasing laser power (Kúdela et al. 2020; Kubovský and Kacik 2013; Sernek 2015). Laser parameters that significantly influence color change include feed rate, scan width, focus position, and power (Li et al. 2021). An increase in color difference with decreasing feed rate and power was also observed in Moso bamboo (*Phyllostachys edulis*) (Lin et al. 2008). Therefore, color variation is directly affected by the operational settings of the laser cutting process.

Subsequent studies have suggested that color measurements, supported by direct chemical analysis, are valid tools for assessing changes in the chemical structure of the wood surface (Bonifazi et al. 2015; Li 2018). These color changes are influenced by various factors, including feed rate, focal position, laser power, and scan width (Li et al. 2021).

5. Methodology

Work phases:

- Bibliographic research.
- Selection of wood material.
- Preparation of the boards.
- Evaluation of the various parameters and properties of the samples before subjecting them to laser cutting.
- Evaluation of the physical properties and surface quality after cutting (color, waviness, roughness, diffusion and hardness).
- Microscopic and chemical analysis.
- Data collection.
- Statistical analysis.
- Preparation of scientific articles.

The study in our laboratory focused on optimizing the processing parameters of the CO_2 laser to improve the quality of the processed surface and ensure energy and economic efficiency. Hardwood species such as beech (*Fagus sylvatica* L.) was selected for their industrial and scientific relevance. Beech wood samples, differentiated moisture content properties, were cut using a CO_2 laser at the TRUMPF company site in Melnik, Czech Republic. The CO_2 laser was chosen for its suitability in treating wood, ensuring good beam quality, high power, and reasonable cost per watt. This technology offers complete radiation absorption on wood materials at low cost and shorter irradiation times than other technologies such as Nd, fiber, or disk lasers.

5.1 Materials and methods

Detailed information on the CO_2 laser process, including its chemical and physical analysis methods for the cut surface and the selected laser processing parameters (cutting speed, power, gas pressure, focal point position), are given below.

5.1.1 Materials

The experiment was conducted on a single hardwood species, namely European beech (*Fagus sylvatica* L.), with a density of 770 kg/m^3 (±12 kg/m^3) and a moisture content of 16% (±0.8) preconditioned for one month at 65 ± 3 % relative humidity (RH) and 20 ± 2 ◦C temperature, purchased by the company from Wood Store ®, Czech Republic. Beech wood (*Fagus Sylvatica* L.) was reduced to eight sawn boards with dimensions of 50 cm × 25 cm × 3 cm (length (L) × width (T) × thickness (R) and was stored in a semi-open outdoor space for a fortnight. Two boards of the total eight were conditioned in a climate chamber at 20 ± 2 °C and 65 ± 5% relative humidity (RH) until the weight became constant (12% MC). To achieve a target moisture content of approximately 18%, two beech boards (*Fagus Sylvatica* L.) were transferred to a climate chamber with controlled temperature and relative humidity conditions, to allow uniform redistribution of moisture within the material and reduce moisture gradients between the surface and core. The samples were kept in the climatic chamber until a stable mass was reached, a criterion adopted to indicate the achievement of hygroscopic equilibrium under the set conditions. During this conditioning phase, the moisture content was monitored periodically at various points using an electric hygrometer to verify the homogeneity of the moisture within the boards. Two more boards were oven-dried at 103 °C for 48 hours to obtain a moisture content of approximately 0%, while the two remaining boards were air-dried in an open, sheltered location for two months, obtaining a moisture content of approximately 8% (low MC). The moisture content was calculated using representative samples according to ISO 13061-1 (2014) and ISO 13061-2.

5.2 Methods

5.2.1 CO_2 cutting process.

The final samples of beech wood (*Fagus Sylvatica* L.) were cut using a CO_2 laser (TRUMPF®, Czech Republic) with different machine parameters, of which fixed, the nozzle diameter, cut-off distance and material thickness, and variable, the focal point, gas pressure, cutting power and cutting speed. The radial sections of the pieces were positioned perpendicular to the laser beam (Fig. 17) to obtain a tangential cut along the grain, with a wavelength of 10.6 μm. The final dimensions of the samples were 50 cm × 3 cm × 5 mm (length × width × thickness), as illustrated in Fig. 16 . A total of 125 samples were prepared from the boards with different moisture contents (0%, 8%, 12%, and 18%).

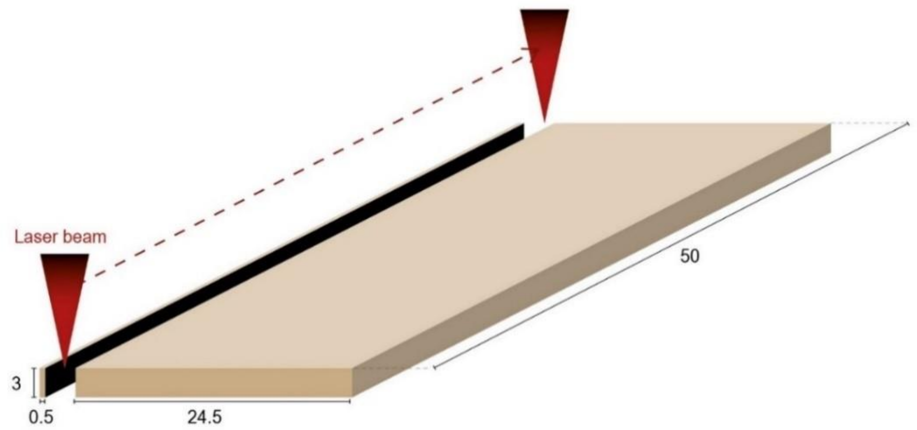

Figure 17. Test specimen: shape and dimensions (The figure has been readapted by the author: Corleto, R. 2024).

The samples were initially covered with a vapour barrier film to equalize the moisture content. After a 14-day equalization period, moisture levels were checked using an electric moisture meter. The samples were cut using various focal point positions, gas pressures, cutting speeds, and laser power, and the nozzle diameter was maintained to a constant level. The specific laser parameters employed in this study are outlined in Table 1. The CO_2 laser machine used offers a power constancy within ± 2% of the nominal laser power, with a continuously adjustable power range from 160 W to 3200 W and a beam quality of 0.55/1.82 k/m², with a standard beam quality of 0.9/1.11 k/m².

Processing parameters of CO_2 laser	**Variations**
Focal point position	P, 1/3rd from the top, ½ from the top, ¾ from the top
Gas pressure (bar)	17, 21, 22
Cutting speed (m/s)	3, 3.5, 2, 1, 0,5
Laser power (W)	3 200, 2 500, 2 000, 1 250
Nozzle diameter (mm)	2.7

Table 1. Variations of laser processing parameters.

Several focal points were used for this research: P on the top; 1/3rd from the top, 2/3rd from the top; ½ from the top; ¾ from the top. The following figure illustrates some of these focal points (Fig. 18).

The position of the focal point, defined as the distance of the cutting head from the surface of the workpiece, significantly influences the quality and depth of the cut. Depending on the focal point's position, the cut's result varies: a focal point located above the surface produces an ‘A’ shaped cut. In contrast, a focal point below the surface produces a ‘V’ shaped cut (Martínez-Conde et al. 2017).

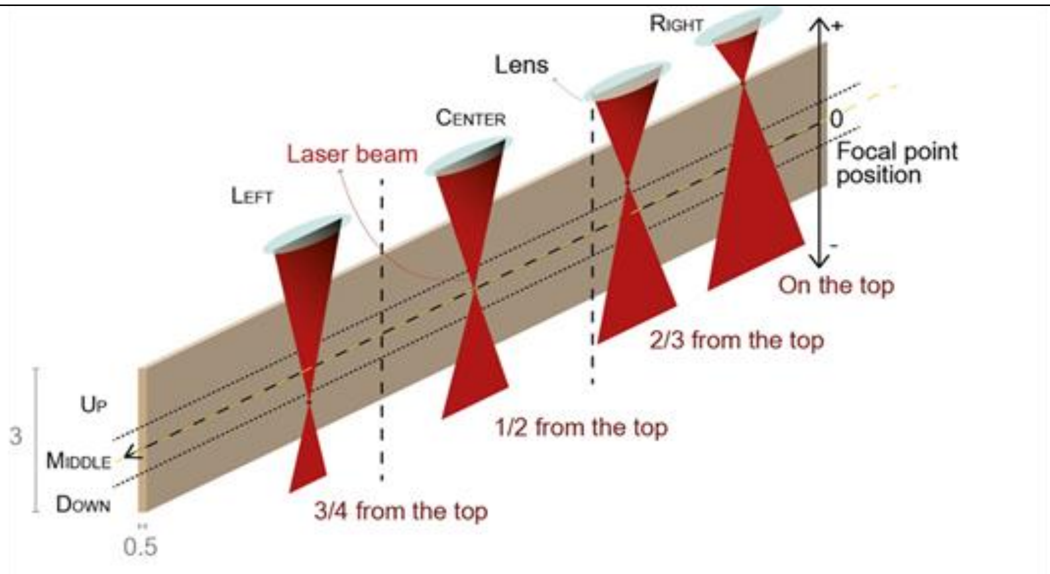

Figure 18. Variations of laser processing parameters: on the top; 2/3rd from the top; 1/2 from the top; ¾ from the top.

The measurement of the total colour change ΔE* on beech wood samples (*Fagus Sylvatica* L.) after laser cutting was carried out using a CM2600d spectrophotometer (Konica-Minolta) (Fig. 19), with the CIE L *a*b* colourimetric system (coordinate system established by the CIE (International Commission on Illumination) in 1964), which comprises three independent axes perpendicular to each other. The three axes are subdivided as follows:

- L * determines brightness from 0 (black) to 100 (white).

- a * determines the ratio between red (positive) and green (negative).

- b * specifies the yellow (positive) to blue (negative) ratio.

Figure 19. Color measurement using a spectrophotometer (©2006–2025 Konica Minolta Sensing Americas Inc.).

For the evaluation of the colour change, the total colour difference ΔE * was used, calculated according to the formula (Equation 5) in accordance with ISO 11664-2 (2007), ISO 11664-4 (2008) and ISO 11664-6 (2014):

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{5}$$

- where ΔE * is the total colour difference.

- ΔL * is the luminance difference.

- Δa * is the red-green index difference.

- Δb * is the yellow-blue index difference.

In the CIELAB geometric color model, L* (luminance) is 0 for black, and 100 for white; the a* axis goes from green (-a*) to magenta (+a*), and the b* axis goes from blue (-b*) to yellow (+b*). Color (Fig. 20) is specified using three chromatic attributes, hue, saturation, and lightness, respectively, which allow color to be organized in a three-dimensional space, where one dimension corresponds to lightness and the other two to chromaticity (hue and saturation) (Kubovský-Babiak 2009).

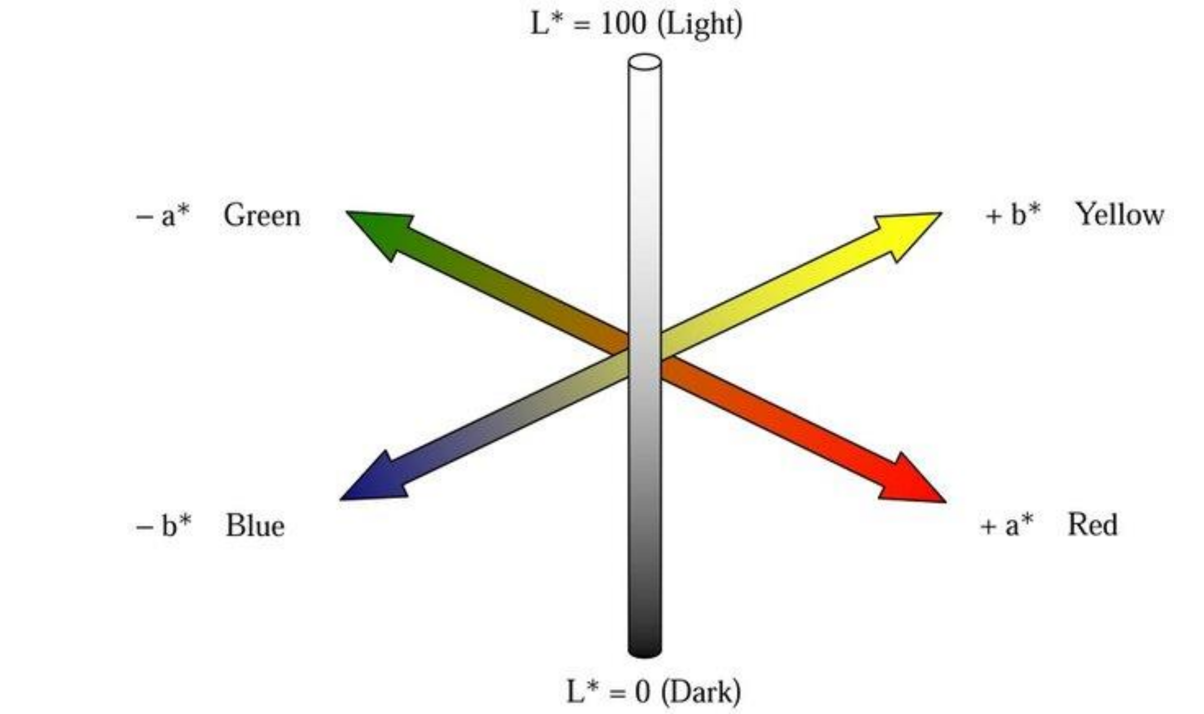

Figure 20. CIELAB color space (Image credit: by Li et al. 2005).

5.2.2 Circular saw

Circular saw cutting was performed by setting the blade rotation speed to 4000 and 6000 rpm, using a manual feeding system. The machine was operated by qualified personnel, who manually adjusted the feed rate according to the wood's characteristics to prevent machining defects. Although automatic feeding systems offer high repeatability, manual feeding allows continuous adaptation of the feed speed based on the material structure and cutting conditions, making it more suitable for solid wood, which is characterized by high anatomical variability. The sample thickness was kept identical to that used for laser cutting to ensure comparability of results. Surface quality measurements were carried out following the same procedure adopted for laser-cut samples. Experimental tests were conducted using a Class SI 400 cutter/planer (Fig. 21), whose technical specifications ensure the accuracy and repeatability required for a comparative analysis of cutting processes. The machine is equipped with a main blade with a maximum diameter of 400 mm and an integrated scoring unit.

Figure 21. Class SI 400 panel saw/router used in the experimental tests.

5.2.3 Surface measurements

The measurement of irregularities on machined surfaces is defined by two important parameters: roughness (*Ra*) and waviness (*Wa*). Roughness (*Ra*) defines the presence of fine irregularities on a machined surface. It is quantified as the mean deviation from the mean line. In contrast, waviness (*Wa*) is defined as the increased irregularity on the machined surface due to vibrations during the machining process and defective operation of woodworking tools.

5.2.4 Stylus profilometer

The surface roughness (*Ra*) (Fig. 24) and surface waviness (*Wa)* of beech wood (*Fagus Sylvatica* L.) samples were measured with a stylus profilometer (Form Talysurf Intra 2, Leicester, UK) (Fig. 23); all values obtained were recorded and stored on a computer connected to it. Measurements were carried out on samples in accordance with ISO 4287, ISO 4288, and ISO 13565-2.

For the measurements, each sample was divided with a marker into three parts: left, middle and right side (Fig. 22). In total, nine measurements of surface roughness (*Ra*) and waviness (*WA)* were taken at the top, middle and bottom of the three sections of the 125 beech samples, including 5 for each combination of laser parameters.

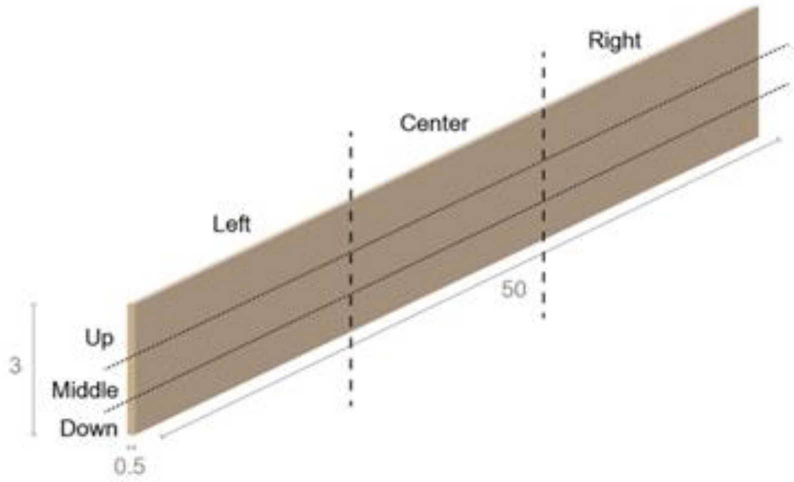

Figure 22. Scheme of subdivision of the specimen for measuring surface quality parameters Corleto et al. 2024).

The measurements obtained for all samples were:

- *Ra* (arithmetic mean deviation).
- *Wa* (profile ripple parameter) ripple.

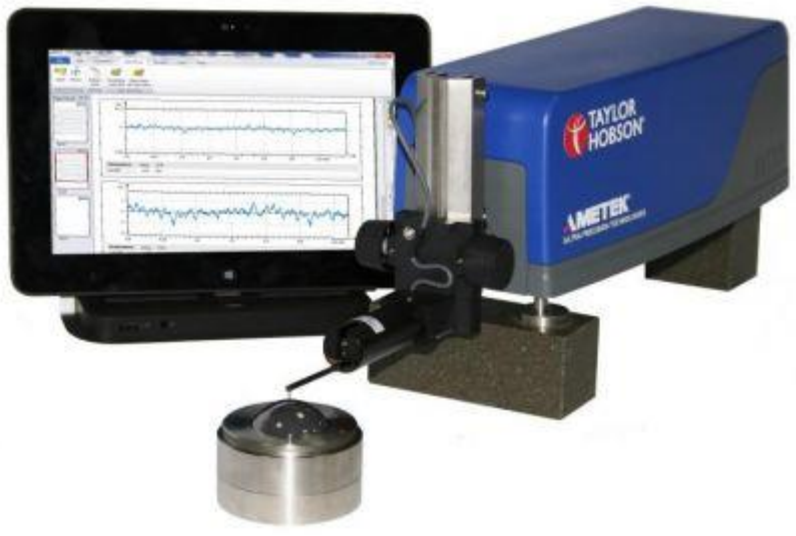

Figure 23. Stylus surface profiler (@2003-24 Spectrum Metrology Ltd.).

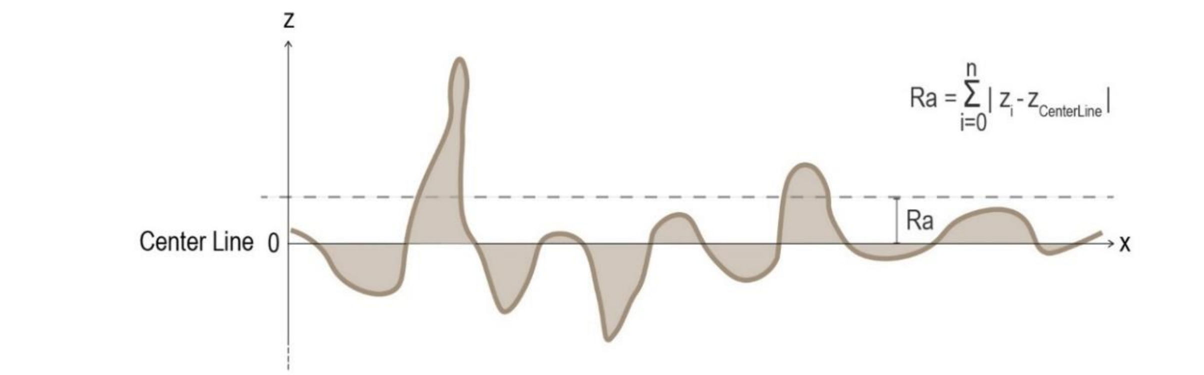

Figure 24. Principles of roughness calculation.

5.2.5 Confocal microscopy

Measurements were performed on specimens cut from the main sample, with dimensions of 3 cm × 3 cm × 5 mm (length × width × thickness), using a laser scanning confocal microscope (*Olympus OLS5100, Japan*) equipped with a Gaussian filter to reduce optical noise and enable three-dimensional surface reconstruction (Fig. 25).

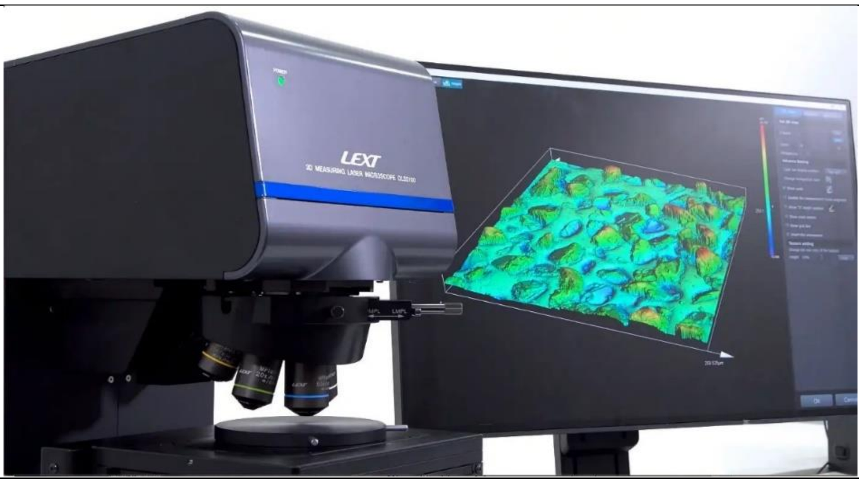

Figure 25. Sample surface imaged using an Olympus OLS5100 laser confocal microscope (Copyright © 2025 Tengrant Ltd.) .

The tangential surfaces of the samples, obtained via CO_2 laser cutting, were analyzed to characterize the surface profile and assess the influence of processing parameters on wood morphology. Collimated light emitted from the microscope source was directed onto the sample surface, allowing the generation of high-resolution 3D images through the image stacking technique (Fig. 26).

From the acquired 3D images, primary surface profiles were extracted and subsequently filtered to isolate the roughness components. For each combination of cutting parameters — feed rate, focal position, and assist gas pressure three independent samples were prepared, and three repeated measurements were performed on each, ensuring statistical robustness of the data. Measurements were taken perpendicularly to the wood grain direction (across the grain) to obtain a complete and reliable representation of the surface microtopography.

The entire experimental protocol was developed in collaboration with the research group reported in Rezaei et al. (2022), to ensure methodological consistency and reproducibility of results. The author of this thesis actively participated in the experimental design, instrument calibration, and data acquisition, although not being the primary author of the referenced study.

Furthermore, this experimental approach was specifically designed to enable a direct comparison of roughness measurements with those obtained using a stylus profilometer, to evaluate differences and correlations between the two surface characterization methods.

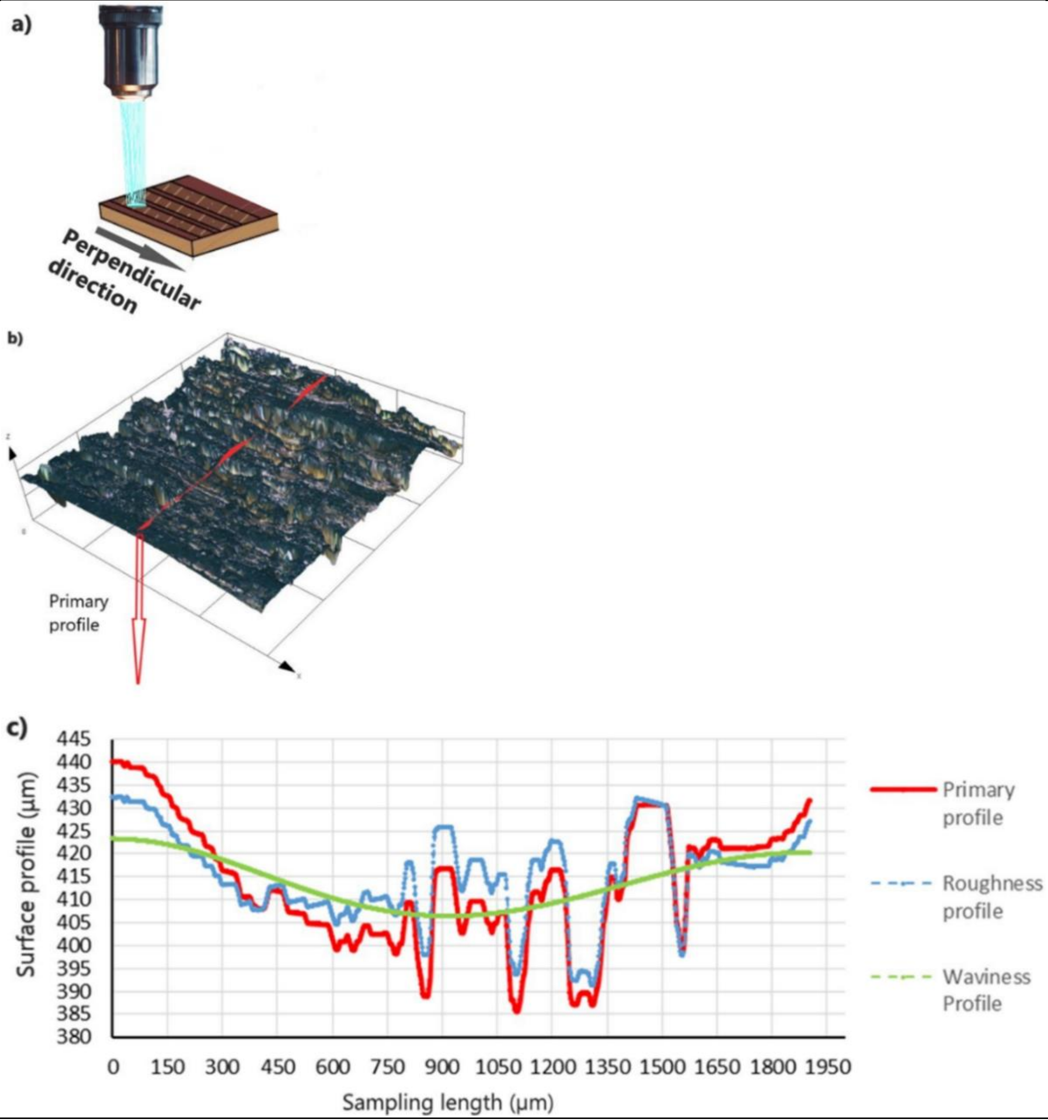

Figure 26. (a) Configuration of the laser-cut sample for surface profile measurement using a confocal microscope; (b) three-dimensional (3D) image of the sample obtained via

image.stacking; (c) primary profile of the 3D image filtered for surface roughness determination (Rezaei et al. 2022), co-authored by the author of this thesis.

The waviness component (*Wa*) was removed from the measured profile to enable a quantitative evaluation of surface roughness.
A cutoff value of 2.5 mm was adopted to separate roughness from waviness (Rezaei et al. 2022; Gurau et al. 2006).
The arithmetic mean roughness (*Ra*) was calculated according to ISO 4287 (2009).
This parameter represents the arithmetic mean of the absolute values of the Z-coordinates (profile peak heights) along the sampling length and is expressed by the following relation (Equation 6):

$$R_a* = \frac{1}{L}\int_0^L |z(x)|\mathrm{d}x \qquad (6)$$

5.2.5 Scanning Electron Microscopy

The SEM observations presented in this study were conducted on the same specimens used in the research reported in this thesis. The electron microscopy methodology is based on that described in Rezaei et al. 2022, of which the author of this thesis is a co-author, suitably adapted for the analyses reported here.

For the morphological analysis of the cross-sections of laser-cut specimens, samples measuring approximately 5 × 5 × 5 mm (length × width × thickness) were prepared. Observations were performed using a FEI Quanta 250 FEG scanning electron microscope (Thermo Fisher Scientific, Hillsboro, USA) operating under high-vacuum conditions. Images were acquired using the Everhart–Thornley detector, employed for secondary and backscattered electron collection, at an accelerating voltage of 20 kV. The specimens were mounted on aluminum stubs using carbon conductive double-sided tape and subsequently coated with an approximately 10 nm thick layer of gold to ensure proper electrical conductivity. Metallization was carried out in an argon atmosphere using a Scancoat Six sputter coater (Edwards, Burgess Hill, UK). Microscopy analyses were conducted immediately after laser cutting and were subsequently repeated following surface cleaning to remove carbonaceous residues using airbrushing.

5.2.6 FITR (Fourier transform infrared spectroscopy)

Fourier transform infrared spectroscopy (FTIR) was performed on beech samples (*Fagus Sylvatica* L.), after CO_2 laser cutting, using an FTIR-ATR spectrometer (FTIR-ATR, Vector 22, Bruker FTIR, Bremen, Germany) with 64 scans per sample, spectral resolution of 4 cm-1 in a wavenumber range of 4000 to 650 cm-1, performing the test on the control sample and on the sample obtained after laser cutting (Fig. 27). The test on the laser-cut sample was performed after each surface smoothing.

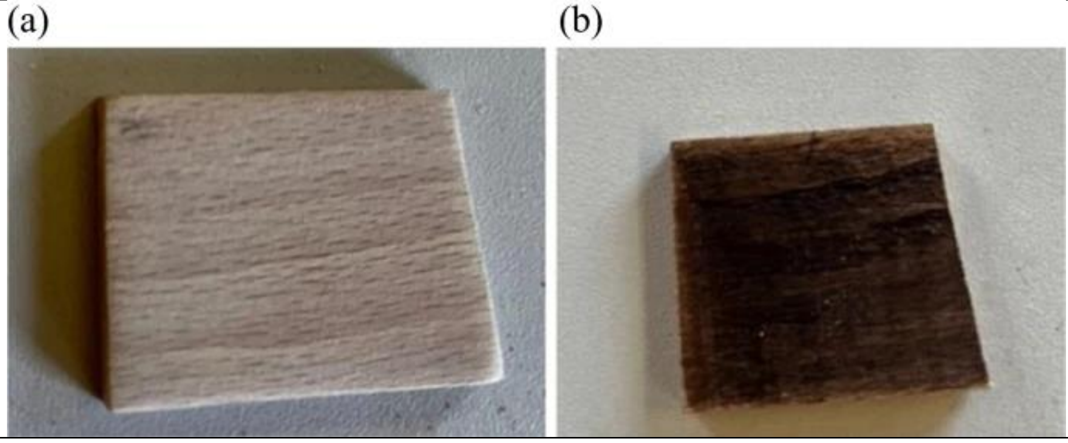

Figure 27. a. Wood specimen with an untreated face (no laser exposure). b. Wood specimen showing the face thermally affected and darkened by the laser cut (Corleto et al. 2025).

The test was conducted to verify thermal changes in the wood surface subjected to laser cutting, where high temperature can cause surface combustion and a thermally altered zone in depth.

FTIR-ATR spectroscopy was used to analyze the structure of the wood. Using the Fourier transform of spectral data, this method provides detailed information on the absorption and emission of solids, liquids, and gases by acquiring high-resolution data over a wide range of wavelengths (Griffiths-Hasseth 2007). The FTIR spectra were initially acquired from the charred surface of the wood, which was prepared by laser cutting. The surface was then sanded with sandpaper to remove a layer of approximately 200 microns, and the spectra were again acquired. This procedure was repeated until a total removal of approximately 600 microns of wood was achieved.

Comparison of the FTIR spectra of the charred and sanded surfaces allowed peak variations to be analyzed to identify chemical changes. Principal component analysis (PCA) was performed to assess absorption in the wavelengths between 500 and 2500 $cm^{-1,}$ with data normalization using OriginPro 9.0 software (Fig. 28) (© OriginLab Corporation).

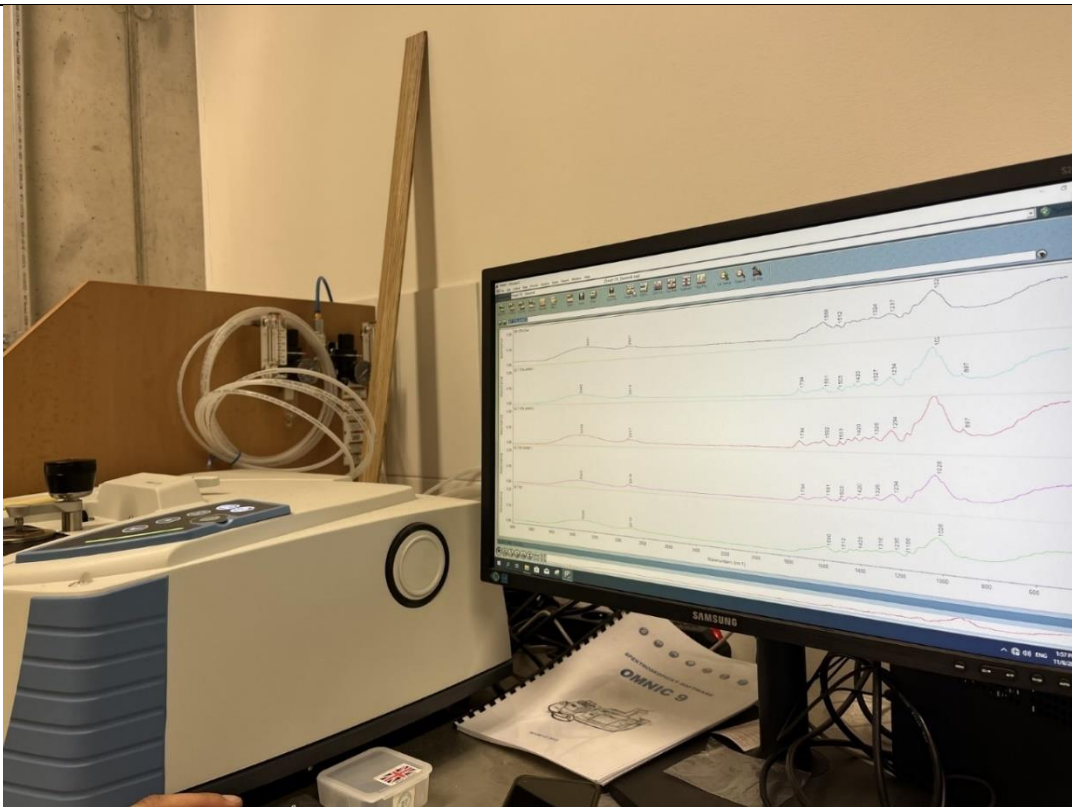

Figure 28. Device and screen with spectra obtained via FTIR.

5.2.7 Diffusion test

In this study, beech wood samples (*Fagus Sylvatica* L.) were laser-cut and subsequently shaped into disks measuring 20 mm in diameter and 5 mm in thickness to fit into a 50 mL flask (Fig. 29). The parameters for this test were defined by keeping the cutting conditions constant—such as the nozzle diameter (2.7 mm), the focal point position on the upper surface, and the cutting power (3200) while varying other parameters, including gas pressure and cutting speed, as reported in the following table (Tab. 2).

Laser Processing parameters	*Cutting power (watts)*	*Cutting speed (m/min)*	*Gass pressure (bar)*	*Focal point position*
V	*3200*	*3*	*21*	*On top surface*
VI	*3200*	*3.5*	*17*	*On top surface*
VII	*3200*	*3.5*	*21*	*On top surface*

Table 2. Parameters for CO_2 laser cutting of beech wood (*Fagus sylvatica* L.) samples.

Before the start of the tests, all samples were conditioned under standard environmental conditions (T = 20 °C, relative humidity = 65 %). The water vapor flux density was determined using the dry cup method, in accordance with ISO 12572:2016.

Figure 29. Laser cut beech samples prepared for diffusion test according to ISO 12572:2016.

To ensure that the relative humidity inside the test cup was 0 %, calcium chloride ($CaCl_2$) was used as a desiccant for dry cup (0 % RH). A total of 3 g of calcium chloride ($CaCl_2$) was placed at the bottom of each cup (with a minimum depth of 15 mm). The samples were then positioned in the cups and the edges were sealed with a silicone sealant to prevent water vapor leakage along the lateral surfaces of the specimens. Subsequently, the sealed samples were weighed and placed in the test chamber at a temperature of (20 ± 0.5) °C and a relative humidity of (65 ± 5) %. Each day, the samples were weighed to monitor the mass change due to moisture transport through the wood.

Water vapour flow rate through the specimens was calculated with equation (Equation 7):

$$G = \frac{m_2 - m_1}{t_2 - t_1} \tag{7}$$

Where:

G the change of mass per time for a single determination (kg/s)

m_1 the mass of the test assembly at time t_1 (kg)

m_2 the mass of the test assembly at time t_2 (kg)

t_1 and t_2 are the successive times of weighings

Density of water vapour flow rate was calculated with equation (Equation 8):

$$g = \frac{G}{A} \tag{8}$$

Where:

g density of water vapour flow rate ($kg/(m^2s)$).

G the change of mass per time for a single determination (kg/s).

A is the exposed area of the test specimen (m^2).

5.2.8 Hardness test

Wood hardness is a fundamental parameter not only for machining operations involving cutting tools such as sawing, milling, and peeling but also for wooden products exposed to scratches and wear, such as flooring and staircases (Gašparík et al. 2016). Hardness is closely related to the mechanical properties of wood, making it one of the key indicators for assessing material quality. It represents the resistance of wood to the penetration of a tool (Rejtő 1920) and plays a crucial role both in manufacturing technologies and in the mechanical durability of the material (Hirata et al. 2001).

However, it is important to note that the hardness value is strongly influenced by the test method and the conditions under which it is performed. The most used methods for determining wood hardness are the Brinell and Janka tests. While the Janka method is primarily used in North and South America, the Brinell method (Fig. 30) is the most widely adopted in Europe (Gašparík et al. 2016).

The ability of wood to resist penetration depends on several factors, including the shape of the indenter, the penetration method, and the anatomical direction of the wood. Depending on the type and duration of the applied load—either instantaneous or prolonged over time, hardness tests can be classified as static or dynamic. Static methods are further divided into two main categories: relative tests, which allow for comparison between different materials, and absolute tests, which provide a direct and precise measurement of hardness. While relative tests are considered more indicative and preliminary, absolute methods yield specific numerical values for a more accurate determination of wood hardness (Gašparík et al. 2016; Hirata et al. 2001; Pallav 1951).

For the hardness test, beech samples (*Fagus sylvatica* L.) were prepared with dimensions of 30 mm × 30 mm × 30 mm and conditioned in a climate chamber under standard conditions of 20 °C and 65% relative humidity (T = 20 °C, φ = 65%). The Brinell–Mörath method was used to evaluate the resistance of the material to tool penetration, in accordance with EN 1534:2011.

Although the standard normally requires cube-shaped specimens, thinner samples were used in this study due to limitations in sample preparation. The reduced thickness was applied consistently to all specimens, including both control and differently treated samples. Therefore, while the absolute hardness values may differ from those obtained using standard-sized specimens, the relative differences between the sample groups remain comparable and meaningful.

In the test, a load of 500 N was applied to the sample surface using a 10 mm diameter steel ball, and each specimen was tested three times on the same surface (Fig. 31).

The hardness value was calculated according to the Brinell–Mörath method (HBM) using the following equation (Equation 9):

$$H_{BM} = \frac{F}{D\pi h} = \frac{2F}{D\pi(D-\sqrt{D^2-d^2}} \quad (9)$$

Where:

(F) Loading force (500 N).

(h) Is the depth of the indentation.

(D) Is the diameter of the steel ball.

(d) Is the diameter of the spheres footprint.

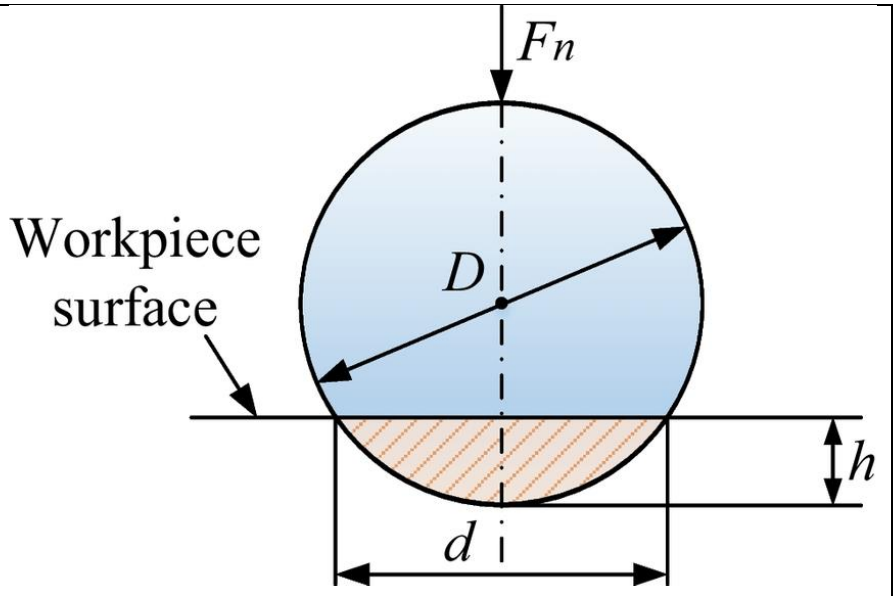

Figure 30. Schematic view of the Brinell hardness test indentation method (Shao et al. 2023).

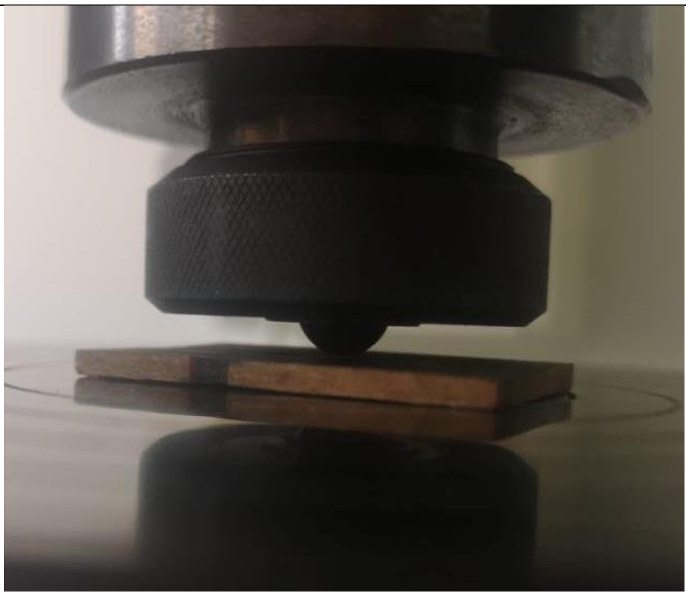

Figure 31. Brinell-Mörath hardness testing setup during the experiment.

As with the previous diffusion test, the laser parameters for this experiment were selected according to the configuration reported in the following table (Tab. 3).

Laser Processing parameters	***Cutting power (watts)***	***Cutting speed (m/min)***	***Gass pressure (bar)***	***Focal point position***
V	*3200*	*3*	*21*	*On top surface*
VI	*3200*	*3.5*	*17*	*On top surface*
VII	*3200*	*3.5*	*21*	*On top surface*

Table 3. Parameters for CO_2 laser cutting of beech wood (*Fagus sylvatica* L.) samples.

5.2.9 Statistical analyses

For the statistical analysis of the data obtained, the STATISTICA 14 software (StatSoft Inc., Oklahoma, USA) and Microsoft Excel were used to perform a four-factor analysis of variance (ANOVA). This method was employed to determine the effect of each factor on the surface characteristics, based on p-values derived from Duncan's test and Fisher's F-test. ANOVA is a powerful statistical tool used to verify whether significant differences exist between groups of data while accounting for multiple interacting variables. Specifically, Fisher's F-test assesses the variability between groups relative to the variability within groups, thus allowing the identification of statistically relevant effects.

If an observed factor is found to be statistically significant, the result is interpreted according to the chosen significance level (p-value). The evaluation of statistical significance follows these general guidelines:

- $P = 0$ – The probability that the factor has no effect is zero, indicating strong evidence that the factor exerts a significant influence.
- $P < 0.05$ – The influence of the factor is considered statistically significant, meaning there is less than a 5% probability that the observed differences are due to random variation.
- $P = 0.05$ – The factor lies exactly at the threshold of statistical significance. This value is often adopted as a conventional cutoff, though it should be interpreted cautiously, as results near this limit can be sensitive to small data fluctuations.
- $P > 0.05$ – The factor's effect is not statistically significant, suggesting insufficient evidence to reject the null hypothesis that the factor has no meaningful impact on the observed data.

In addition to the ANOVA results, Duncan's multiple range test was applied for post-hoc comparisons to identify which specific groups differed significantly from each other. It should be noted, however, that Duncan's test is somewhat less conservative than other multiple comparison tests, such as Tukey's, and its sensitivity to data distribution should be considered when interpreting results.

Finally, it is essential to recognize that p-values do not indicate the magnitude or practical relevance of an effect, but rather the probability that the observed results occurred by chance. Therefore, alongside statistical significance, practical significance and the actual impact of the evaluated factors must also be considered when interpreting the results.

Results and discussion

In this chapter, I present the results and discussion of my doctoral research, including findings that have already been published in scientific journals. The study was designed to evaluate the surface quality of CO_2 laser-cut beech wood and to identify the factors that may influence the cutting process. The surface characteristics of laser-processed wood are determined by the individual and combined effects of several variables, particularly the moisture content of the material and specific laser-processing parameters such as cutting speed and focal point position. Understanding how these factors interact is essential for optimizing surface quality and improving the efficiency and consistency of laser-based wood processing.

6.1 Overview of All Tested Process Parameters

The comparative graphs show that the interaction between process parameters and moisture content produces clear trends. In general, medium to high cutting speeds (3–3.5 m/min), a laser power of 3200 W, and the focal position "P" consistently resulted in lower surface roughness (*Ra*) values and narrower variability ranges across multiple moisture content levels. These conditions were therefore identified as the most stable and effective for reducing surface roughness. For waviness surface (*Wa*), the trends were more moisture-dependent, but the same parameters frequently offered a good compromise between low waviness and high reproducibility. In most cases, the differences observed were not statistically significant ($p > 0.05$). However, the results show clear and consistent trends with reduced variability, which allowed us to identify the most stable and reliable processing parameters.

Based on this global overview, the study concentrated on the parameter values that showed the best combination of low *Ra*/*Wa* and reduced dispersion, ensuring that the subsequent in-depth analysis focused on the most representative and efficient operating conditions. Although the cutting speed of 1 m/min yielded the lowest average waviness (*Wa*) for samples with a 12 % moisture content ($Wa \approx 5.79$), this condition proved optimal only within that specific case. In this study, however, priority was given to identifying process parameters with broader applicability, settings capable of delivering stable performance across a wider moisture content range or configurations that ensured a more substantial reduction in average roughness (*Ra*), which represented a primary objective of the research. This approach made it possible to select operating conditions that are more robust and representative of the material's overall behaviour.

Overall, standard deviation and p-values helped identify the most reliable settings. Cutting speeds of 3–3.5 m/min, a laser power of 3200 W, and the "P" focal position consistently showed the lowest *Ra* values and the most stable behaviour across all moisture levels.

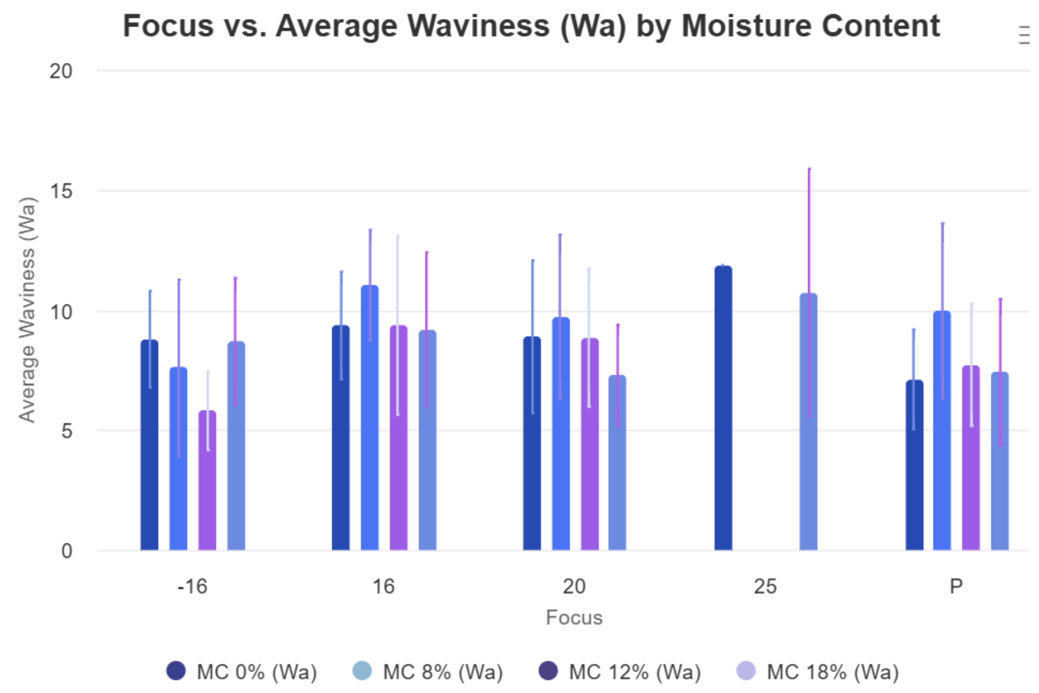

Figure 32. Effect of laser focus position on average surface waviness (*Wa*) at different moisture contents of beech wood.

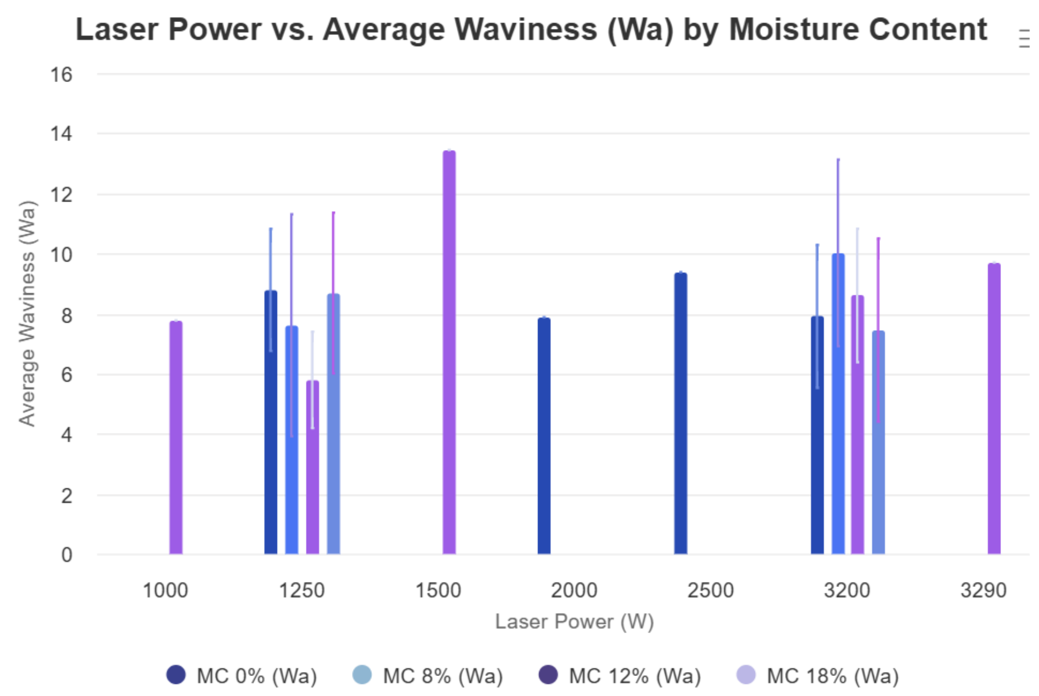

Figure 33. Effect of laser laser power on average surface waviness (*Wa*) at different moisture contents of beech wood.

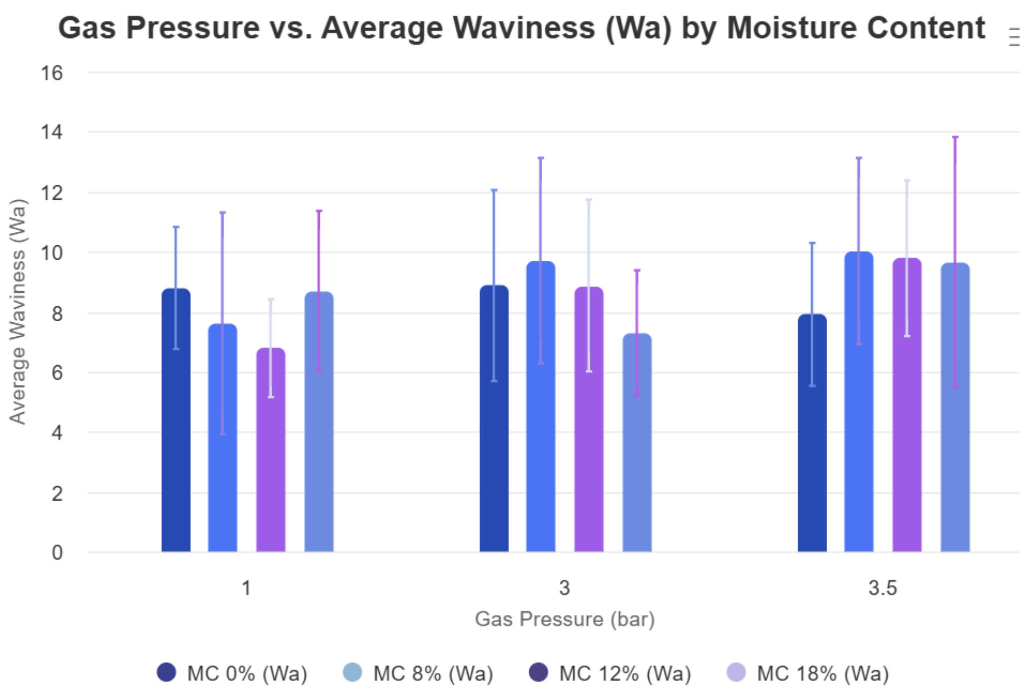

Figure 34. Effect of gas pressure on average surface waviness (*Wa*) at different moisture contents of beech wood.

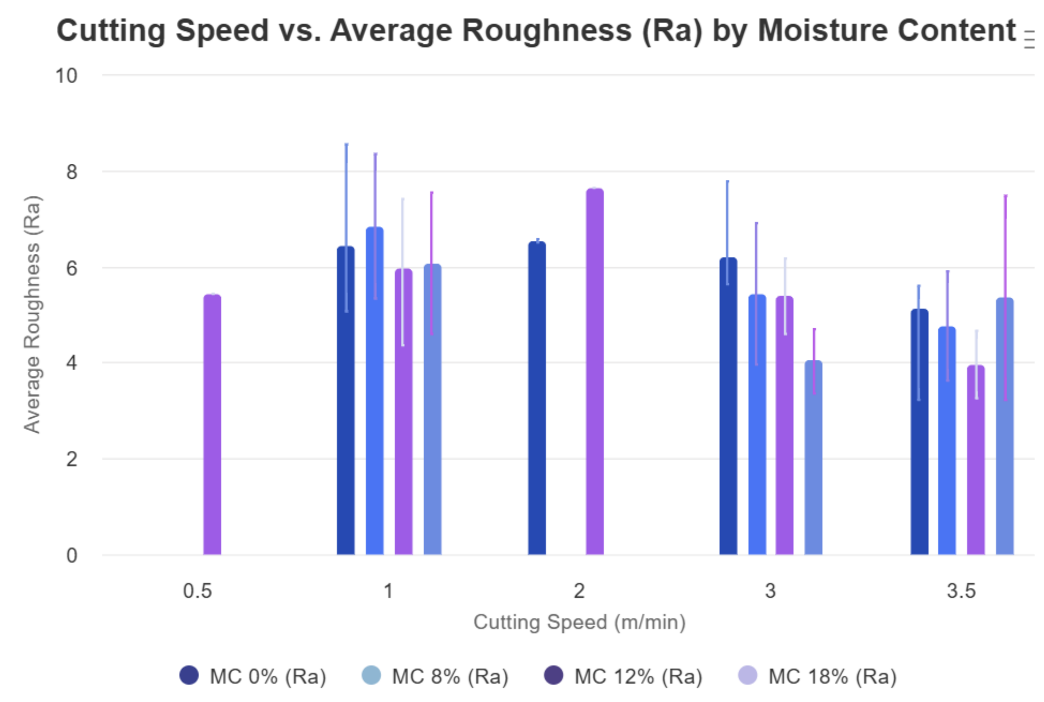

Figure 35. Effect of cutting speed on average surface roughness (*Ra*) at different moisture contents of beech wood.

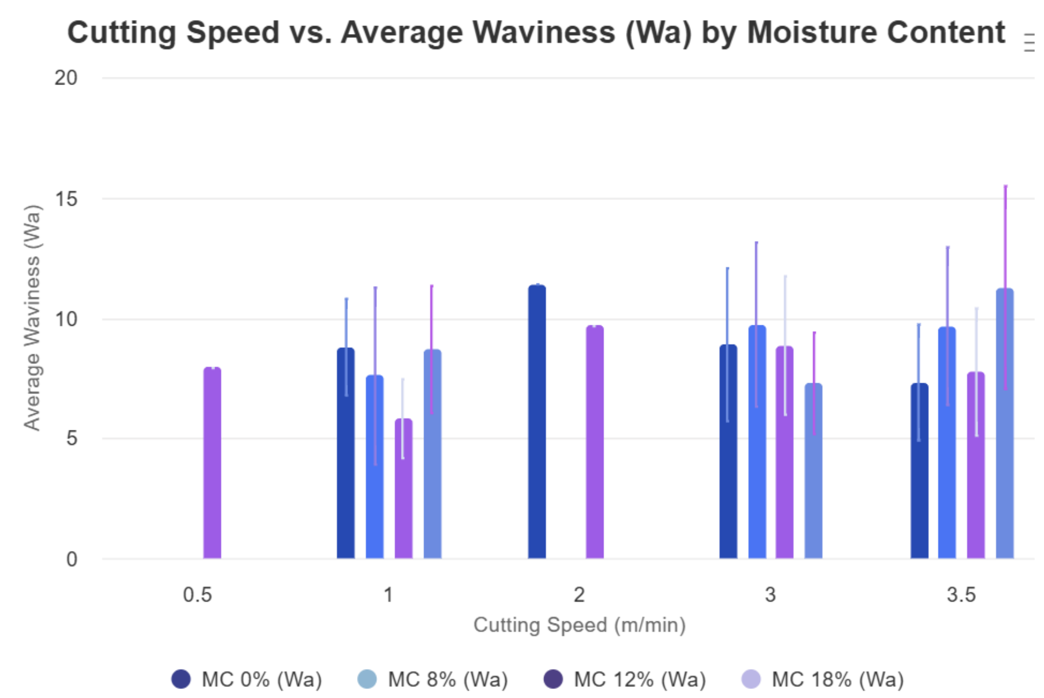

Figure 36. Effect of cutting speed on average surface waviness (*Wa*) at different moisture contents of beech wood.

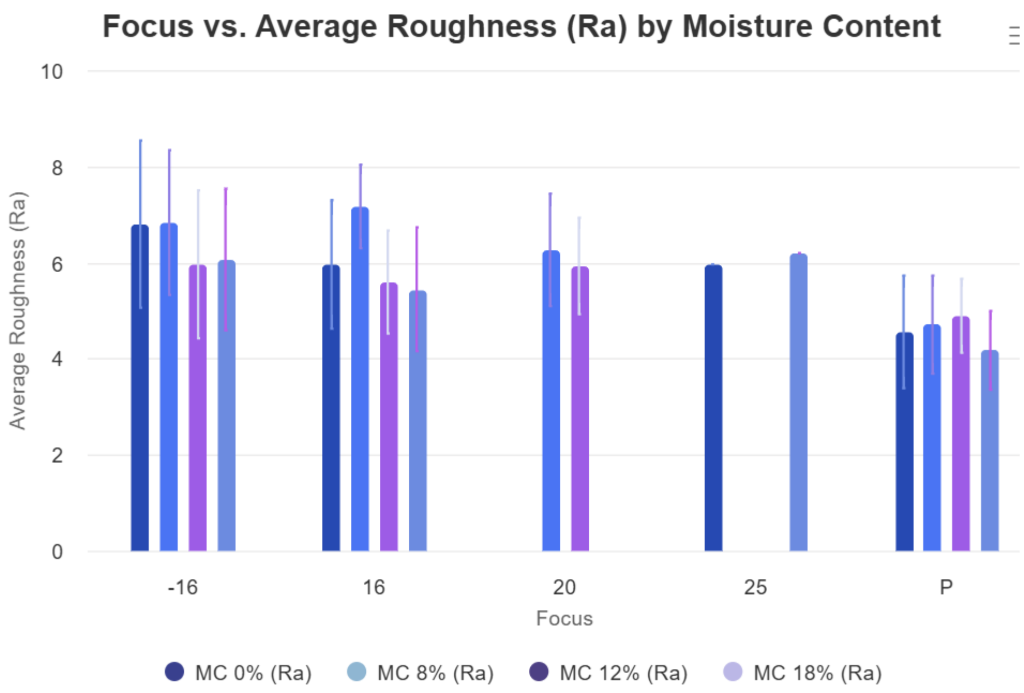

Figure 37. Effect of focus position on average surface roughness (*Ra*) at different moisture contents of beech wood.

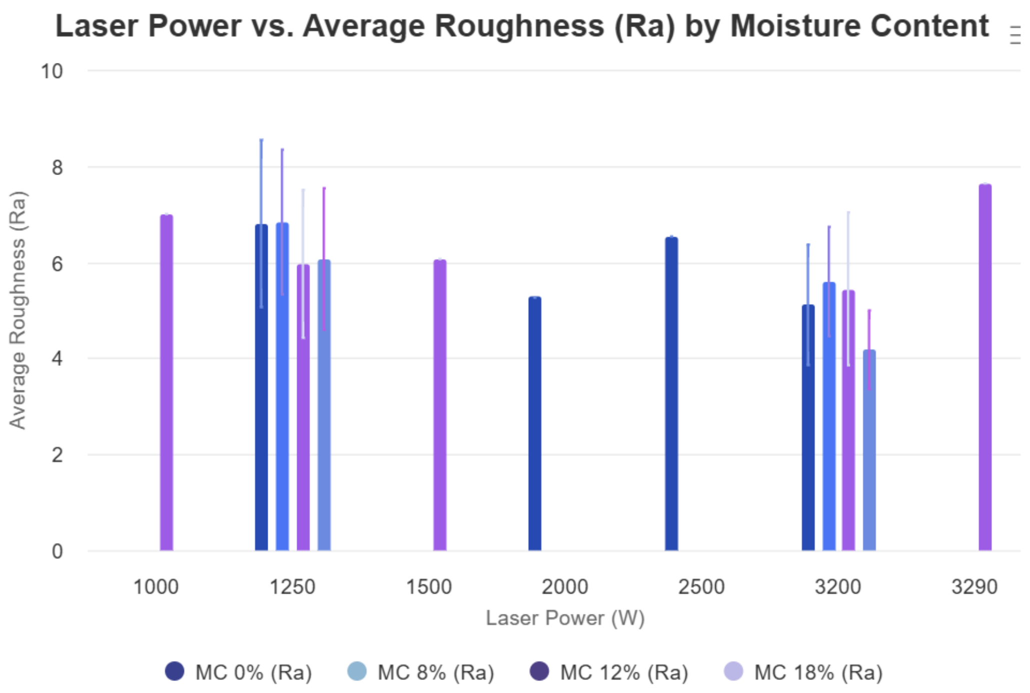

Figure 38. Effect of laser power on average surface roughness (*Ra*) at different moisture contents of beech wood.

MC (%)	Best Cutting Speed (m/min)	Best Laser Power (W)	Best Focus	Lowest *Ra* (µm)	Lowest *Wa* (µm)	P-value (*Ra*)	P-value (*Wa*)
0	3.5	3200	P	4.61	7.64	N/A	N/A
8	3 / 3.5	1250 / 3200	P	4.96	7.59 (-16)	0.908	0.165
12	3.5	3200	P	4.90	5.79 (-16)	0.723	0.820
18	3	3200	P	4.03	7.28	0.762	0.720

Table 4. Optimal laser parameters and corresponding surface roughness (*Ra*) and waviness (*Wa*) of beech wood (*Fagus Sylvatica* L.) at different moisture contents (MC %). Focus P generally provides the most stable results, while Focus –16 sometimes improves *Wa*. N/A indicates that the P-value could not be calculated due to insufficient variability in the data.

6.2 Overview of Thickness Variations as a Function of Cutting Speed.

Material thickness plays a crucial role in laser cutting, and its variation can be influenced by the selected cutting speed through changes in energy input and thermal exposure. Fig. 39 provides an overview of the general trend observed in the experimental results. Increasing the cutting speed from 1 to 2 m/min is associated with a slight increase in effective specimen thickness, which may be related to reduced thermal degradation and limited material removal. In this context, a reduction in effective thickness can be interpreted as an indicator of increased material loss caused by *kerf* formation and thermal effects. Nevertheless, even when thickness reduction occurs, the amount of material removed by CO_2 laser cutting remains generally lower than that associated with conventional mechanical cutting methods, owing to the narrower kerf width and the contactless nature of the process. Overall, the observed variations in effective specimen thickness reflect a balance between energy input, interaction time, and heat dissipation across the material thickness.

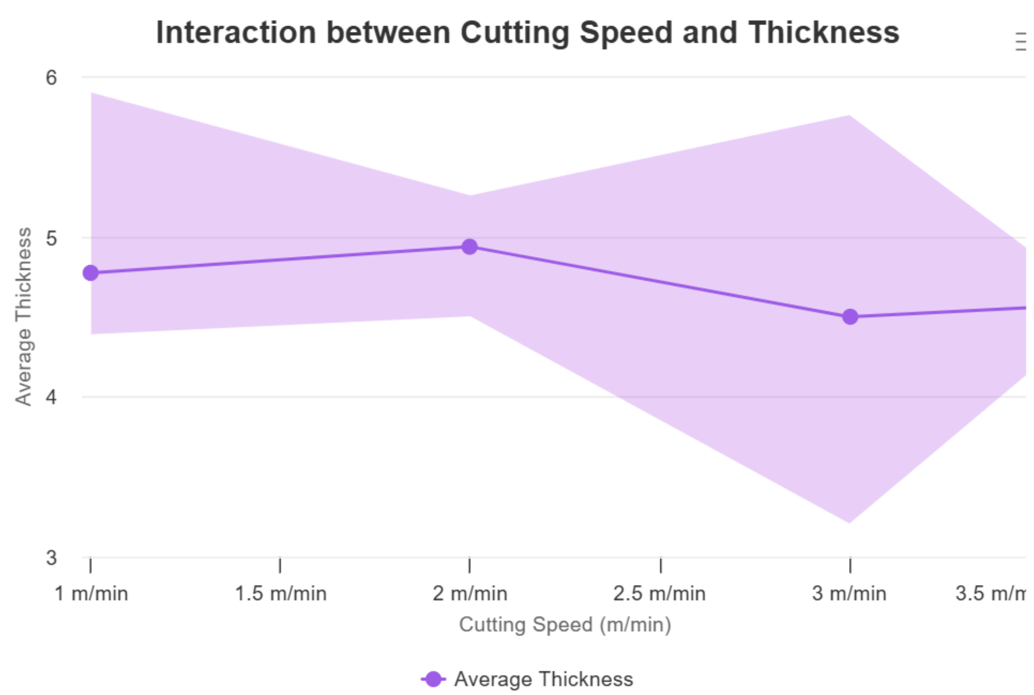

Figure 39. Variation of effective specimen thickness as a function of cutting speed.

6.3. Effect of Moisture Content on Surface Roughness (*Ra*)

The influence of moisture content (0%, 8%, 12%, and 18%) on the average surface roughness (*Ra*) is illustrated in Fig. 40. According to the results reported in Corleto et al. (2024), the surface roughness (*Ra*) values obtained with the contact profilometer showed only slight variations across the four moisture levels, with measurements of 5.6 µm, 5.5 µm, 5.4 µm, and 5.2 µm, respectively. Statistical analysis confirmed that these differences were not significant (Tab. 5).

When compared with non-contact measurements, these values are noticeably lower. In fact, Rezaei et al. (2022) reported *Ra* values of 11.1 µm, 13.4 µm, and 13.3 µm for CO_2 laser-cut samples conditioned at 8%, 12%, and 18% moisture content and processed under typical laser conditions (3.5 m/min, 21 bar, 3200 W, focal point at the surface). Similar trends were described in the study of sawn Norway spruce by Rezaei et al. (2020), where the optical method captured higher roughness values due to its ability to detect fine-scale depressions that stylus-based instruments tend to overlook.

In contrast, Gurau et al. (2001) reported the opposite behaviour for conventionally machined wood, showing that the contact method provided more accurate and repeatable detection of surface irregularities than a laser triangulation system. These findings emphasize that surface roughness (*Ra*) measurements are influenced not only by the measurement technique itself but also by anatomical and surface-related factors such as wood structure, machining, finishing, and prior treatments.

For surfaces modified by laser energy where thermal and chemical degradation generate carbonized residues confocal microscopy represents the most suitable measurement method. When the focal point of a CO_2 laser is positioned at the upper surface, the region closest to the beam receives higher energy input, which can intensify chemical degradation and increase char formation (Martinez-Conde et al. 2017).

To determine whether this uneven energy distribution affects roughness, *Ra* was evaluated at three vertical positions (top, middle, and bottom). As shown in Fig. 41, moisture content did not result in statistically significant differences among these positions. This observation contradicts the expectation that variations in focal point and energy concentration would lead to measurable roughness gradients along the cut.

This behaviour can be explained by moisture-related effects: at higher MC levels, a considerable portion of the laser energy is expended on water evaporation, thus reducing the energy available for thermochemical degradation. The interaction between moisture content and laser processing parameters has been widely documented in previous research (Piili et al. 2009; Cebrail, Acik, and Tutuş, 2020).

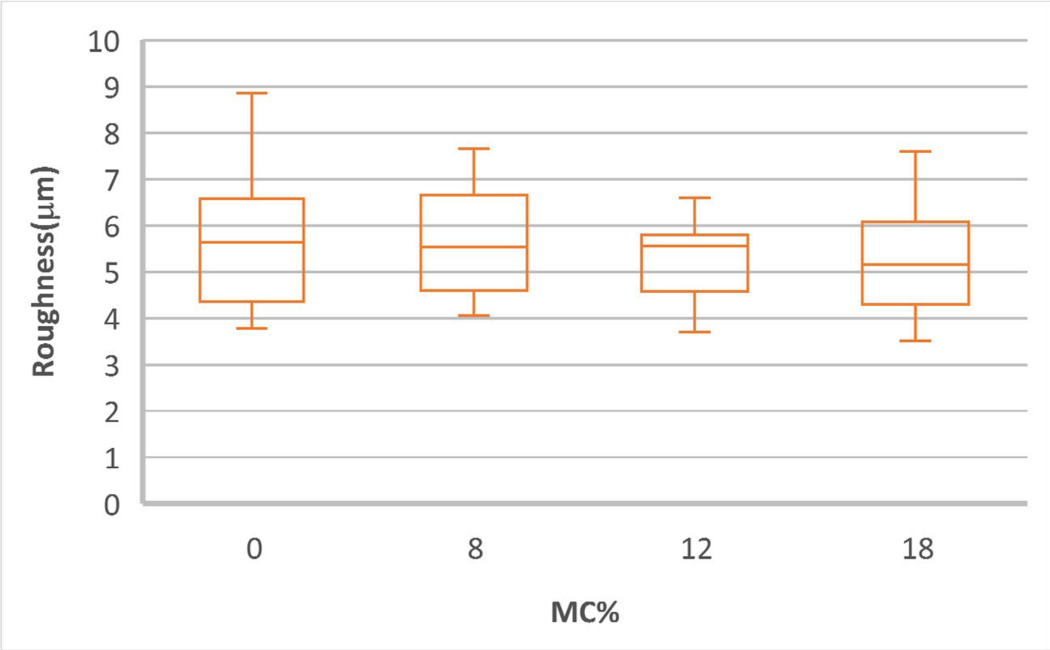

Figure 40. Influence of moisture content on the surface roughness (*Ra*) of CO_2 laser-cut beech wood (*Fagus Sylvatica* L.) (Corleto at al. 2024).

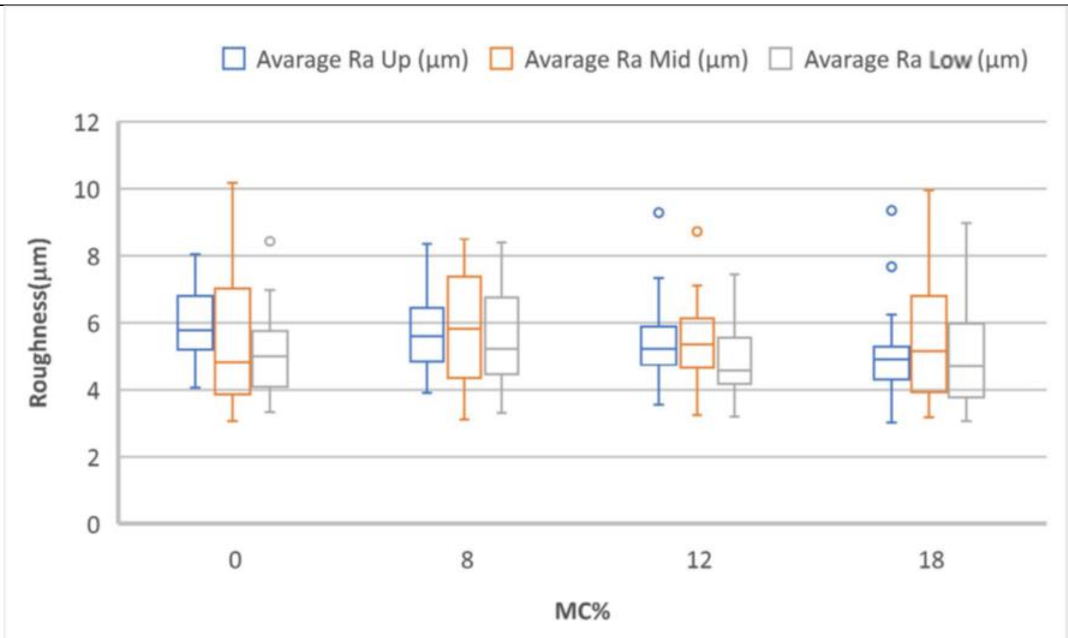

Figure 41. Influence of moisture content on surface roughness (*Ra*) at different vertical positions (top, middle, and bottom) of CO_2 laser-cut beech wood (Corleto et al.2024).

Response variable	Source of variation	Sum of squares	df	Mean square	F-value	P-value
Total *Ra* (µm)	Moisture content	4.013	3	1.338	1.123	0.343
	Error	120.330	101	1.191	—	—
Average *Ra* – upper (µm)	Moisture content	9.166	3	3.055	1.876	0.138
	Error	164.478	101	1.628	—	—
Average *Ra* – middle (µm)	Moisture content	2.476	3	0.825	0.263	0.852
	Error	316.618	101	3.135	—	—
Average *Ra* – lower (µm)	Moisture content	7.297	3	2.432	1.275	0.287
	Error	192.610	101	1.907	—	—

Table 5. Statistical evaluation of average surface roughness (*Ra*) of laser-cut beech wood specimens conditioned at moisture contents of 0%, 8%, 12%, and 18%. Results were considered statistically significant at $P < 0.05$, while values of $P > 0.05$ indicated a lack of significant differences.

6.4 Effect of Moisture Content on Surface Waviness (*Wa*)

The relationship between moisture content (0%, 8%, 12%, and 18%) and surface waviness (*Wa*) is illustrated in Fig. 42. According to the results reported in Corleto et al. (2024), variations in moisture content did not produce statistically significant differences in surface waviness (*Wa*). These findings are consistent with previous investigations on beech and oak wood species, where a notable effect of moisture content was observed only in oak specimens with values exceeding the fiber saturation point (FSP). In that case, higher MC % led to lower waviness compared to air-dried wood (8% MC), likely due to oak's more uniform anatomical structure. Beech wood (*Fagus Sylvatica* L.), by contrast, possesses a finer microstructure, which may contribute to the limited influence of moisture content on its waviness profile.

Further analysis of surface waviness (*Wa*) at three vertical positions on the cut surface (top, middle, and bottom) confirms this trend. As shown in Fig. 43 and Tab. 6, no statistically significant differences were detected across positions for any of the moisture levels examined. This outcome suggests that, despite the uneven distribution of laser energy throughout the material during CO_2 laser cutting, the overall waviness remains relatively stable.

The stability of surface waviness (*Wa*) across moisture levels and vertical positions may be attributed to intrinsic wood characteristics. Differences in annual ring patterns, the proportions of earlywood and latewood, and the presence of extractives—combined with variations in chemical components such as lignin, cellulose, and hemicellulose can influence how the surface responds to thermal processing (Gaff et al. 2020; Corleto et al. 2024). These anatomical and chemical variables likely play a more dominant role than moisture content alone in determining the waviness profile of laser-cut beech wood.

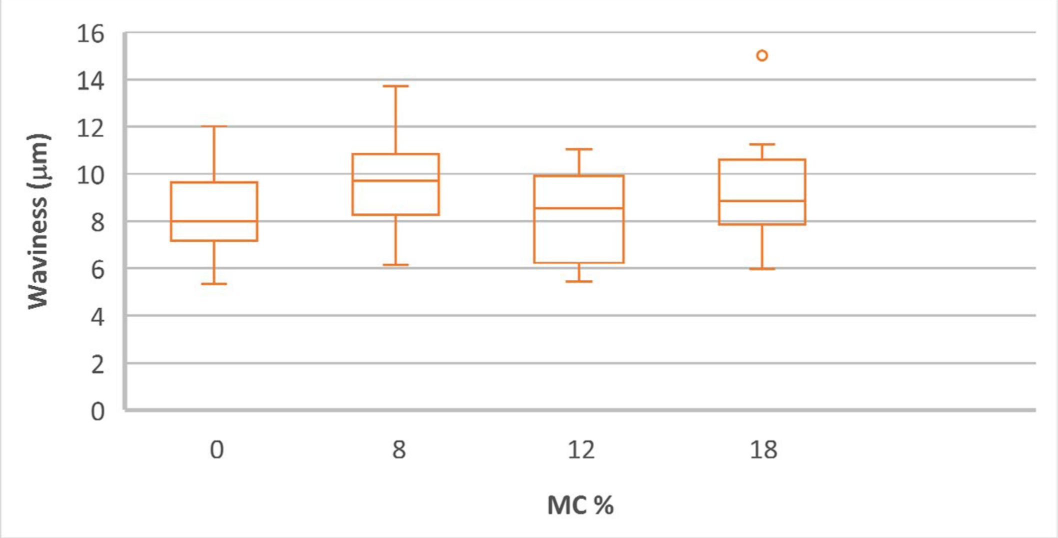

Figure 42. Influence of moisture content on surface waviness (*Wa*) of beech wood processed by CO_2 laser (Corleto et al. 2024).

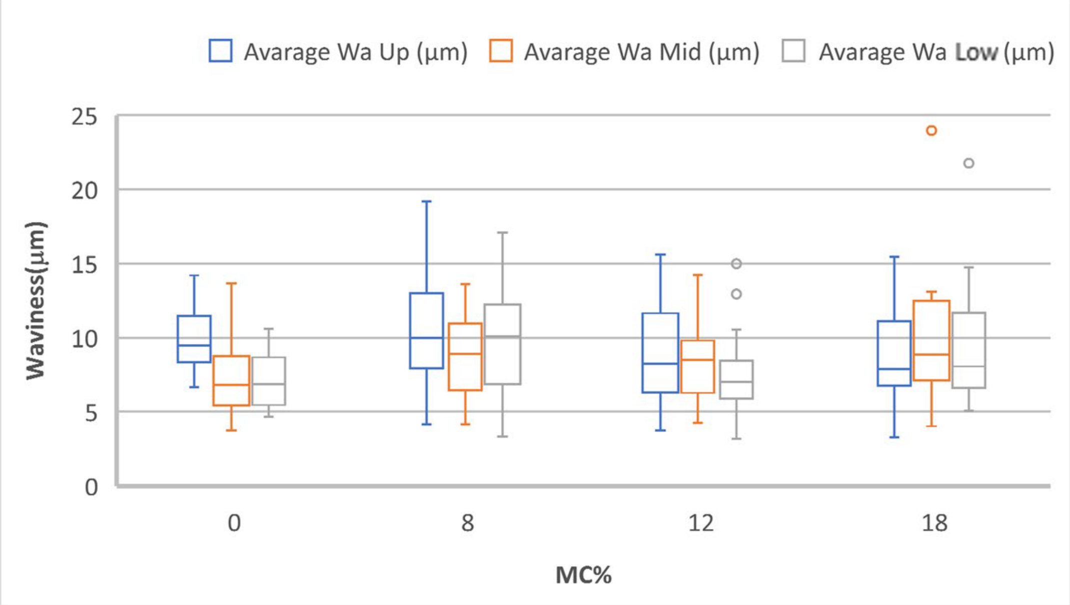

Figure 43. Influence of moisture content on surface waviness (*Wa*) at different vertical positions (top, middle, and bottom) of CO_2 laser-cut beech wood (Corleto et al. 2024).

Response variable	Source of variation	Sum of squares	df	Mean square	F-value	P-value
Total *Wa* (µm)	Moisture content	49.002	3	16.334	4.246	**0.007**
	Error	388.563	101	3.847	—	—
Average *Wa* – upper (µm)	Moisture content	47.590	3	15.863	1.506	0.218
	Error	1063.999	101	10.535	—	—
Average *Wa* – middle (µm)	Moisture content	68.566	3	22.855	2.375	0.075
	Error	971.811	101	9.622	—	—
Average *Wa* – lower (µm)	Moisture content	165.062	3	55.021	5.875	**0.001**
	Error	945.923	101	9.366	—	—

Table 6. Statistical analysis of average surface waviness (*Wa*) of laser-cut beech wood specimens conditioned at 0%, 8%, 12%, and 18% moisture content (MC %). Differences were considered statistically significant at $P < 0.05$, while $P > 0.05$ indicated non-significant variation.

6.5 Effect of moisture content (MC %) on color of laser-cut surface

The colour of the wood surface is an important indicator of both its visual appearance and its technological performance (Acik & Tutuş 2020). In the present study, CO_2 laser cutting resulted in a noticeable darkening of the surface, primarily associated with carbonization processes. This darkening is linked to the photochemical degradation of the main wood components—hemicellulose, cellulose, and lignin which contain chromophoric groups capable of absorbing radiation at specific wavelengths (Kubovský 2019; Gašparík 2019).

Analysis of the influence of moisture content (0%, 8%, 12%, and 18%) on total colour variation (ΔE^*) showed only slight differences between the tested conditions (Fig. 44), consistent with the findings reported in Corleto et al. (2024). The initial and most evident effect of laser exposure was a reduction in lightness, caused by the thermal degradation and carbonization of lignin, cellulose, hemicellulose, and extractives. Among these components, lignin exhibited the greatest susceptibility to oxidative and hydrolytic reactions, while chromophoric groups absorbed energy selectively, contributing to visible colour shifts (Gašparík 2019; Li 2018).

Specimens conditioned at 18% moisture content tended to darken less than those at 0%, likely because the additional water absorbs part of the CO_2 laser radiation, thereby reducing the energy available for thermal decomposition (Kacík 2011; Gaff 2020). When ΔE* was evaluated at three vertical positions (top, middle, bottom), samples generally displayed lower colour changes at the top surface, except for those at 12% MC (Fig. 45). This outcome suggests that the focal point position—responsible for concentrating thermal energy on the uppermost region—did not substantially intensify carbonization along the vertical axis. Instead, variations in the anatomical and chemical characteristics of beech wood appear to modulate the observed colour response.

Samples at 12% MC showed consistent ΔE* values compared with the 8% and 18% MC conditions, likely due to a more homogeneous distribution of moisture during conditioning. In these samples, all colour coordinates (L*, a*, b*) decreased following laser cutting, with the greatest reduction observed in L*, confirming a general darkening of the surface. A slightly smaller colour change occurred when the focal point was positioned one-third below the top surface, although the differences in ΔE* were not statistically significant (Tab. 7).

Overall, total colour variation (ΔE*) was primarily driven by changes in lightness (ΔL*), whereas Δa* and Δb* contributed minimally to the final value. This trend is consistent with the findings of Kubovský and Kacík (2014). Interestingly, the lowest ΔE* values were recorded at the top portion of the samples, contradicting the initial hypothesis that greater energy density at the focal point would intensify thermal degradation and therefore produce more pronounced darkening.

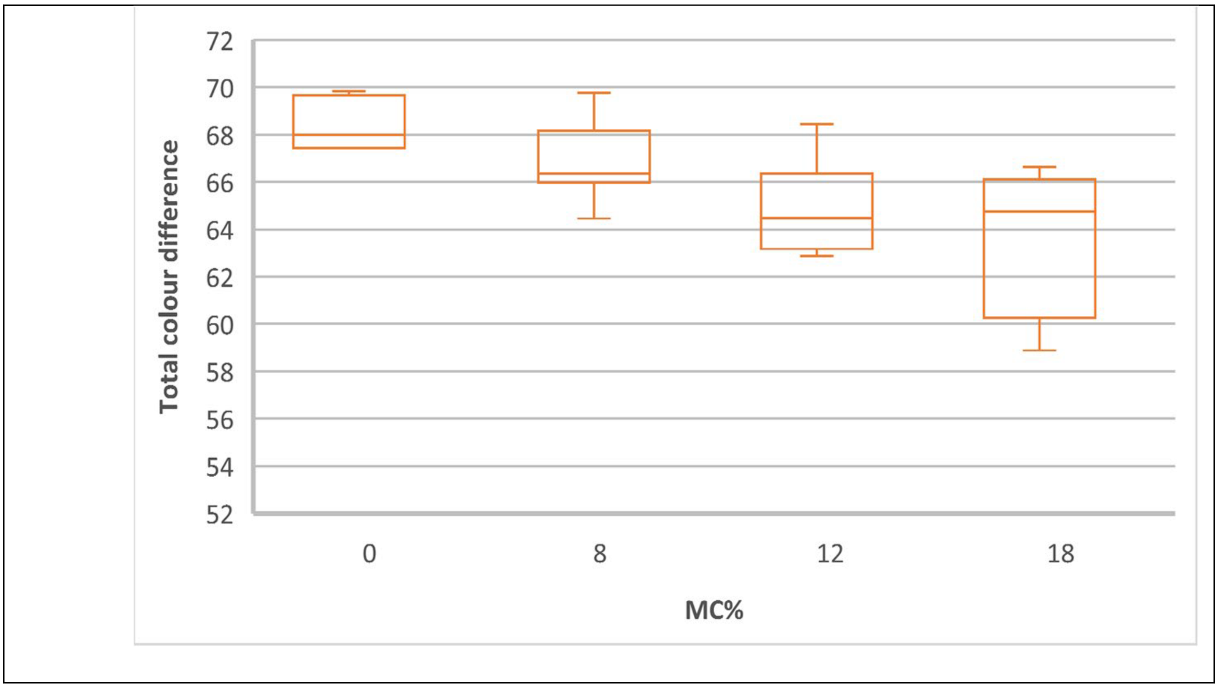

Figure 44. Effect of moisture content interaction on the total color difference (ΔE) of CO_2 laser–cut beech wood surfaces (Corleto et al.2024).

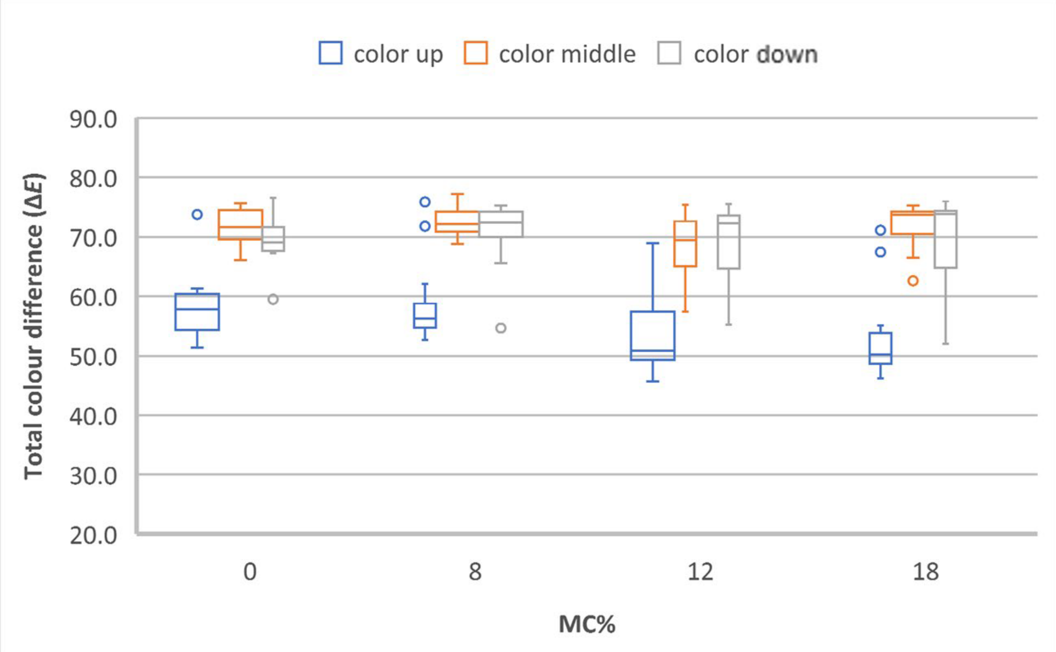

Figure 45. Influence of moisture content (from top to bottom) on the surface color variation of beech wood processed with a CO_2 laser (Corleto et el. 2024).

Response variable	**Source of variation**	**Sum of squares**	**df**	**Mean square**	**F-value**	**P-value**
Total color difference (ΔE)	Moisture content	102.8	3	34.3	4.52	**0.007**
	Error	364.0	48	7.6	—	—
Color difference – upper	Moisture content	360.8	3	120.3	2.18	0.102
	Error	2645.2	48	55.1	—	—
Color difference – middle	Moisture content	132.4	3	44.1	2.94	**0.042**
	Error	720.6	48	15.0	—	—
Color difference – lower	Moisture content	35.9	3	12.0	0.267	0.848
	Error	2149.9	48	44.8	—	—

Table 7. Statistical evaluation (ANOVA) of total color difference (ΔE) in laser-cut beech wood specimens conditioned at 0%, 8%, 12%, and 18% moisture content (MC %).

Results were considered statistically significant at $P < 0.05$, while $P > 0.05$ indicated non-significant differences

6.6 Effect of Laser Cutting Parameters on the Surface Quality of Wood Samples at 12 % Moisture Content

The effects of three key parameters focal point, cutting speed, and gas pressure on the surface quality (*Ra* and *Wa*) of wood material with 12% moisture content, cut using a CO_2 laser, are discussed below. Precise characterization of these parameters is crucial for optimizing the production process and enhancing the final performance of wood products.

6.6.1 Focal point position

The results shown in Fig. 46, indicate that surface roughness (*Ra*) increases as the focal point depth moves deeper into the wood, from the surface (P) to the center of the sample (-16). The increase in *Ra* values was statistically significant (p-value > 0.03), rising from 4.93 µm to 6.88 µm, in line with previous studies that reported this deterioration in surface quality (Barnekov et al. 1986; Lum et al. 2000; Kubovský et al. 2020). A similar trend was observed when surface roughness was measured using confocal microscopy, a non-contact technique (Rezaei et al. 2022), although *Ra* values were approximately 2.5 times higher.

Similarly, surface waviness (*Wa*) increased from 9.7 µm to 10.89 µm when the focal point was shifted from the surface toward the center. However, the increase in surface waviness (*Wa*) was marginal and not statistically significant (p-value > 0.275). Positioning the focal point deeper within the wood leads to the formation of a thermally affected zone (TAZ), resulting in carbonization and combustion, which increases surface roughness (*Ra*) (Koohi 2020). Moreover, variations in moisture content across the wood's cross-section contribute to uneven cuts or incisions in the central region of the material (Hernandez-Castaneda et al. 2011). Wood grain characteristics also influence the uniformity of deep cuts, while high concentrations of resins and extractives at the center can result in uneven material removal (Raj and Mohandass 2014). Focusing on the central region can generate mechanical stress, leading to microcracks and splinters that further exacerbate surface roughness.

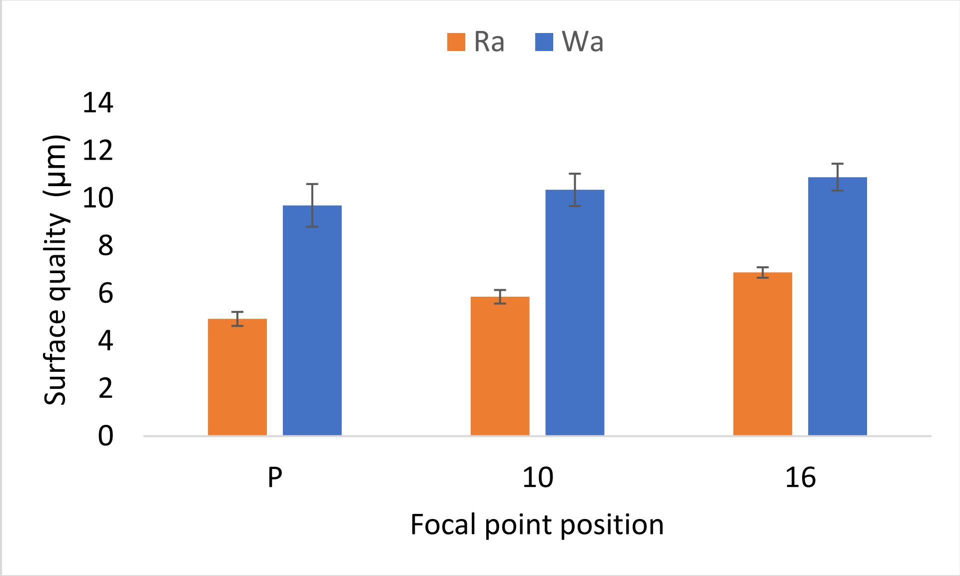

Figure 46. Effect of focal point position on surface roughness (*Ra*) and surface waviness (Wa) of laser cut samples. (P: on the top surface, 10: 10 mm or 1/3rd from the top and 16: 16 mm or about ½ from the top) (Corleto et al. 2025).

6.6.2 Gas pressure

In Fig. 47, the effect of gas pressure (17 bar and 21 bar) on *Ra* and *Wa* is shown. It can be observed that surface roughness (*Ra*) slightly increased with higher gas pressure, although the difference was not statistically significant (p-value = 0.468 and 0.852 for *Ra* and *Wa*, respectively) (Lum et al. 2000). This effect may be due to additional heat generated by the exothermic reaction, which could cause localized thermal expansion or slight surface degradation. Another possible explanation is that higher gas pressure could increase the velocity of the material ejected during the cutting process, leading to uneven material removal and a minor increase in roughness.

Conversely, the slight improvement in surface waviness (*Wa*) could be attributed to the higher gas pressure, which facilitates more efficient removal of carbonized material and debris, reducing surface irregularities. A higher gas flow can also cool the surface more effectively, minimizing prolonged heat exposure and preventing excessive thermal damage. These results are consistent with observations obtained via confocal microscopy (Rezaei et al. 2022) and are supported by previous studies (Lum et al. 2000).

During laser cutting of wood, gas jets are essential for removing smoke, controlling combustion, and protecting the lens. Typically, pressures up to 4 bar are used for solid wood (Barnekov et al. 1986). Increasing the pressure improves laser–material interaction, reducing carbonization and protecting the lens

(Hernandez-Castaneda et al. 2011; Powell 1993). Eltawahni et al. (2011) reported that higher pressures decrease surface roughness (*Ra*). However, in our study, using higher pressures did not lead to a significant improvement in the surface quality of the wood.

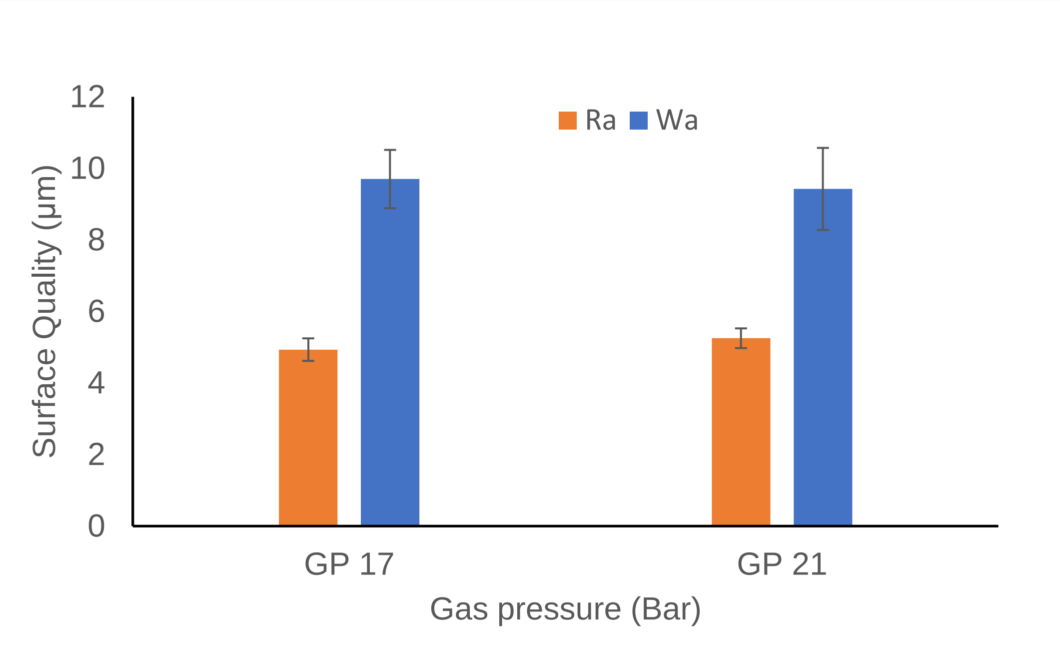

Figure 47. Effect of exhaust gas pressure on surface roughness (*Ra*) and Surface waviness (*Wa*) of laser cut wood (Corleto et al. 2025).

6.6.3 Cutting speed

In Fig. 48 the relationship between cutting speed and surface roughness quality (*Ra* and *Wa*) is shown. It can be observed that the mean *Ra* value increased from 4.76 µm to 5.25 µm as the cutting speed increased from 3.0 to 3.5 m/s. Meanwhile, the *Wa* value decreased slightly from 9.83 µm to 9.42 µm with increasing cutting speed. Surface roughness (*Ra*) therefore did not show significant variation with the increase in cutting speed (p-value = 0.254). This observation is consistent with the results reported by Rezaei et al. (2022) using confocal microscopy, although the *Ra* values in that study were approximately two and a half times higher. This difference may be attributed to the reduced interaction time between the laser beam and the material at higher cutting speeds, which limits combustion and heat diffusion. Higher cutting speeds reduce the amount of heat absorbed by the material, preventing excessive carbonization or burning, which would otherwise increase surface roughness. Moreover, higher cutting speeds may lead to reduced thermal expansion and localized melting of the wood, further contributing to stable surface roughness. Previous studies

(Cebrail and Tutus, 2020; Magoss et al. 2008; Kubovský et al. 2020) support this relationship, showing that higher speeds help avoid prolonged heat exposure.

The relationship between cutting speed and surface waviness (*Wa*) showed a slight tendency toward lower values, from 9.83 µm to 9.42 µm, within the same speed range (from 3 to 3.5 m/min), although the difference was not statistically significant (p-value = 0.774). This slight variation may be due to minor mechanical vibrations at higher speeds, which can cause small undulations in the material. However, the effect is minimal, likely due to the balance between reduced thermal distortion and mechanical factors during the cutting process.

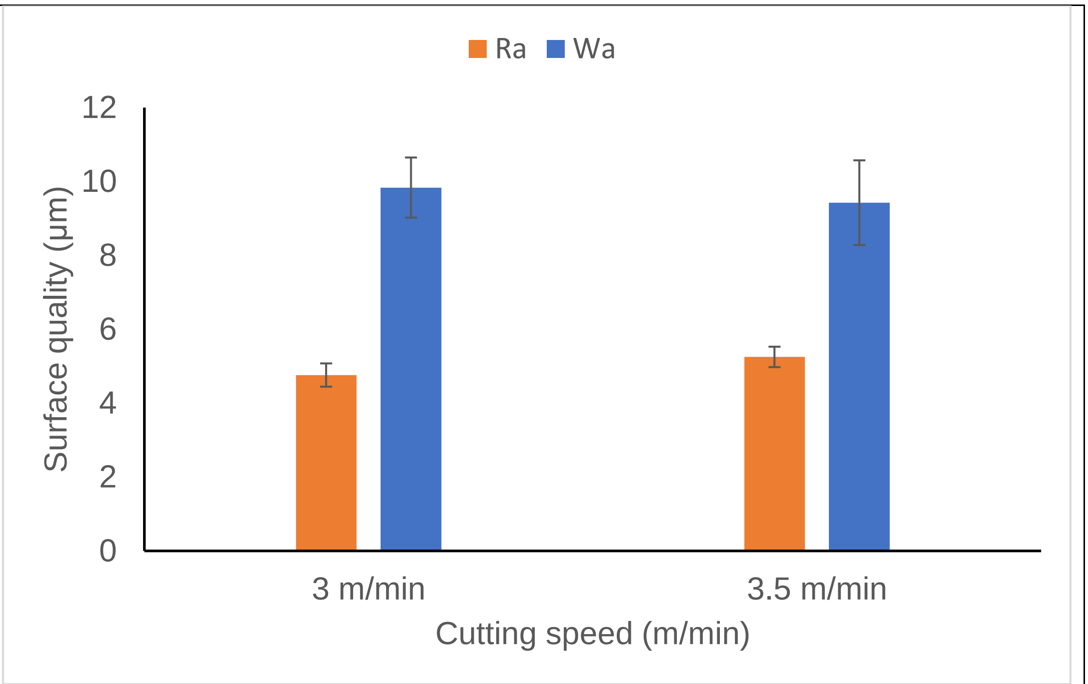

Figure 48. Effect of cutting speed on surface roughness (*Ra*) and surface waviness (*Wa*) of laser cut wood (Corleto et al. 2025).

6.7 Diffusion and hardness

6.7.1 CO_2 laser cutting parameters on diffusion behavior

Moisture transport in untreated samples was significantly lower compared to laser-cut samples, a surprising result since high-temperature treatments generally tend to reduce water absorption in wood (Sayar and Tarmian 2013; Olek et al. 2016).

Laser cutting caused an increase in water vapor flux density of approximately 35–70%, regardless of the process parameters used. Neither the cutting speed (V vs. VII) nor the gas pressure (VI vs. VII) had a significant effect on vapor diffusion in laser-cut wood, as variations in cutting parameters did not result in significant differences (Tab. 8).

In addition to the substantial change in diffusion properties, an increase in standard deviation was also observed following laser cutting. This phenomenon could be attributed to anatomical differences between samples, such as variations in pore volume or lignification status (presence of juvenile wood).

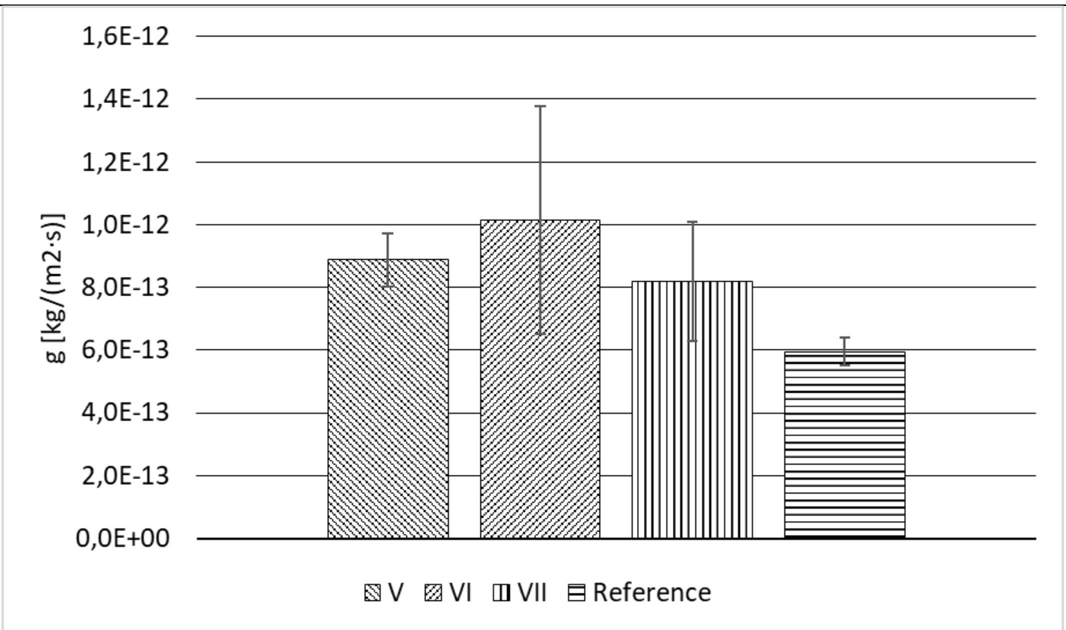

Figure 49. Effect of changes in cutting speed and gas pressure on water vapor flux density in laser-cut wood samples.

Variations in cutting speed, 3 m/min, and 3.5 m/min on the density of water vapor flow rate					
Effect	**Sum of square**	**Degr. Of Freedom**	**Mean square**	**F**	**P-level***
Intercept	5.82 E-24	1	5.82 E-24	267.7164	0.000003

V vs VII, Cutting speed (m/min)	9.57 E-27	1	9.57 E-27	0.4397	0.531871
Error	1.30 E-25	6	2.17 E-26		
Variations in gas pressure, 17 bar and 21 bar, on the density of water vapor flow rate					
Intercept	6.71 E-24	1	6.71 E-24	79.7797	0.000109
VI vs VII, Gas pressure (bar)	7.61 E-26	1	7.61 E-26	0.9033	0.3786
Error	5.05 E-25	6	8.42 E-26		

Table 8. ANOVA Analysis to Examine the Influence of Laser Parameters on Water Vapor Flow Rate Density.

During the study, the influence of cutting speed (3 m/min and 3.5 m/min) and gas pressure (17 bar and 21 bar) on the density of water vapor generated by the wood during laser cutting was examined (Fig. 49). The data showed that neither variable had a statistically significant impact on the vapor density. Specifically, for cutting speed, an F-value of 0.44 with a p-value of 0.53 was calculated, while for gas pressure, the F-value was 0.90 with a p-value of 0.38. Both results exceed the significance threshold of 0.05, suggesting that within the considered ranges, neither changes in speed nor in pressure significantly affected the amount of vapor emitted.

6.7.2 CO_2 laser cutting parameters on Brinell hardness

To compare the hardness values of samples cut at different cutting speeds (V: 3 m/min, VII: 3.5 m/min) and gas pressures (VI: 17 bar, VII: 21 bar), reference is made to Fig. 50.

When different cutting speeds were tested, the constant laser parameters were 3200 W (power), 21 bar (gas pressure), and the focal point positioned on the upper surface of the beech wood sample. When varying the gas pressure, the fixed parameters were 3200 W, 3.5 m/min (cutting speed), and the focal point positioned on the upper surface of the sample.

As shown in the figure, the hardness values of samples cut at 3 m/min (V), equal to 16.9 N/mm², were nearly identical to those of samples cut at 3.5 m/min

(VII), which had a value of 17.3 N/mm². ANOVA analysis (Tab. 6) confirms that there is no significant difference between the two groups ($p = 0.824$). This result was unexpected, as it was hypothesized that a lower cutting speed would allow more time for the wood's chemical compounds to degrade completely, thereby increasing the carbonization rate of the cut surface. Furthermore, the layers beneath the carbonized wood are influenced by the laser power and may undergo surface integrity loss. Consequently, increasing the cutting speed could be expected to improve the surface integrity of the laser-cut samples.

Fig. 50 also shows that changing the gas pressure from 17 bar to 21 bar leaves the hardness values of the laser-cut samples virtually unchanged. Hardness values for samples cut at 17 bar (VI) and 21 bar (VII) were 17 N/mm² and 17.3 N/mm², respectively. The similarity between groups VI and VII is confirmed by Table 9, based on the p-value. This outcome contradicts expectations, as increasing gas pressure is generally thought to reduce the carbonization rate (Powell 1993; Quintero et al. 2011). Therefore, chemical degradation of the wood decreases, surface integrity improves, and hardness values may increase.

The most notable observation from Fig 48. is that the hardness of laser-cut samples is significantly lower than that of saw-cut samples. Sedlar et al. (2019) reported that the Brinell hardness of thermally modified beech wood (200 °C for 48 hours) decreased compared to untreated beech. Similarly, Gunduz et al. (2009) found that increasing the thermal treatment temperature from 170 °C to 210 °C over 4–12 hours reduced the hardness of hornbeam wood.

Variations in cutting speed, 3 m/min, and 3.5 m/min on the B-M hardness					
Effect	**Sum of square**	**Degr. Of Freedom**	**Mean square**	**F**	**P-level***
Intercept	17550.41	1	17550.41	398.6475	0.000000
V vs VII, Cutting speed (m/min)	2.20	1	2.20	0.0500	0.824
Error	2553.44	58	44.02		
Variations in gas pressure, 17 bar and 21 bar, on the B-M hardness					
Intercept	16774.08	1	16774.08	325.8398	0.000000
VI vs VII, Gas pressure (bar)	0.76	1	0.76	0.0148	0.903
Error	2831.37	55	51.48		

Table 8. ANOVA Analysis to Explore the Impact of Laser Parameters on Brinell Hardness.

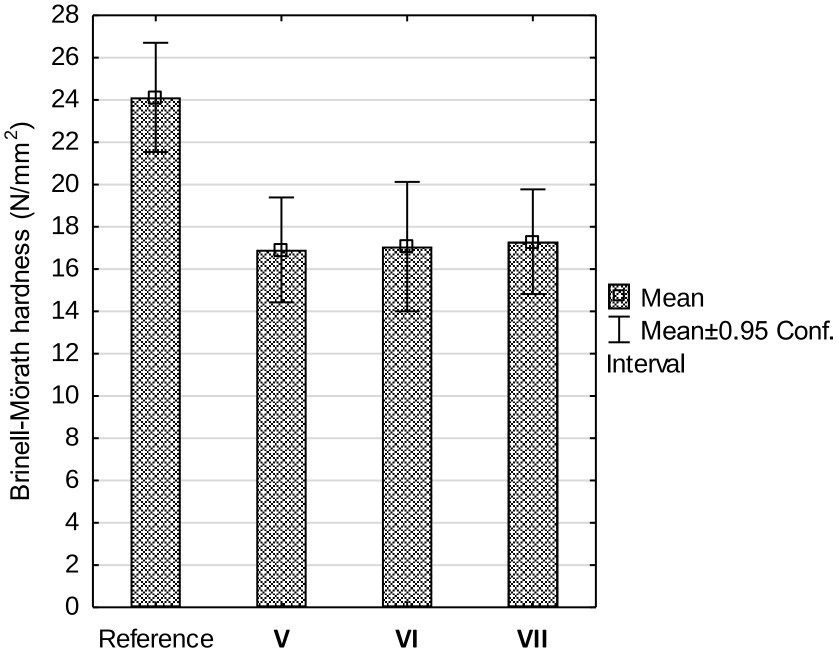

Figure 50. Effect of changes in cutting speed and gas pressure on the surface hardness of laser-cut samples.

6.8 Chemical change of the surface after cutting

The chemical modifications occurring on hardwood surfaces because of laser cutting were analyzed to better understand the thermal effects of the process. It is essential to investigate the changes in functional groups within the different wood layers after laser processing.

The FT-IR spectra of the samples subjected to laser cutting and subsequent sanding showed significant variations in the absorption bands of cellulose, hemicellulose, and lignin (Fig. 51). A marked reduction was observed in the intensity of the absorption peak at 1735 cm^{-1} compared with the sanded samples. This decrease is attributed to the thermal degradation induced by the laser, which promotes the acetylation and xylan degradation of hemicellulose, a component more susceptible to thermal effects than cellulose. These results are consistent with the findings of Rezaei et al. (2023), of which I am a co-author, which reported a significant reduction in the hemicellulose C=O band in CO_2-laser-cut samples, confirming surface deacetylation.

Laser-cut samples also exhibited a strong reduction in the absorption at 1655 cm^{-1} (associated with aromatic ketones in lignin), accompanied by an increase in the band at 1594 cm^{-1}, indicative of structural changes in lignin, such as the condensation of conjugated carbonyl groups in the propanoid side chain.

Cellulose showed only slight variations in absorption intensity, suggesting that laser cutting does not significantly affect cellulose in the adjacent layers, particularly up to a depth of approximately 200 µm. These findings demonstrate that laser cutting induces substantial surface modifications in wood, affecting primarily lignin and, to a lesser extent, hemicellulose in the treated zone.

The thermal energy from the CO_2 laser causes the degradation of the main chemical constituents of beech wood (*Fagus Sylvatica* L.), with the alteration depth mainly observed in the first two layers (approximately 50 µm each). Furthermore, the decrease in the intensity of the C–O peak around 1330 cm^{-1} suggests the cleavage of methoxyl groups in lignin. The peak at 1235 cm^{-1}, associated with syringyl units, also shows a decrease, highlighting lignin degradation due to elevated temperatures.

On the carbonized surface, the peak around 1030 cm^{-1}, linked to alcoholic hydroxyl groups, exhibits a marked reduction, suggesting their involvement in condensation reactions with phenyl groups. Finally, the peak at 896 cm^{-1}, associated with cellulose, shows slight alterations.

These results are consistent with the findings reported in the other study by Rezaei et al. (2023): FTIR spectroscopy reveals evidence of heating, oxidation, and the formation of a carbonized layer, with significant chemical modifications limited to the surface layers. The increased intensity of the O–H band around 3336 cm^{-1} and the C–H peaks between 2918–2928 cm^{-1} in the laser-cut samples confirm the decomposition of hydroxyl groups and local pyrolysis, supporting the alignment between the two studies.

Hemicellulose and lignin therefore undergo more extensive degradation, resulting in a reduction in the number of hydrogen bonds available for adhesion with resin systems. This decrease in bonding potential may explain why the adhesive properties of laser-cut surfaces are inferior to those of surfaces cut with traditional contact tools.

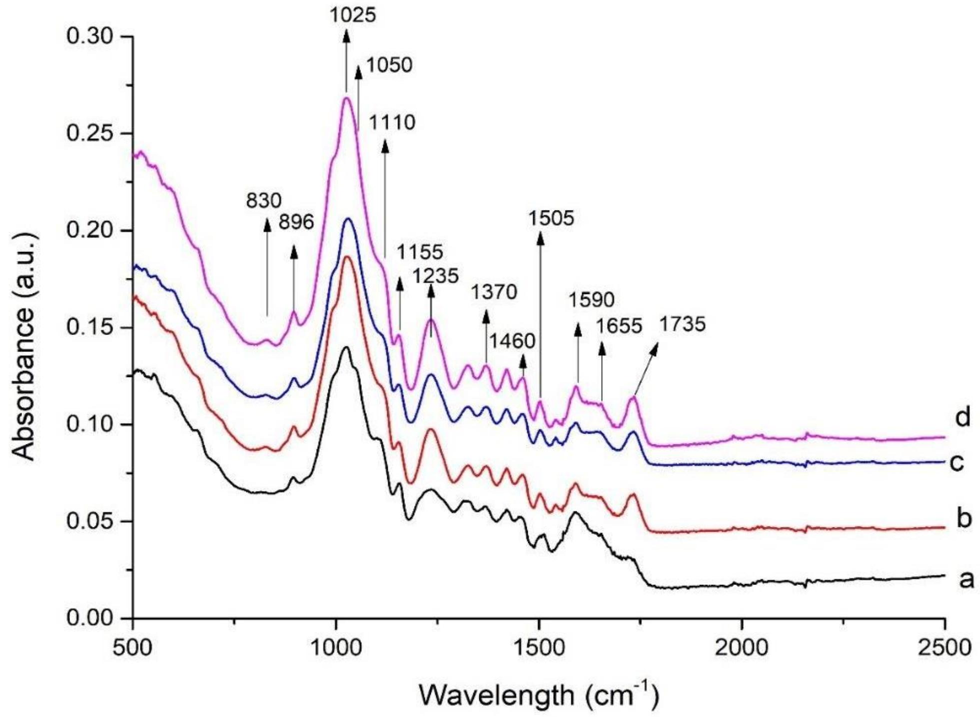

Figure 51. FT-IR spectra of lasercut (char) surface (a) and sanded surface (b-200 µm below the laser cut surface, c- 400 µm below the laser cut surface and d-600 µm below the laser cut surface) (Corleto et al. 2025).

6.8.1 Principal Component Analysis (PCA)

To investigate the chemical modifications induced by laser cutting on both the processed and polished wood surfaces, a Principal Component Analysis (PCA) was carried out. The multivariate results showed that the first three principal components (PC1, PC2, and PC3) explained more than 98% of the total variance (Tab.10 and Tab.11), indicating a strong data representation.

The PCA results highlighted distinct spectral variations in the laser-cut samples, confirming that the process induced measurable chemical changes on the surface. In contrast, the FTIR absorption intensities of samples polished at different depths did not exhibit significant differences, suggesting that the laser effect diminishes rapidly below the surface. As illustrated in the PCA plot, samples S1, S2, and S3 formed a compact cluster (Fig. 52), whereas the unpolished laser-cut sample was clearly separated from the group. This separation reflects the alteration of functional groups caused by the heat generated during laser cutting.

Nevertheless, below approximately 200 µm, the differences among the spectra became negligible, confirming that the thermal impact of the laser is restricted to the outermost surface layer (Corleto et al. 2025).

Eigen Value	**Variance (%)**
3.95	98.75
0.047	1.18
0.0026	0.07
1.58 E^{-4}	0.0

Table 9. Eigen values obtained from the FTIR analysis of laser-cut and sanded specimens (Corleto et al. 2025).

Wavelength (cm^{-1})	**PC 1**	**PC 2**
830	0.233	0.832
896	0.531	0.01
1025	2.62	-2.37
1050	2.31	-2.3
1155	0.31	0.45
1235	0.40	0.30
1370	0.01	1.01
1460	-0.15	0.97
1505	-0.39	0.94
1655	-0.4	1.03
1735	-0.50	-1.27

Table 10. Principal component scores associated with the characteristic absorption wavelengths identified in the FTIR spektra (Corleto et al. 2025).

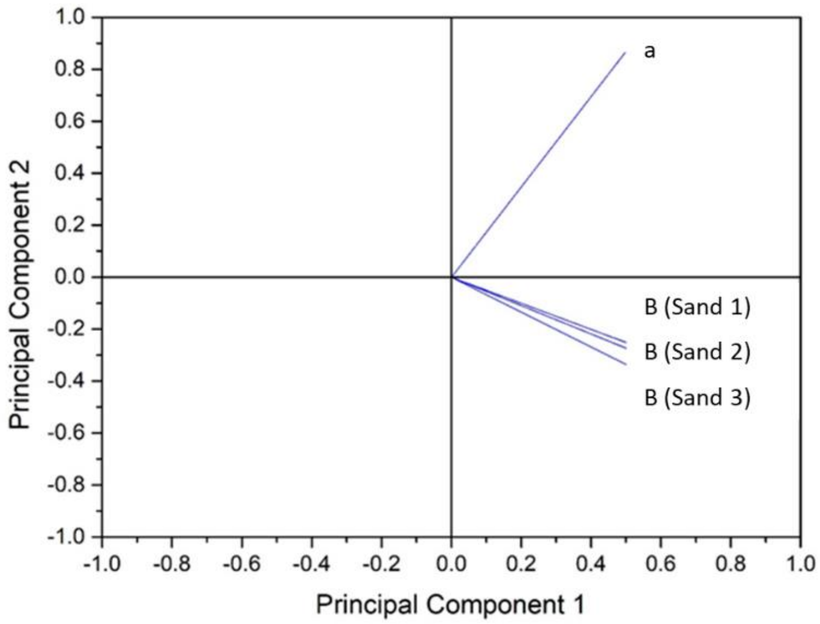

Figure 52. Screen plot for laser-cut and sanded surfaces (B1, B2, and B3) (Corleto et al. 2025).

The chemical modifications identified through FTIR analysis, particularly the degradation of lignin and hemicellulose in the surface layers, are consistent with the morphological observations obtained using scanning electron microscopy, as described in the following chapter.

6.9 Effect of CO_2 Laser Cutting Parameters on the Anatomical Structure of Beech Wood

To analyze the morphological modifications induced by laser cutting, scanning electron microscopy (SEM) observations were carried out on beech samples with a moisture content of 8%, processed at different feed speeds (3 and 3.5 m/min) while keeping the laser focus on the upper surface.

The micrographs show that reducing the cutting speed results in more pronounced degradation of the anatomical structure (Fig. 53). In samples cut at 3 m/min, the middle lamella between the cell walls is destroyed, whereas at 3.5 m/min the damage is more limited, and some fiber connections remain distinguishable. This difference is attributable to the longer exposure time and consequent accumulation of thermal energy occurring at lower cutting speeds.

The middle lamella, rich in lignin and pectins, is the portion most sensitive to heat because lignin—although degrading at higher temperatures than cellulose and hemicellulose is more susceptible to the localized thermal effects of the laser beam. The infrared radiation of the CO_2 laser acts primarily through molecular vibrations that generate heating, rather than through electronic transitions as occurs in the visible or UV spectrum.

At higher cutting speeds, the shorter beam residence time reduces the residual energy at the point of incidence, limiting degradation to the superficial layers. Under these conditions, part of the cellulose in the inner wall layers (S2 and S3) retains its integrity, appearing in the micrographs as protruding white structures. In slower cuts, however, the accumulated energy is sufficient to fully degrade both lignin and cellulose, resulting in a complete loss of structural definition.

In summary, increasing the feed speed reduces thermal alteration, partially preserving the cellulosic components and limiting the carbonization of lignin, whereas at lower speeds, the heat generated induces deeper degradation and a greater degree of fusion of decomposition products on the cell walls.

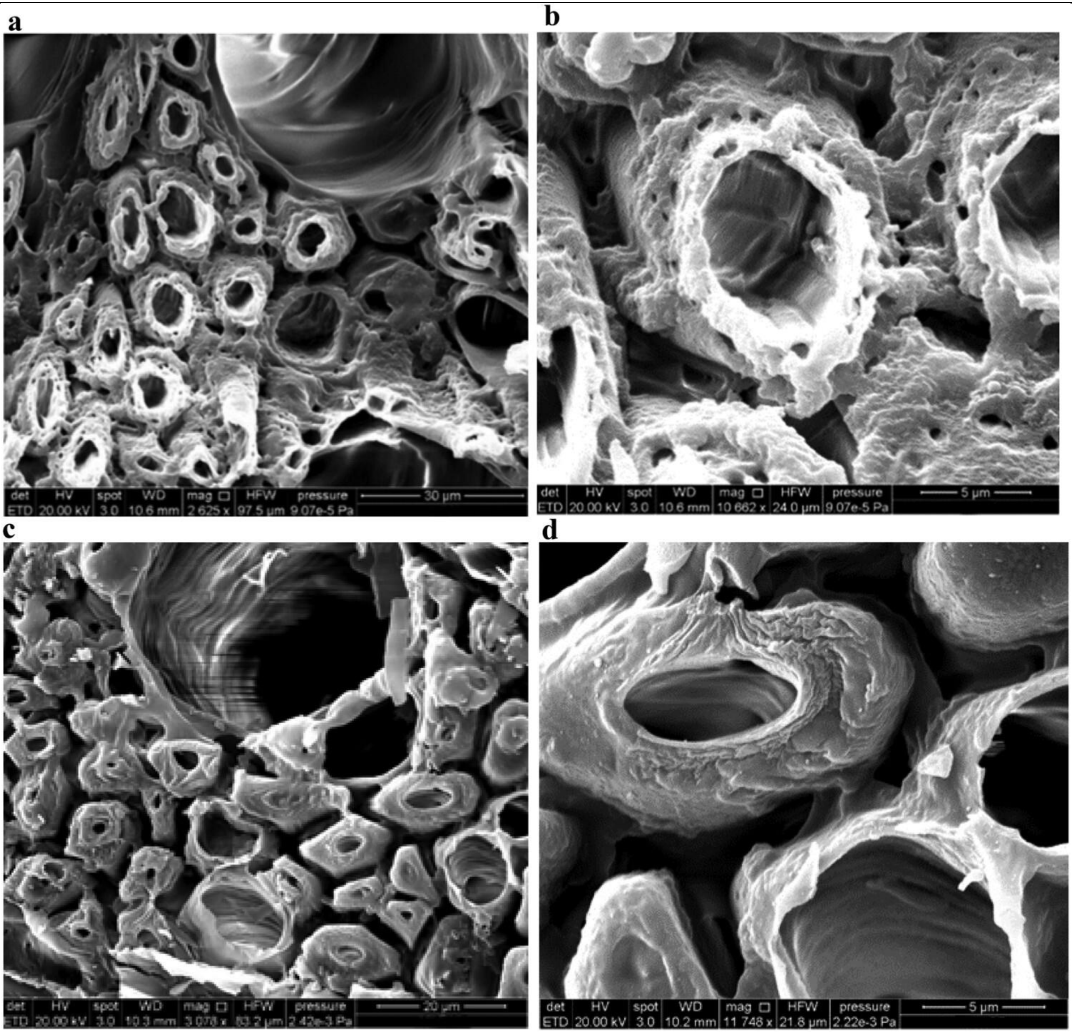

Figure 53. SEM micrographs of the cross-section of beech samples cut with a CO_2 laser. Images (a) and (b) correspond to the sample processed at a feed speed of 3.5 m/min, while images (c) and (d) show the sample cut at 3.0 m/min (Processing based on data from Rezaei et al. 2022).

The visible projections of residual polymer chains and the cavities associated with the degradation of the middle lamella, observed in the cross-sections of the laser-cut samples, can be considered indicators of morphological modifications influencing the surface roughness profile. It is plausible that such structural variations, evident in the cross-sectional view, are also reflected on the tangential surface, contributing to local changes in the micro profile. However, as shown in Fig. 53, the increase in cutting speed from 3.0 to 3.5 m/min did not produce significant variations in the mean roughness value (*Ra*) of the tangential samples.

This result suggests that the anatomical alterations induced by laser processing do not necessarily translate into measurable changes in the surface roughenss (*Ra*) parameter, indicating a limited influence of microstructural transformations on the overall surface topography.

SEM analyses of the samples cut with a CO_2 laser at different focal point positions are presented in Fig. 54.

The specimens, conditioned to a moisture content of 8%, were processed at a constant feed speed of 3.5 m/min and an assist gas pressure of 17 bar. Images (a) and (b) show the cross-section of a sample cut with the focus positioned on the surface, whereas images (c) and (d) refer to the sample in which the focal point was placed at the mid-thickness of the workpiece. For SEM observations, the lower portion of the cross-section was examined.

When the focus is located on the surface, the laser beam energy is initially concentrated in the upper layers and gradually decreases toward the lower part. Consequently, the lower zone receives less energy, displaying better anatomical integrity and reduced carbonization compared with samples cut with a centered focal point. Under these conditions, the middle lamella is less damaged, and the cells partially retain their original connections (Fig. 54 a,b).

In contrast, in samples cut with the focus positioned at the center, the greater energy penetration causes more pronounced degradation of the middle lamella, with the formation of voids and microfractures in the cross-section (Figure 54 c,d). It is likely that these cavities also extend in the tangential direction, contributing to the variations in surface roughness profile observed in samples with higher moisture content. As shown in Fig. 52, the increase in tangential roughness at 12% moisture content is indeed associated with shifting the focal point from the surface to the center of the workpiece.

Moreover, in the high-magnification micrographs (Fig. 54 d), small bubbles can be observed on the cell walls, attributable to the pressure exerted by vapors generated during the pyrolysis of lignocellulosic material. These gases—including carbon monoxide, carbon dioxide, hydrogen, methane, and other light hydrocarbons are formed as a result of the thermal degradation of the organic components of wood (Ghany & Newishy 2005; Commandré et al. 2011).

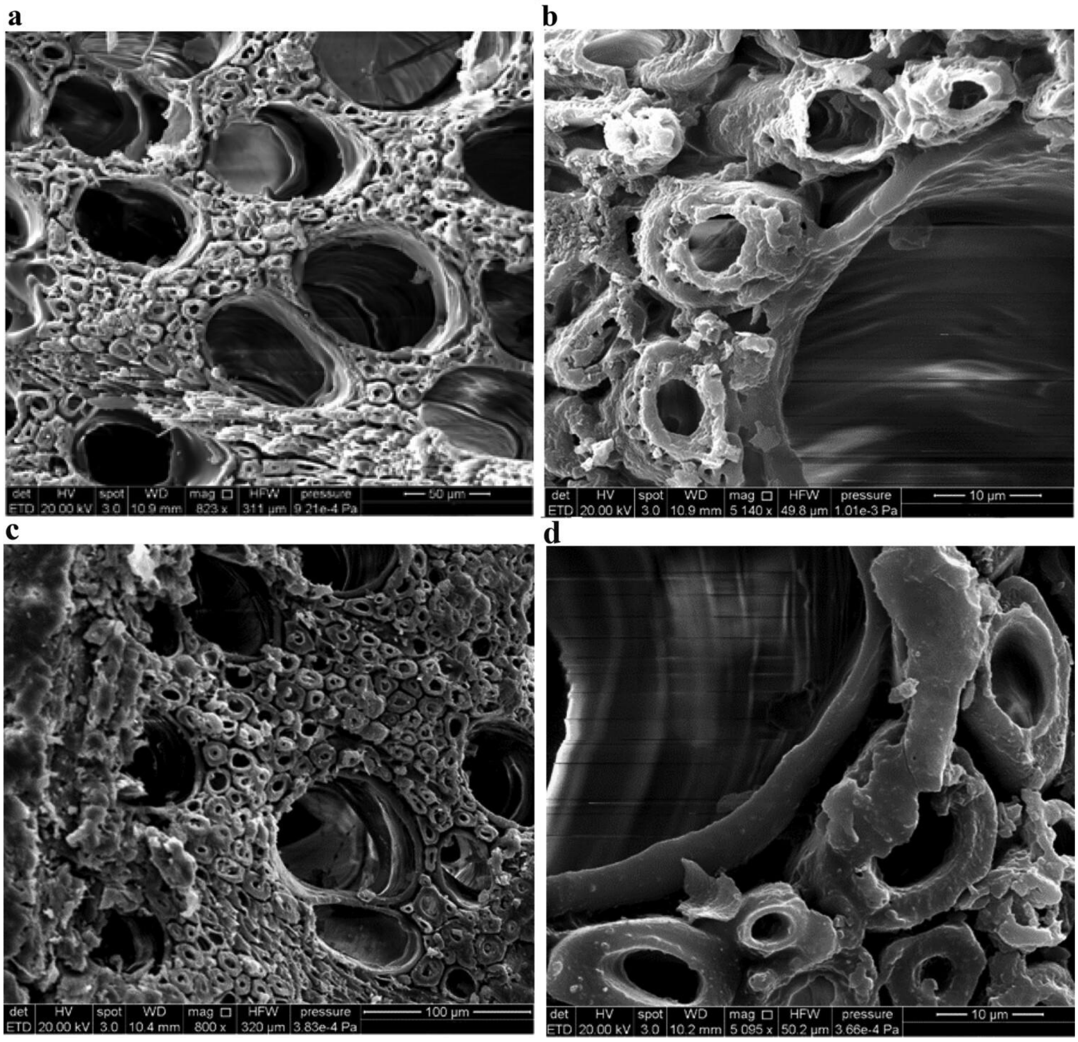

Figure 54. SEM micrographs of the cross-section of beech samples cut with a CO_2 laser at different focal point positions. Images (a) and (b) correspond to the sample cut with the focus positioned on the upper surface, while images (c) and (d) show the sample processed with the focus centered within the thickness of the workpiece (Processing based on data from Rezaei et al. 2022).

The SEM micrographs of the cross-sections of beech (*Fagus sylvatica* L.) samples cut at different moisture contents (MC %) are shown in Fig. 55. All specimens were processed with a constant cutting speed of 3 m/min, a laser power of 3200 W, a gas pressure of 21 bar, and the focal point positioned at the mid-thickness of the workpiece. Images (a,b) refer to samples conditioned at 8% MC, images (c,d) to 12% MC, and images (e,f) to 18% MC.

Observations showed that higher moisture content promotes improved cut surface quality. In low-MC % samples, the middle lamella was completely degraded and the cell lumina appeared empty, indicating marked thermal degradation. This is since at low moisture levels, laser energy is absorbed more effectively by the wood components, accelerating pyrolysis and carbonization processes.

With increasing moisture content, the degradation of the middle lamella becomes less pronounced. This effect is attributed to the higher thermal conductivity of moist wood, which enhances heat dissipation by conduction (MacLean 1941; Vay et al. 2015), and to the energy required for water evaporation (Barnekov et al. 1986; Piili et al. 2009; Hernandez-Castañeda et al. 2011).

During the cutting process, the products of thermal degradation may combine with water vapor to form a viscous suspension that deposits on the cell walls, partially sealing the lumina and the fissures of the middle lamella, resulting in a more compact and homogeneous surface, as visible in the Fig. 55.

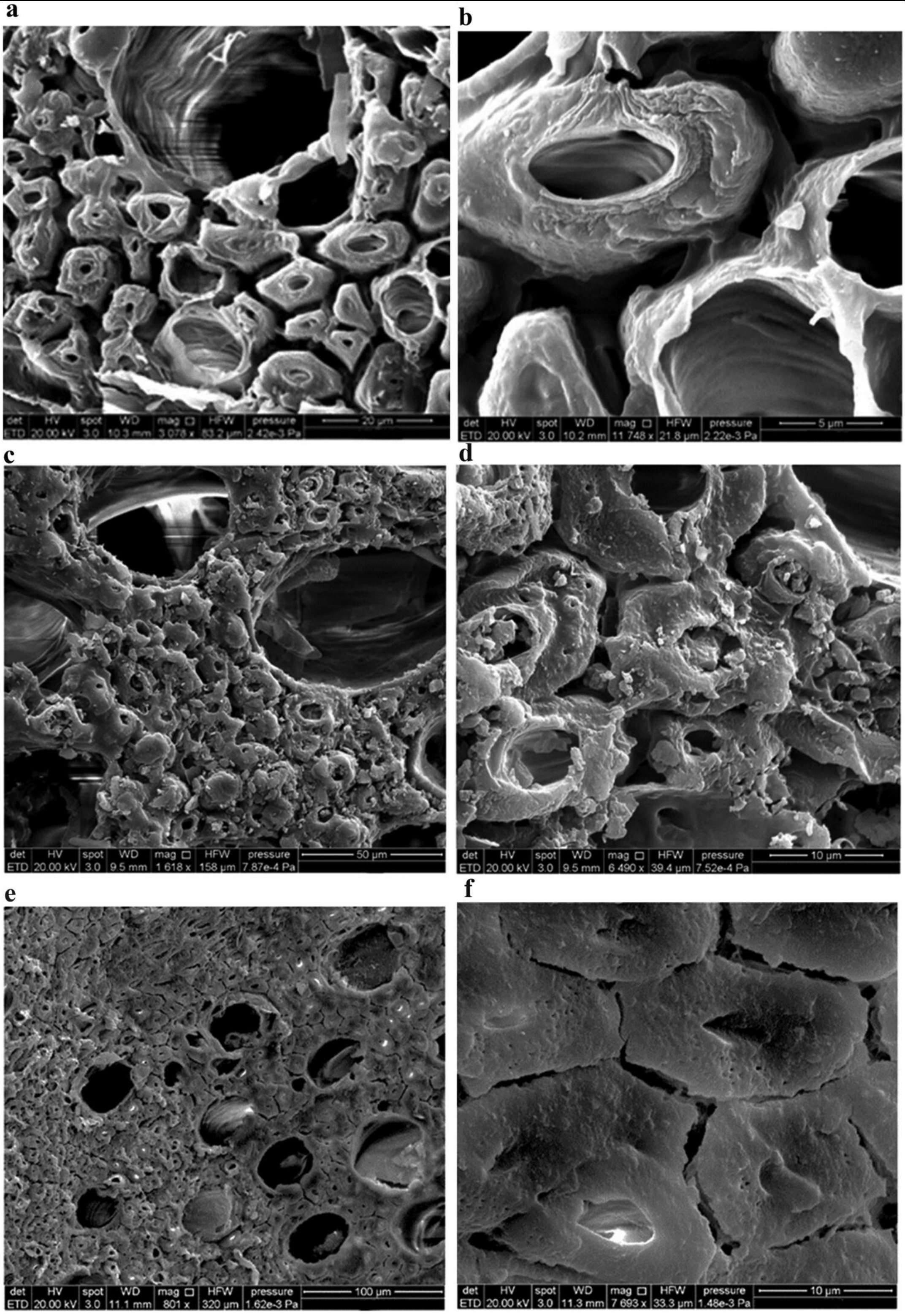

Figure 55. SEM micrographs of the cross-section of beech samples cut with a CO_2 laser and conditioned to different moisture contents: (a,b) 8% MC, (c,d) 12% MC, and (e,f) 18% MC. All samples were processed using constant cutting parameters: cutting speed of 3 m/min, gas pressure of 21 bar, and focal point positioned at the mid-thickness of the workpiece. (Processing based on data from Rezaei et al. 2022).

6.10 Contact vs. non-contact methods for evaluating laser-cut quality.

Two measuring devices were used on beech wood (*Fagus Sylvatica* L.) samples cut after laser CO_2 to identify which surface profile measurement method was more reliable and accurate. Confocal microscopy provided more precise data and higher roughness values (Fig. 56, 57, 58) (Rezaei et al. 2022) than the contact method, which showed lower roughness values (Fig. 40, 42) (Corleto et al. 2024). On average, *Ra* and *Wa* values obtained with the conventional stylus method were approximately 5 µm and 6 µm, whereas the confocal microscope consistently yielded higher values, generally between 12 and 15 µm, depending on the parameter considered. This difference is due to the ability of the laser in confocal microscopy to penetrate and measure finer surface details. At the same time, the larger stylus tip used in the contact method cannot accurately capture areas with tiny depressions and valleys. Another study by Rezaei et al. (2020), which compared these two measurement methods on samples cut with a conventional circular saw, supports these findings. However, the wood species and treatment differed in that study, as it focused on thermally modified spruce. In a previous study by Gurau et al. (2001), it was found that the contact method was preferable for detecting wood surface irregularities, as it provided more accurate and repeatable data compared to non-contact methods. This suggests that surface roughness (*Ra*) values depend not only on the measurement method but also on the anatomical characteristics of the wood and its surface treatment (e.g., processing, finishing). However, there is a lack of statistically significant research on this topic, and further studies involving various wood species with different densities are needed to validate this observation. Analysis of the processing parameters of laser-cut samples using both methods revealed divergent results, affecting the surface profiles obtained. Another study highlighted the limitations of non-contact methods for measuring wood surface irregularities after CO_2 laser cutting due to inherent issues with the measuring device. The digital microscope used in this study could not effectively capture the depth of cellular elements in certain wood types, resulting in inaccurate evaluations of surface irregularities. It showed distortions in surface features with short wavelengths (roughness) while performing better with irregularities of longer wavelengths (waviness).

Consequently, this study suggests that optical methods for measuring irregularities should focus on surface waviness. The analysis also revealed significant differences in the castings on the laser-cut surfaces, with their distribution affected by the wood structure, as seen in beech, spruce, and oak. The use of 3D topographic analysis helped to clarify the origin of surface irregularities and addressed the limitations of stylus profilometers (Adamčík 2023)

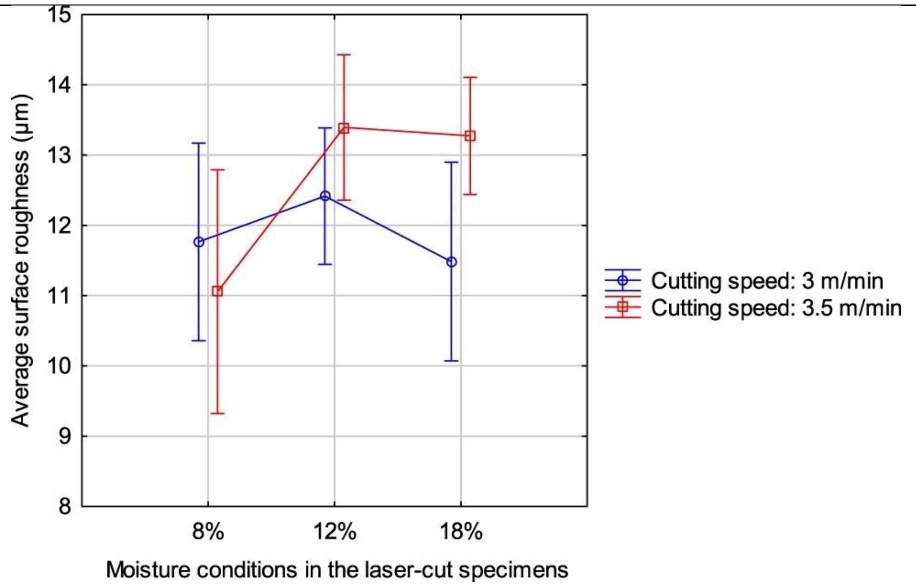

Figure 56. Influence of laser cutting speed and specimen moisture content on mean surface roughness (*Ra*) measured across the grain using a confocal microscope. Error bars represent 95 % confidence intervals (Rezaei et al. 2022).

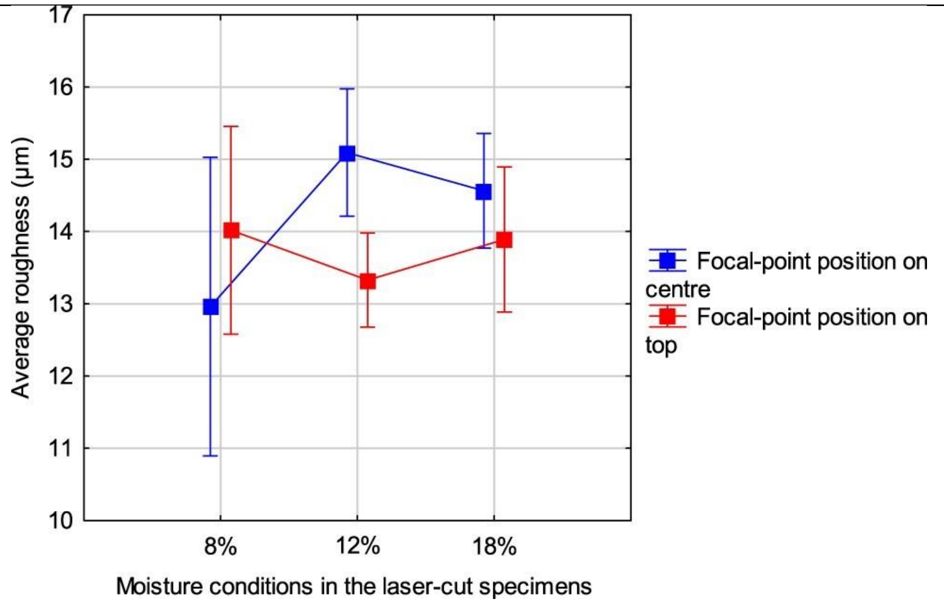

Figure 57. Influence of focal point location and wood moisture content on mean surface roughness (*Ra*) measured across the grain using a confocal microscope (Rezaei et al. 2022).

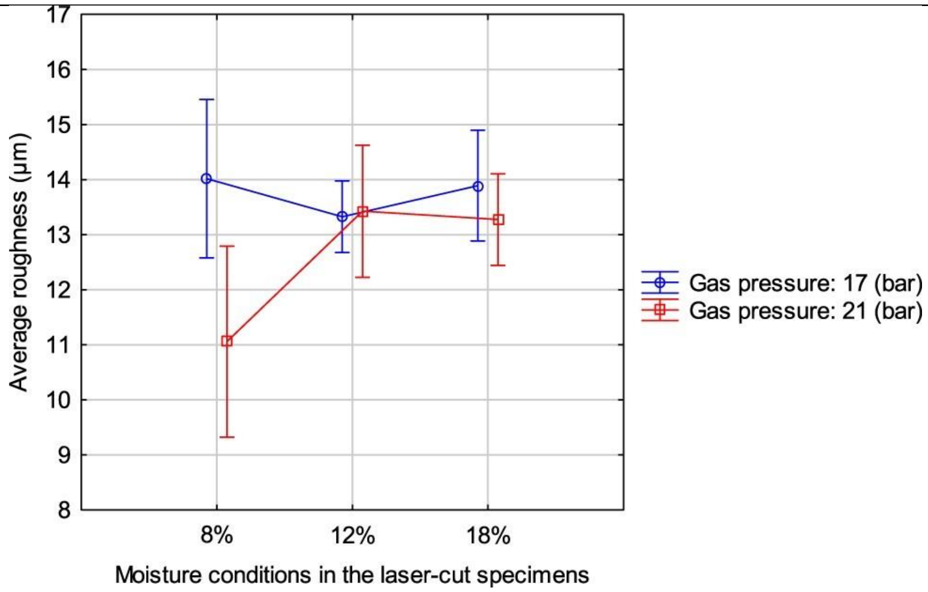

Figure 58. Influence of combined gas pressure and wood moisture levels on the mean surface roughness (*Ra*) measured across the grain using a confocal microscope (Rezaei et al. 2022).

6.11 Surface quality of beech wood (*Fagus Sylvatica* L.) using circular saw cutting and its comparison with CO_2 laser cutting

Traditional wood processing with a circular saw has a long history, but it often results in significant material waste and requires additional effort for finishing. The exploration of alternatives, such as CO_2 laser cutting, offers the potential to improve resource efficiency during wood processing, reducing the need for subsequent interventions. This study compares the effects of circular saw cutting and CO_2 laser cutting on beech wood (*Fagus sylvatica* L.), focusing on surface roughness (*Ra*) and waviness (*Wa*).

Previous research has suggested that laser cutting tends to produce significantly smoother surfaces compared to circular saw machining, due to the thermal nature of the process that, under equal conditions, laser cutting provides superior surface quality in terms of precision and uniformity. The samples, processed at different cutting speeds, were tested with commercial wood moisture content (12%), a common condition for industrially treated wood. The results related to average roughness (*Ra*) show that at 4000 RPM, the circular saw presents a *Ra* value of 7.111 µm, while at 6000 RPM, the value decreases to 6.088 µm (Fig. 59), indicating an improvement in surface finish with increased blade speed (Tab. 12: Statistical Comparison of *Ra* and *Wa* Values for Circular Saw at Different RPMs Using Tukey HSD, LSD, and Duncan Tests). However, both values are significantly higher than those obtained with laser cutting, which shows an average surface roughness (*Ra*) ranging from 4.76 µm to 5.25 µm, as the cutting speed increases from 3 m/min to 3.5 m/min (Fig. 48). These data suggest that, regardless of speed, the laser is more effective at producing smoother surfaces by reducing surface irregularities through its controlled thermal action. Regarding average waviness (*Wa*), the values for the circular saw are 17.10 µm at 4000 RPM and 11.79 µm at 6000 RPM (Fig. 60), while laser cutting showed a *Wa* value decreasing from 9.83 µm to 9.42 µm as cutting speed increased (Fig. 48). Again, the laser proves superior in producing more uniform surfaces, with lower variations in waviness surface (*Wa*), especially at lower cutting speeds.

These results confirm that, although the circular saw is a faster cutting method, laser cutting provides superior surface quality in terms of *Ra* and *Wa*, with smoother and more uniform finishes. This improvement is primarily due to the precise thermal action of the laser, which significantly reduces surface irregularities, while the circular saw, although effective for cutting, tends to generate more waviness and roughness due to mechanical vibrations and stresses during the process. The results are in line with previous studies (Gaff et al. 2020), which show that laser cutting reduces both roughness and waviness of wood, especially compared to circular saw cutting. However, it is important to note that measurement methods, such as confocal microscopy, may influence the obtained values, compared to techniques like contact profilometers, which may show discrepancies (Rezaei 2022). Additionally, laser process variables such as power, cutting speed, and focal point play a crucial role in surface quality, suggesting that optimized settings are essential for achieving superior results.

Finally, although conventional cutting methods generally require post-processing to improve the surface and resolve issues related to cell wall damage, laser cutting can still produce surfaces that may require further refinement, depending on the specific processing conditions and material used.

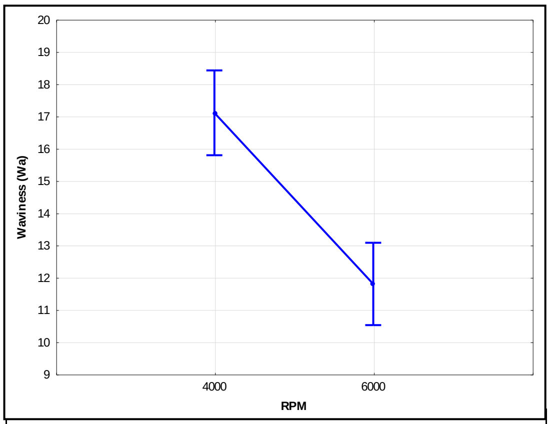

Figure 60. Interaction between cutting speed (4000 RPM and 6000 RPM) and surface waviness (*Wa*) Current effect: $F(1, 98) = 33.823$, $p = .00000$, Vertical bars denote 0.95 confidence intervals.

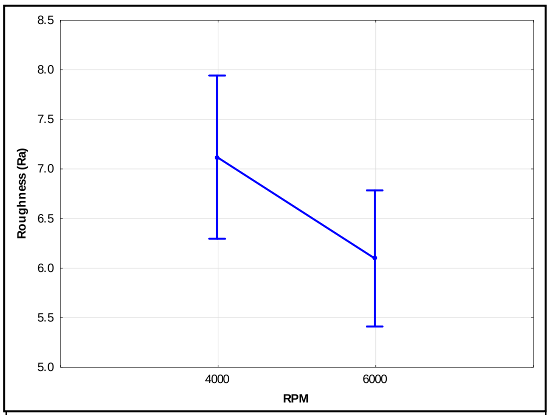

Figure 59. Interaction between cutting speed (4000 RPM and 6000 RPM) and surface roughness (*Ra*) Current effect: $F(1, 98) = 3.6782$, $p = .05804$, Vertical bars denote 0.95 confidence intervals.

Test	**Variable**	**RPM (rev/min)**	**P-value**	**Interpretation**
Tukey HSD	*Ra* (Roughness)	4000 / 6000	0.058141	No significant difference between 4000 and 6000 RPM
F-LSD	*Ra* (Roughness)	4000 / 6000	0.058038	No significant difference between 4000 and 6000 RPM
Tukey HSD	*Wa* (Waviness)	4000 / 6000	0.00011	Significant difference: 6000 RPM shows lower *Wa*

LSD	*Wa* (Waviness)	4000 / 6000	0	Significant difference; 6000 RPM shows lower *Wa*
Duncan	*Wa* (Waviness)	4000 / 6000	0.00011	Significant difference; 6000 RPM shows lower *Wa*

Table 11. Statistical Comparison of *Ra* and *Wa* Values for Circular Saw at Different RPMs Using Tukey HSD, LSD, and Duncan Tests.

6.11 The optimum combination of parameters for improved surface quality

The following tables illustrate the optimal parameter configurations identified through the analysis of the *multidimensional contingency table*, aimed at achieving the best surface quality in terms of roughness (*Ra*) and waviness (*Wa*) during CO_2 laser cutting of beech wood (*Fagus sylvatica* L.). Specifically, Tab. 13 presents two parameter combinations that are effective in improving surface roughness (*Ra*). This improvement can be attributed to the use of adequate laser power together with a controlled cutting speed. In addition, increasing the gas pressure from 17 to 21 Bar, keeping the laser power constant at 3200-kW, and slightly reducing the cutting speed lead to comparable quality results. A relatively low moisture content (8%) ensures a high-quality surface finish. In contrast, a higher moisture content (18%) requires more attention to avoid problems during finishing. Although a lower moisture content is preferable for some applications, optimization of the cutting parameters allows adaptation to different wood moisture conditions.

Gas pressure (Bar)	**Laser Power (kW)**	**Cutting speed (m/min)**	**Focal Point**	**MC %**
17	3200	3,5	P	8
21	3200	3	P	18

Table 12. Optimal configuration surface roughness (*Ra*).

Table 14. presents two optimal configurations of laser parameters to improve waviness (*Wa*) quality in wood cutting. In the second configuration, the

increase in gas pressure from 17 Bar to 21 Bar contributes to better smoke evacuation and greater stability of the cut, promoting a more uniform surface finish and reducing waviness. Cutting speeds vary between the two configurations: 3.5 m/min in the first configuration and 3 m/min in the second. A higher cutting speed can be advantageous when working with lower moisture content wood, as it allows a faster process. However, a lower speed offers a more precise and controlled cut at higher moisture content, reducing the risk of imperfections. In the first configuration, with a moisture content (MC %) of 8 %, a surface with fewer undulations is observed. Conversely, in the second configuration, with an MC % of 18 %, a careful balancing of parameters is required to maintain optimal surface finish results. These observations highlight the importance of adapting the cutting parameters to the specific material conditions.

Gas pressure (Bar)	**Laser Power (kW)**	**Cutting speed (m/min)**	**Focal Point**	**MC %**
17	3200	3,5	P	8
21	3200	3	P	12

Table 13. Optimal configuration surface waviness (*Wa*).

Table 15. presents the optimal combinations of laser parameters to maximise the surface quality of beech (*Fagus sylvatica* L.) wood in terms of roughness (*Ra*) and waviness (*Wa*). These configurations, designed to minimise *Ra* and *Wa*, offer specific advantages and provide an important basis for future research and optimisation in wood processing. Careful balancing of gas pressure, laser power, cutting speed and moisture content is essential to achieve high-quality results.

Gas pressure (Bar)	**Laser Power (kW)**	**Cutting speed (m/min)**	**Focal Point**	**MC %**
17	3200	3	P	8
21	3200	3,5	P	8

Table 14. Optimal configuration (*Ra*/*Wa*).

The information gathered is valuable and can serve as a foundation for future studies. It is crucial to note that subsequent research, with larger and more diverse samples, could generate more reliable and better results.

7 Conclusion and future work

This study examined the effect of the moisture content of beech wood (*Fagus sylvatica* L.) and machine parameters on the surface quality of CO_2 laser-cut samples. The main results are as follows:

- Effect of Moisture Variations and Laser Processing Parameters on Surface Quality of Laser-Cut Specimens: No significant differences were observed in surface roughness (*Ra*) and waviness (*Wa*) among samples conditioned at different moisture levels (0%, 8%, 12%, and 18%). However, the laser-cut surface exhibited increased roughness when the focal point position was shifted from the surface to the centre of the material. Additionally, variations in cutting speed and gas pressure did not affect the surface quality of the laser-cut specimens.

- Contact and Contactless Methods of Quality Measurement in Laser-Cut Specimens: Confocal microscopy, a non-contact method, provided more accurate and higher surface roughness measurements than contact methods. This discrepancy arises from confocal microscopy's ability to detect finer details, while the stylus tip of contact methods may overlook small depressions and valleys. However, non-contact methods may struggle with short-wavelength surface features, indicating that optical techniques are better suited for assessing surface waviness.

- Color Changes of Laser-Cut Specimens: The changes in total color (ΔE^*) of the samples after CO_2 laser cutting were more pronounced in those with lower moisture content (0 % and 8 %) compared to samples with higher moisture content (12 % and 18 %). This phenomenon can be attributed to the increased absorption of laser energy by moisture in the wood, which may dissipate some of the laser energy that would otherwise contribute to color change. Lower moisture content allows for greater penetration of the laser beam, leading to more significant thermal effects on the wood surface and resulting in enhanced color changes.

- Chemical Changes in Laser-Cut Specimens: Laser cutting induces significant chemical changes in the surfaces of hardwoods, particularly affecting the composition of cellulose, hemicellulose, and lignin. Fourier-transform infrared spectroscopy (FT-IR) analysis revealed a notable reduction in the absorption peaks associated with hemicellulose and lignin. These alterations suggest that laser cutting modifies the wood's chemical structure, potentially reducing the adhesion potential of adhesives used in subsequent applications. The observed reduction in hemicellulose and lignin content is critical, as these components play essential roles in maintaining wood's structural integrity and bonding capacity.

- The quality of CO_2 laser-cut beech wood (*Fagus Sylvatica* L.) depends on cutting speed, focal position, and moisture content. High speeds and surface-focused laser reduce degradation of the middle lamella and preserve the cellular structure, while low speeds and centered focus promote microcracks and carbonization. Higher moisture improves heat dissipation, limiting thermal damage and producing smoother, more uniform surfaces. Optimizing these parameters is therefore essential to maintain microstructural integrity and achieve superior surface quality.

- CO_2 laser cutting significantly modifies wood surfaces, increasing moisture diffusion by 35–70 % due to enhanced porosity. Variations in cutting speed and gas pressure had minimal effect on both diffusion and surface hardness, while the cell wall structure and the thermal effect of the laser dominated. Compared with saw-cut specimens, laser-cut samples exhibited higher moisture diffusion but slightly lower surface hardness, reflecting mild thermal degradation. These results highlight the importance of considering both laser-induced thermal effects and wood microstructure when optimizing cutting for surface quality and integrity.

- The comparison between circular saw cutting and laser cutting highlighted that the latter offers superior surface quality in terms of roughness (*Ra*) and waviness (*Wa*), demonstrating greater precision and uniformity, especially at a commercial moisture content of 12 %.

The findings suggest that laser cutting can be optimized for various wood species by considering moisture content and laser parameters. This can lead to enhanced surface quality and aesthetic finishes, making laser cutting a preferred method in the furniture and cabinetry industries. Understanding the chemical changes induced by laser cutting can inform the development of specialized adhesives compatible with laser-cut surfaces. This can enhance the durability of bonded assemblies in applications such as engineered wood products, furniture, and cabinetry. The insights gained from the chemical analysis of different wood species can facilitate the development of targeted heat treatment processes that improve wood properties. This can include enhancing stability, durability, and appearance for high-end applications in flooring, panelling, and decorative elements. The comparison of contact and non-contact measurement methods opens up opportunities for refining quality assessment techniques in the wood industry. Implementing advanced measurement methods can lead to more accurate evaluations of surface characteristics, ultimately improving production standards.

Future research should expand the investigation to include a broader range of hardwood species and densities. This can provide a more comprehensive understanding of how different wood types respond to laser cutting and the subsequent effects on surface quality and adhesive performance. Longitudinal studies evaluating the long-term performance of laser-cut wood products in various environmental conditions would provide valuable insights into durability and adhesion over time. This can help in understanding how chemical changes influence the longevity of products. Further studies should optimise laser cutting parameters (e.g., speed, power, and gas pressure) for different moisture contents and wood types to maximize surface quality while minimizing adverse chemical effects. This could lead to the development of industry standards for laser cutting in wood processing. Exploring post-laser cutting surface treatments, such as coatings or sealants that can enhance adhesion and protect against chemical degradation, could be beneficial. Research into the compatibility of these treatments with laser-cut surfaces would also be advantageous. Incorporating advanced technologies, such as machine learning algorithms, to predict surface quality and chemical changes based on initial wood characteristics and processing parameters could enhance the efficiency and accuracy of laser cutting processes.

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