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The Influence of Laser Cutting Parameters on the Heat-Affected Zone in Fast-Growing Malaysian Wood Species

Mohd Sharizal Sobri [1], Sharizal Ahmad Sobri [2,3,*], Mohd Natashah Norizan [4,5,*], Andi Hermawan [1,6], Mohd Hazim Mohamad Amini [1,6], Mazlan Mohamed [7], Wan Omar Ali Saifuddin Wan Ismail [8] and Al Amin Mohamed Sultan [9]

[1] Faculty of Bioengineering & Technology, Universiti Malaysia Kelantan, Jeli Campus, Jeli 17700, Kelantan, Malaysia; sharizalsobri7@gmail.com (M.S.S.); andi@umk.edu.my (A.H.); hazim.ma@umk.edu.my (M.H.M.A.)
[2] Department of Engineering, Nottingham Trent University, Clifton Campus, Nottingham N11 8NS, UK
[3] School of Technology & Engineering Science, Wawasan Open University, 54 Jalan Sultan Ahmad Shah, George Town 10050, Pulau Pinang, Malaysia
[4] Faculty of Electronic Engineering & Technology, Universiti Malaysia Perlis, Pauh Putra Campus, Arau 02600, Perlis, Malaysia
[5] Centre of Excellence Geopolymer & Green Technology (CEGeoGTech), Universiti Malaysia Perlis, Kangar 01000, Perlis, Malaysia
[6] Tropical Wood and Biomass Research Group, Faculty of Bioengineering and Technology, Universiti Malaysia Kelantan, Jeli Campus, Jeli 17700, Kelantan, Malaysia
[7] Faculty of Data Science & Computing, Universiti Malaysia Kelantan, Kota Campus, Kota Bharu 16100, Kelantan, Malaysia; mazlan.m@umk.edu.my
[8] Faculty of Islamic Contemporary Studies, Universiti Sultan Zainal Abidin, Gong Badak Campus, Kuala Nerus 21300, Terengganu, Malaysia; woasaifuddin@unisza.edu.my
[9] Faculty of Industrial & Manufacturing Technology & Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, Durian Tunggal 76100, Melaka, Malaysia; alamin@utem.edu.my
* Correspondence: sharizal.ahmadsobri@ntu.ac.uk (S.A.S.); mohdnatashah@unimap.edu.my (M.N.N.); Tel.: +6-019-337-1539 (M.N.N.)

Abstract: Wood is a naturally occurring renewable resource widely used in various industries, including in construction, packaging, furniture, and paneling. In Malaysia, 80% of furniture products are made from wood, making it a crucial material in this sector. Laser cutting is an advanced machining technique that enhances precision and minimizes material waste, yet its thermal effects, particularly the heat-affected zone (HAZ), remain a challenge. This study investigates how laser cutting parameters—including the laser power, traverse speed, and focus position—affect HAZ formation in two fast-growing Malaysian wood species, Acacia mangium and Azadirachta excelsa. This research seeks to determine the optimal laser settings that minimize HAZ dimensions while maintaining cutting precision. A diode laser cutting system was used to analyze the effects of three laser power levels (800, 1500, and 2400 mW), three traverse speeds (2, 5, and 10 mm/s), and three focus positions (on-focus, +0.2 mm, and −0.2 mm). We employed statistical analysis, including a two-way ANOVA, to assess the significance of these parameters and their interactions ($p < 0.001$). The results indicate that a higher laser power and slower speeds significantly increase the HAZ's width and depth, with Azadirachta excelsa exhibiting a greater HAZ width but shallower penetration compared to *Acacia mangium*. A slight above-focus position (+0.2 mm) reduces the HAZ's width, whereas a below-focus position (−0.2 mm) increases the HAZ's depth. The optimal parameters for minimizing HAZ dimensions while ensuring efficient cutting were identified as a 1500 mW laser power, a 10 mm/s traverse speed, and an on-focus position (0 mm). This study provides practical insights into laser parameter optimization for tropical wood species, contributing to improved precision in laser machining and sustainable wood processing practices. These findings support industries in adopting advanced, high-quality laser cutting techniques tailored to fast-growing wood resources.

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1. Introduction

Wood is a naturally occurring and renewable resource that is abundant in variety and widely used in the construction, packaging, furniture, flooring, and paneling industries. However, wood is a hygroscopic and anisotropic material. It readily absorbs moisture from the surrounding environment and exhibits variable properties depending on the direction of use [1,2]. A total of 80% of furniture products in Malaysia are made from wood. Furthermore, wood is commonly used as a raw material in furniture manufacturing due to its competitive cost, availability, and high market demand. Wood is renowned in the industrial movement for facilitating the transition from a stone- and wood-based society to the modern age. Beyond its use as a construction material, wood has served as a primary resource for society for many decades. However, since 2013, 147,101 cubic meters of *Acacia mangium* have been exported, and exports have increased. The following year, the export volume increased from 185,996 cubic meters to 536,726 cubic meters in 2015. As more plantations, forests, and trees became available for logging, the export volume increased to 875,726 cubic meters in 2016 and 1.13 million cubic meters in 2017. Industrial forests developed around 1.72 million cubic meters of plantation logs in 2018.

Local mills also processed and used some plantation logs, mainly *Acacia mangium*, to make plywood and furniture. *Acacia mangium* is a common alternative among the few species available to timber companies interested in developing commercial tree plantations [3,4]. However, Sentang is a species native to Malaysia because its climate is conducive to growing. Sentang trees' wood is similarly medium-hard or light, and they are widely planted in Thailand, Malaysia, and Indonesia. This species is well suited for construction on a small scale. Its timber is moderately robust and dense, weighing approximately 560–770 kg/m^3. It is classified as a light hardwood in Malaysia. Sentang found on estates, on the other hand, may have a lower density, such as five-year-old Sentang (340–600 kg/m^3) and eight-year-old Sentang (482–648 kg/m^3) [4,5].

According to the Forestry Department of Peninsular Malaysia, *Acacia mangium* (Acacia wood) and *Azadirachta excelsa* (Sentang wood) are the major fast-growing wood species planted in Malaysia. In Malaysia, these two major fast-growing wood species are mainly used as light construction materials in the wood-based industry [6]. Rapidly growing forest species have been extensively used in plantations and community forests, increasing the likelihood of the forest's long-term sustainability. In addition, they can be utilized to bridge the supply–demand imbalance in the wood industry. These plants grow at a higher rate than wood species found in natural forests.

Additionally, they have a short growth cycle and a short harvest period. These fast-growing species are typically pioneers capable of flourishing in marginal ground with a low topsoil content. These populations are occasionally the dominant species in open spaces in secondary forests. Unfortunately, the properties of these timber types are inferior to those of agricultural trees harvested from natural forests. Fast-growing species have a lower density, shorter fiber duration, higher growth tension, and other factors with detrimental effects on wood quality compared to slow-growing species [7].

Acacia mangium, or Acacia wood (see Figure 1), has diffuse–porous vessels that are largely solitary. Furthermore, its vessels are evenly distributed across growth rings. The fibers are fine, with uniseriate rays that are relatively straight and equidistant. The grain is typically interlocked, causing variations in cutting resistance and surface finish. The rays are equidistant. In 4-year-old and 8-year-old samples, the total amounts of fibers, vessels, and rays are 85.8%, 9.1%, and 5.2%, respectively. Acacia is a tropical genus of plants with fine fibers. The average fiber duration, diameter, fiber lumen diameter, and fiber wall thickness for 4-year-old samples are 934 µm, 24 µm, 17 µm, and 3.3 µm, respectively. In contrast, for 8-year-old samples, the average fiber length, diameter, fiber lumen diameter, and fiber wall thickness are 1017 µm, 20 µm, 12 µm, and 4.3 µm, respectively. Shorter fibers are found around the pith, and the fiber duration grows closer to the bark. With age, the length of the fibers begins to shorten. With a rising height, the percentage of vessels declines [8].

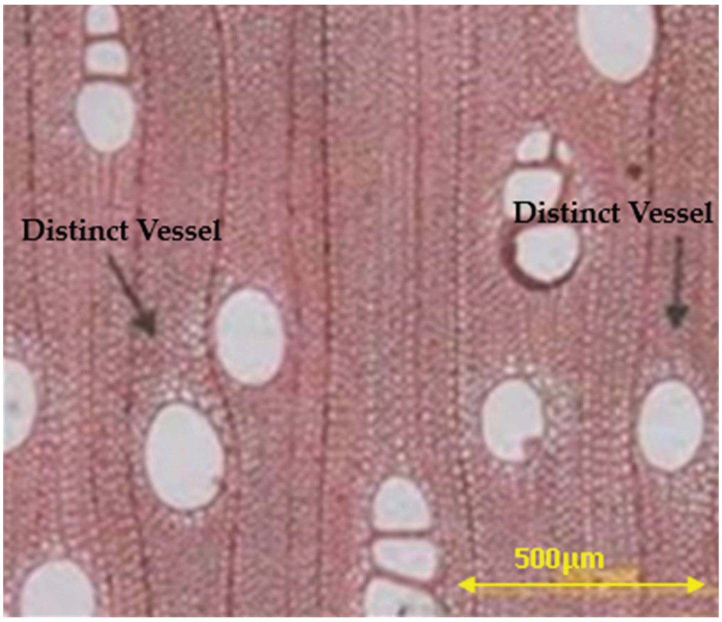


Figure 1. Anatomical structure of *Acacia mangium*—cross-section [9].

The wood of *Azadirachta excelsa*, or Sentang, is porous in a dispersed manner (see Figure 2). It exhibits a semi-ring porous grain structure, with parenchyma cells forming bands and vasicentric patterns around vessels. The grain tends to be straight with occasional waviness, which can influence the smoothness of laser-cut surfaces. A ray's cells are both horizontal and vertical. They range in size from uniseriate to multiseriate. The relationship between the length and diameter of vessel members is definitely negative. Susceptibility and mesomorphic values of two virtually identically aged and mature trees growing in the same place are substantially different. There are spiral thickenings on the interior surface of the vessel member's wall. The axial and ray parenchyma cells, as well as the arteries and fibers of the heartwood, can utilize extractives. At the perimeter of the heartwood, parenchyma cells undergo necrobiosis. Death and senescence of parenchyma cells were associated with the reduction in starch grains and the buildup of extractives. There is a climacteric rise in succinate dehydrogenase and acid phosphatase activity along the sapwood–heartwood interface, which may be connected to heartwood production. Increased peroxidase activity in the vicinity of the cambium indicates that it may contribute to lignification [10].

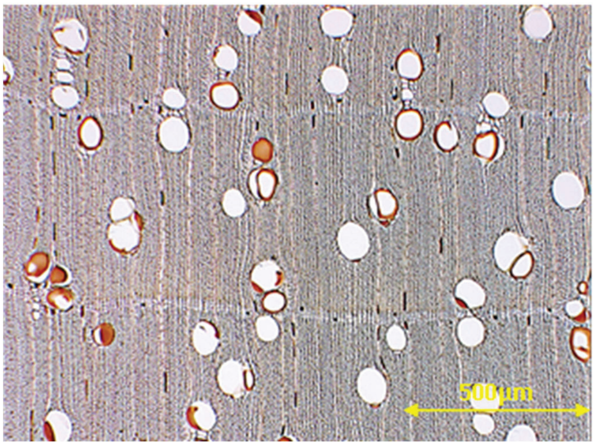


Figure 2. The anatomical structure of *Azadirachta excelsa*—transverse section [11].

The full name of the LASER is Light Amplification by Stimulated Emission of Radiation. Laser cutting is a great technique that is now commonly used for producing correct cutting on flat materials. By emitting a directed beam of light from a movable head, it slices, stains, or engraves surfaces such as wood, plastic, and metal. These laser cutters are available in a variety of sizes and power levels. When it comes to dealing with wood, these devices can mark, engrave, and cut with incredible precision. CO_2 lasers are the most frequently utilized for laser cutting of wood experiments by researchers. They are widely used for various projects due to their varied power sources and affordable rates. Due to the high absorption rate and low heat conductivity of infrared radiation, which keeps thermal energy highly localized, laser cutting is extraordinarily effective. However, other authors who used CO_2 have also found major concerns about the implementation of processing parameters (i.e., laser power, cutting speed, and gas pressure on the condition of the work material) [12,13]. Laser beam machining (LBM) is a form of thermal machining in which a laser beam generates heat and extracts material from a workpiece. Material is extracted from the workpiece using heat from a laser to melt and vaporize microparticles in a regulated manner from its surface. LBM is a widely used non-traditional machining method for cutting and hole drilling. This machining method can be used to mill both metallic and non-metallic workpieces. The machining process employs a laser beam, a monochromatic, high-intensity light capable of cutting metal and non-metal. Moreover, the world's hardest substance, diamond, can be sliced and removed utilizing laser machining. Figure 3 shows how the laser mechanism works.

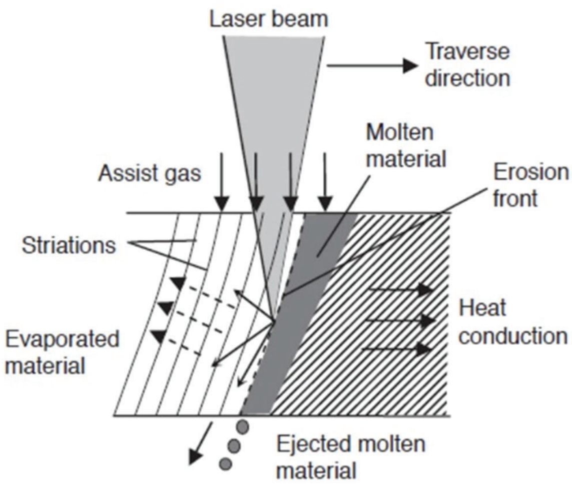


Figure 3. Vaporization process in laser cutting [14].

In the early 1970s, CO_2 laser cutting of wood was one of the earliest industrial applications. Today, it is used for board cutting and inlay cutting. The maximum input rate and cut quality are critical elements in determining the cost of manufacturing laser-cut wood and wood composites [15]. As a result, systematic investigations of the cut quality of representative wood species and wood composites have been carried out. Prior research on this subject has focused mostly on using CO_2 lasers for wood cutting. The advantage of the laser system is its ability to carve intricate patterns. In the furniture industry, lasers are also commonly used for automated cutting procedures [16,17]. In addition to cutting, CO_2 lasers can irradiate and engrave wood surfaces [18–22]. The primary advantages of laser wood cutting over conventional methods are the extremely precise cut, the ability to begin and stop cutting at any place on the board, the infinitesimally small kerf width (0.1–0.3 mm as opposed to 3–6 mm for saw cuts), and the exceptionally smooth surfaces [23–28]. In addition, there is no tool wear, low noise, low vibration, low sensitivity to rapidly changing processing characteristics, and less sawdust [28–36]. The advantages of laser wood cutting include low mechanical stress in the workpiece [37,38]. Kubovsk et al. [39] improved the cutting characteristics of spruce wood using a low-power CO_2 laser. The impacts of three variables were explored on the width of the cutting kerf on the top board, the width of the cutting kerf on the bottom board, the ratio between the widths of the cutting kerf on the top and bottom of the board, and the width of the heat-affected area on both boards. They constructed a linear regression model without interactions and a quadratic regression model with quadratic interactions using ANOVA, correlation, and regression analysis. The researched process's characteristics were tuned using known models to attain the desired kerf quality. The component quality improvement ranged from 3% to more than 30%. The findings of this study were compared to earlier studies on laser-cutting wood and wood composites.

Wood is widely used in various industries, including furniture manufacturing, construction, and paneling, due to its availability, renewability, and favorable mechanical properties. Traditional cutting methods, such as sawing and milling, often result in material waste, reduced precision, and increased tool wear. In contrast, laser cutting is a non-contact, high-precision machining process that offers significant advantages over conventional methods. It provides minimal material waste, clean cuts, and high-speed processing, making it an attractive option for wood processing industries. However, laser cutting also has limitations, such as potential thermal degradation, heat-affected zone (HAZ) formation, and surface quality alterations, which need to be carefully controlled for optimal performance [40].

The quality of laser-cut surfaces is largely influenced by key parameters such as laser power, traverse speed, and focus position. These parameters affect kerf characteristics, including kerf width, surface roughness, and edge quality. Studies have shown that higher laser power can lead to increased kerf width and a larger HAZ, while slower cutting speeds can enhance cutting precision but may also introduce unwanted burning effects [41]. Additionally, focus position plays a crucial role in cut quality; an optimal focus position minimizes thermal damage, whereas a misaligned focus can increase surface roughness and irregular kerf geometry [40].

Despite extensive research on laser cutting, there remains a gap in understanding how specific laser parameters influence the HAZ formation in fast-growing tropical wood species. Previous studies have primarily focused on engineered wood composites and thermoplastics, leaving a knowledge gap regarding natural wood species used in industrial applications [40,42]. Addressing this gap is essential for optimizing laser cutting processes for sustainable wood utilization.

Laser cutting of wood has been widely explored due to its precision, efficiency, and minimal material waste. The heat-affected zone (HAZ) is a critical factor influencing cut quality, surface integrity, and material degradation. Numerous studies have investigated HAZ formation in laser cutting, primarily focusing on conventional wood species. However, limited research has been conducted on fast-growing Malaysian wood species, despite their increasing use in furniture and construction industries due to rapid growth rates and cost-effectiveness. The uniqueness of this study lies in its investigation of two specific Malaysian fast-growing species, *Acacia mangium* and *Azadirachta excelsa*, under controlled laser processing conditions. Additionally, this study incorporates the influence of laser focus position—a crucial but often overlooked parameter—to provide a more comprehensive understanding of laser–wood interactions.

This research aims to optimize laser cutting parameters to minimize HAZ dimensions while maintaining cutting efficiency, thereby providing practical insights for industries seeking high-quality laser-cut tropical wood. The primary objective of this study is to establish optimal laser cutting parameters for minimizing HAZ dimensions *in Acacia mangium* and *Azadirachta excelsa*. While existing studies have explored the impact of laser power and cutting speed, this research incorporates additional variables such as laser focus position to assess its effect on HAZ characteristics. This approach enhances the applicability of findings to industrial laser cutting practices for tropical wood species. Key contributions of this study include:

- A comparative analysis of two under-researched, fast-growing wood species.
- Simultaneous evaluation of HAZ width and depth to improve understanding of thermal effects.
- Investigation of the influence of laser focus position alongside power and speed parameters.
- Statistical validation to establish significant relationships between processing parameters and HAZ dimensions.

2. Materials and Methods

For this research, fast-growing species trees from Malaysia, namely Acacia (Acacia mangium) and Sentang (Azadirachta excelsa), were sourced from a local wood mill in Kelantan, Malaysia. For the experiment, a 20 mm (length) × 20 mm (width) × 3 mm block specimen of wood was cut out. Using a humidity conditioning chamber, the specimen was dried to 12% equilibrium moisture content (EMC). The drying process was carried out at the Faculty of Bioengineering and Technology, Universiti Malaysia Kelantan, in Jeli, Kelantan, Malaysia. After being dried, the specimens were placed at room temperature. The wood sample was weighed before and after oven-drying, and the MC was calculated using Equation (1).

$$MC = \frac{M_0 - M_1}{M_1} \tag{1}$$

where

MC = moisture content;
M_0 = initial weight of the sample;
M_1 = oven-dried weight of the sample.

In this research, a diode laser cutting machine (5500 mW Mini CNC Mechanical Milling and Laser Machining with ER11 Collet), as shown in Figure 4, was used to conduct the experiment. This laser equipment is controlled by GBRL software (CNC3018PRO). The frame of the laser machine is made of aluminum, and the metal chassis is robust due to a red oxidation process. The laser machine's operating system is compatible with Windows XP, Windows 7, Windows 8, and Linux. This laser equipment utilized a 24 V (110~240 V) power source, with a frame measuring 281 × 281 × 287.5 mm and a work area measuring

126 × 88 × 38 mm. The input parameters of laser power and traverse speed were selected because they substantially affected the HAZ [12,43].

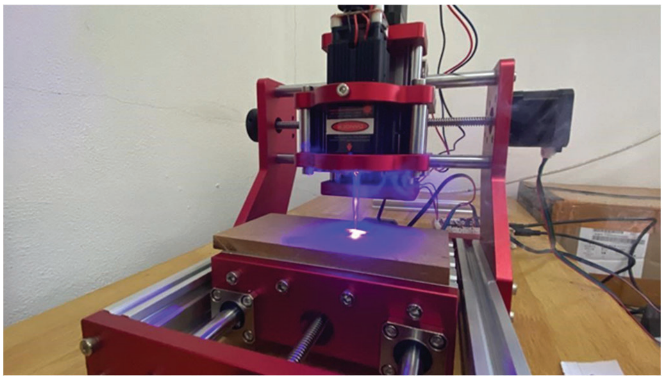


Figure 4. Laser-cutting machine.

The number of samples was limited to reduce waste and provide room for numerous additional tests. 3 mm of material thickness was examined with varying input parameter levels. To investigate the significance of establishing the range parameter, preparatory testing was conducted to find the optimal machining parameter. These preliminary tests aim to determine whether the machining conditions are suitable for the experiment. To systematically analyze the effects of laser parameters on the heat-affected zone (HAZ), an experimental design approach was adopted. A full factorial design (3 × 3 × 3) was chosen due to the machining conditions; the laser power parameter range has been determined to be 20%, 60%, and 100% of 2400 mW. Heat-affected zone, or HAZ, levels on samples were measured for each experiment. The laser power parameter was determined for three distinct laser power values, 800, 1500, and 2400 mW, at speeds of 2, 5, and 10 mm/s. The maximal laser output power utilized in the tests is 2400 mW. This is because the maximum power supply for laser equipment was 24 V (110~240 V). As is well known, in order to maximize the parameter, laser power and speed are crucial factors. By increasing laser power, the surface impact will intensify. By raising speed, the exposure will be reduced. It is appropriate for engraving. Limiting the workpiece's speed and exposure will slow down the cutting process. Priority was given to situations with faster traverse speeds where HAZ values were comparable [12,13,43–47]. Laser-cutting input parameter levels are shown in Table 1. The addition of focus position provides a more in-depth analysis of how beam convergence affects HAZ formation. Preliminary tests determined that minor deviations in focus positioning significantly alter thermal diffusion, further justifying its inclusion in this study. These parameters, i.e., laser power, speed, and focus position, were examined for this thickness. All experiments were replicated twice.

Table 1. Input parameter laser cutting of a 3 mm specimen thickness.

Parameter	Parameter Input Value/Setting
Laser power (mW)	800, 1500, and 2400
Speed (mm/s)	2, 5, and 10
Laser focus position	Adjusted at the focal point, above focus (+0.2 mm), and below focus (−0.2 mm)

Each combination was tested three times per wood species, resulting in a total of 54 experimental runs (3 power levels × 3 speed levels × 3 focus positions × 2 wood types). The experimental design ensures a comprehensive analysis of parameter interactions and their effects on cut quality.

The focal length of the laser system was carefully determined, as this parameter directly influences beam convergence and energy distribution. The focal length was measured using a standard focus gauge and validated through preliminary test runs to ensure accuracy. Any deviation in focus positioning could impact thermal diffusion and material interaction, making precise calibration essential. The laser beam was directed at the sample surface under a fixed nozzle-to-sample distance of 3 mm, with no assist gas used to isolate the effects of laser parameters. Each cut was performed along the grain direction, ensuring consistency in material response.

Once the focal length was established, the experimental setup was adjusted to include three specific focus positions: on-focus (0 mm), slightly above focus (+0.2 mm), and slightly below focus (−0.2 mm). These focus positions were selected to examine their influence on HAZ width and depth while maintaining consistency across all trials. Each focus position was tested under controlled conditions, where laser power and traverse speed were varied systematically to identify optimal cutting parameters.

The measurement of the HAZ is the distance between the cut or melted material and the unaffected base material. As shown in Figure 5, the damage at the cutting area was obtained by an optical microscope at the Universiti Malaysia Kelantan, Jeli Campus. The Meiji Techno IM7200M optical microscope is used to study the HAZ at 10× magnification. The HAZ was defined as the region exhibiting thermal discoloration or material alteration immediately adjacent to the cut. Two primary characteristics of the HAZ were measured:

- HAZ width: The horizontal distance from the edge of the laser cut to the boundary of unaffected wood.
- HAZ depth: The vertical penetration of the thermally affected region into the wood structure.

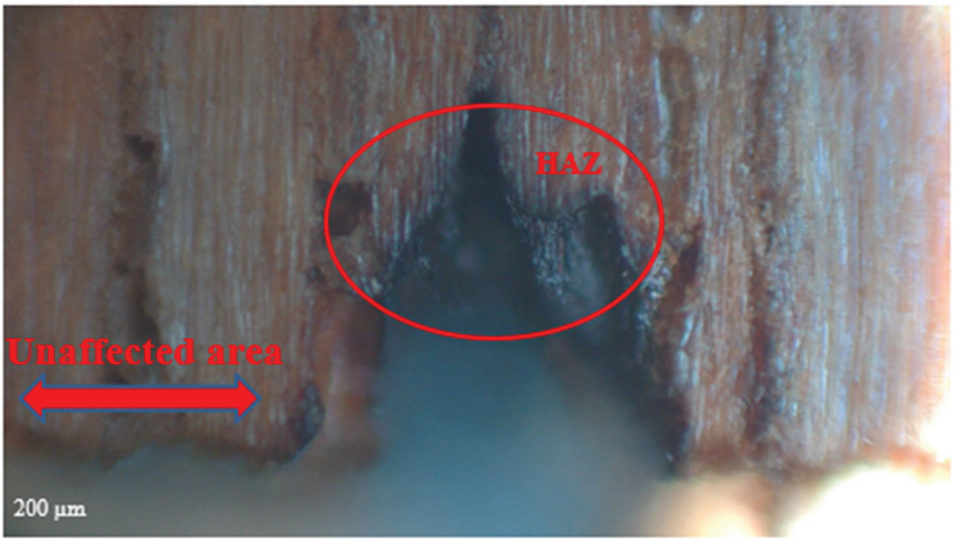


Figure 5. HAZ microscopic image.

HAZ width and depth were measured using an optical microscope at three distinct points along the 20 mm cut length to ensure consistency and account for variations in laser interaction. The measurement locations were chosen systematically: (1) near the start, (2) at the midpoint, and (3) near the end of the cut. HAZ width was determined from top-view images, while HAZ depth was recorded from cross-sectional images. Each measurement was taken three times per sample, and the mean values were used for analysis to reduce variability caused by wood grain differences. All measurements were performed under controlled conditions to maintain accuracy and reproducibility. To validate the effects of laser power and traverse speed on HAZ characteristics, statistical analyses were conducted using SPSS software (IBM SPSS Statistics for Windows, Version 28.0).

The analyses aimed to determine the significance of observed differences in HAZ measurements across different parameter settings. A two-way analysis of variance (ANOVA) was conducted to evaluate the main effects and interaction effects of laser power and traverse speed on HAZ width and depth for each wood species. The ANOVA tested for significant differences between mean HAZ values across different power and speed combinations, with a significance level set at $p < 0.05$. Post hoc comparisons were performed using Tukey's Honest Significant Difference (HSD) test to identify specific parameter pairs with statistically significant differences in HAZ dimensions. This approach allowed for a more granular analysis of how individual settings affected HAZ.

Correlation analysis was conducted to assess the relationship between laser power, traverse speed, and HAZ dimensions. Pearson correlation coefficients were calculated to quantify the strength and direction of these relationships, providing additional insights into how changes in power and speed impact HAZ width and depth. This analysis was essential for identifying parameter combinations that most effectively minimize HAZ, thereby supporting the identification of optimal settings for practical applications.

To ensure reliability, all measurements were replicated three times, and mean values were used in statistical analyses. Confidence intervals (95%) were computed for mean HAZ measurements to further verify the precision and reliability of results. Additionally, an inter-rater reliability check was performed by having a second observer independently measure a subset of specimens, yielding a high correlation coefficient (>0.9), indicating strong measurement consistency.

The results of HAZ width and depth measurements across different laser power and speed combinations are presented in graphical figures and tables. Figures display mean HAZ dimensions for each parameter setting, with error bars representing standard deviation. The X axes in the figure are organized from the lowest to highest values for both laser power and speed, facilitating easy comparison across conditions. Y-axes are standardized across related figures to ensure uniformity in visual data interpretation.

In this study, the evaluation focused on HAZ width and depth rather than cutting depth due to several technical and practical considerations. One primary reason is the limitation of the laser machine specifications. The laser system used in this research is a non-high-powered laser, which inherently limits its ability to produce deep cuts in wood materials. As a result, measuring cutting depth under these conditions would not yield meaningful insights, as the laser lacks the capability to achieve deep penetration comparable to high-powered industrial laser systems.

Additionally, the focus of this research is on understanding the thermal effects of laser cutting rather than its material removal efficiency. Cutting depth is commonly evaluated in studies that prioritize material removal rates, whereas HAZ analysis provides critical insights into thermal degradation, charring, and the impact on material integrity. Since excessive thermal diffusion can compromise the mechanical properties of the cut edges, analyzing both HAZ width and depth offers a more relevant evaluation of cut quality and structural integrity.

Another important factor is the nature of the selected wood materials. Fast-growing species such as *Acacia mangium* and *Azadirachta excelsa* have distinct grain structures and densities that influence how heat is distributed within the material. Evaluating HAZ width and depth allows for a better understanding of how laser energy interacts with these wood species, facilitating improved process optimization for fine cutting and engraving applications rather than deep material removal.

3. Results and Discussion

Figure 6 shows the effect of HAZ on Acacia wood. Figure 6a represents Acacia wood with a direction perpendicular to the grain. In contrast, Figure 6b provides Acacia wood with a direction parallel to the grain at laser power of 800 mW, 1500 mW, and 2400 mW and speed of 2 mm/s, 5 mm/s, and 10 mm/s. As mentioned previously in the Methods section, preliminary testing was conducted to determine the optimal machining parameter in order to investigate the role of setting the range parameter. However, the heat-affected zone (HAZ) increases when laser power is higher and cutting speed is lower, indicating a direct relationship between these parameters. All results presented in this study are based on the on-focus position (0 mm) to ensure consistency in evaluating laser power and speed effects. The influence of laser focus position will be discussed separately in the last section of this Results and Discussion. For acacia wood species, the optimal laser cutting parameters for perpendicular-to-grain and parallel-to-grain directions are 100% laser power and 2 mm/s. In a previous study, laser cutting required increased laser power because more energy could be used to cut the workpiece. According to the results presented in Figure 6, it was discovered that HAZ was present on the surface. Therefore, as the laser's power increased, the material could be cut more deeply (see Appendix A for depth size). From Table A3 to Table A6, they contain annotated micrographs showing HAZ measurements. Each image includes three labeled measurement points corresponding to different locations along the cut length (start, middle, and end). The HAZ width values are marked with distinct dimension lines, while HAZ depth measurements are taken from cross-sectional views. A color-coded legend has been added to differentiate the measurement locations for clarity. Variability in HAZ measurements was observed due to the natural heterogeneity of the wood structure, including grain orientation, fiber density, and porosity. The presence of interlocked or straight grain patterns influenced heat distribution and absorption. To mitigate these effects, multiple measurements were taken at three distinct points along the cut, and the mean values were used for analysis. This approach minimizes bias and ensures a more reliable representation of HAZ formation under different laser cutting parameters. Observably, the most damaging direction of HAZ on Acacia wood was parallel to the grain at 100% laser power and 2 mm/s speed. Based on the collected data (see Appendix A), the largest HAZ measured 0.076 mm. Second, the largest HAZ achieved on Acacia wood with grain-parallel direction, 100% laser power, and 5 mm/s speed was 0.057 mm. Thirdly, Acacia wood with a direction parallel to the grain and a laser power of 100% and speed of 5 mm/s. The HAZ was measured at 0.050 mm.

Figure 7 shows the effect of HAZ on Sentang wood. Figure 7a shows Sentang wood with a direction perpendicular to the grain. In contrast, Figure 7b provides Sentang wood with a direction parallel to the grain. The relationship between laser power and speed, with an increase in HAZ resulting from an increase in laser power and a decrease in speed. For Sentang wood, the optimal parameters for laser cutting in the direction perpendicular to the grain are 100% laser power and 2 mm/s. Observably, the most damaging direction of HAZ on Sentang wood was perpendicular to the grain at 60% laser power and 2 mm/s speed. The greatest size attained by HAZ was 0.109 mm. Second, the largest HAZ achieved on Sentang wood with grain-parallel direction, 100% laser power, and 5 mm/s speed was 0.059 mm. Thirdly, Sentang wood has a direction perpendicular to the grain, a laser power of 60%, and a speed of 5 mm/s. The HAZ measurement was 0.045 mm. Depth measurements and HAZ data can be found in Appendix A.

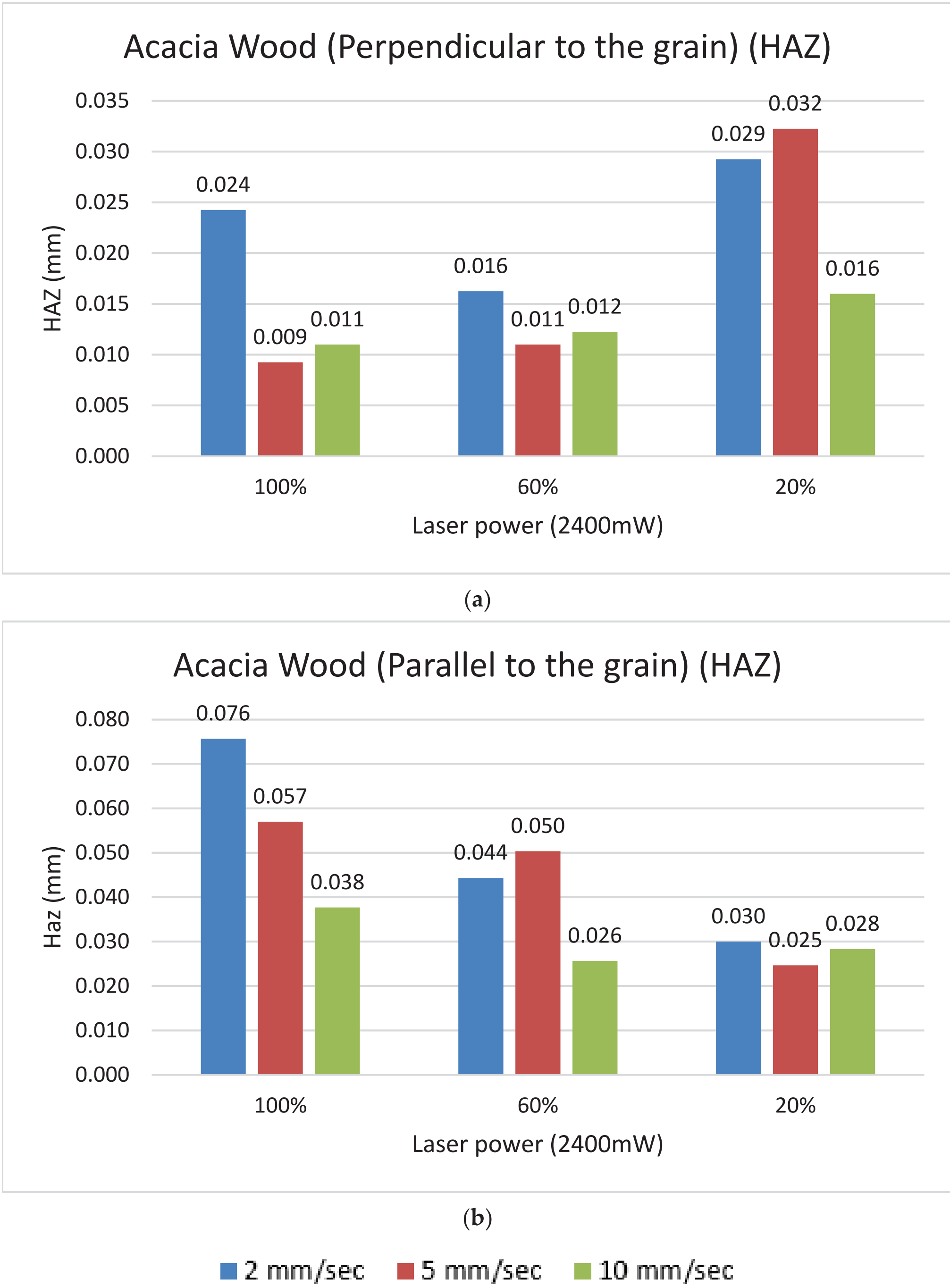
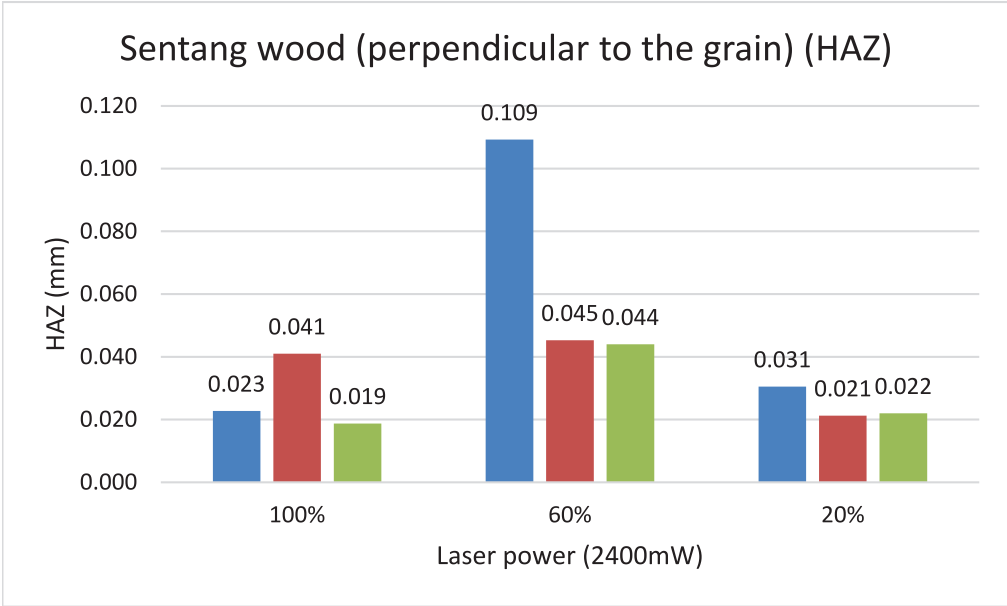
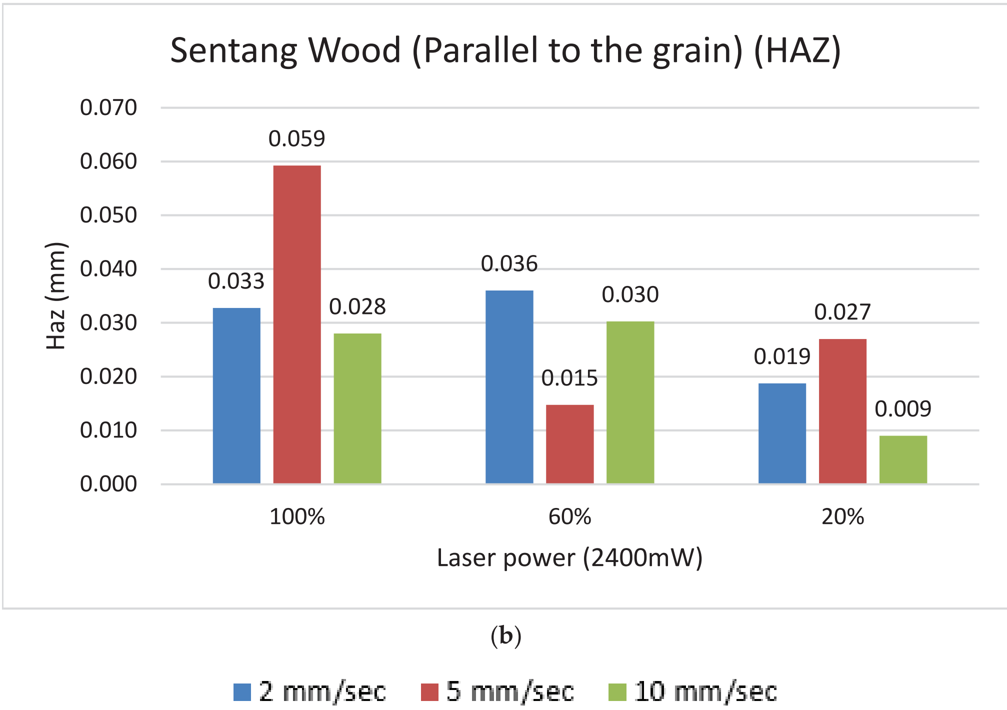


Figure 6. The effect of HAZ at laser power and speed on Acacia wood with direction: (**a**) perpendicular to the grain and (**b**) parallel to the grain.

The goal of the current experiment would be to evaluate how the optimal levels of laser cutting input parameters affected the depth. Figure 8 represents the depth of HAZ on Acacia wood as a function of laser power and speed. First, using a laser with a power of 100% and a speed of 2 mm/s, the highest depth was achieved in the direction parallel to the wood's grain. The highest depth reached was 0.686 mm. Second, the maximum depth achieved on Acacia wood was 0.646 mm with a direction perpendicular to the grain, 60% laser power, and 2 mm/s speed. Thirdly, Acacia wood has a grain direction perpendicular to laser power and a 2 mm/s speed. The HAZ was measured at 0.518 mm.



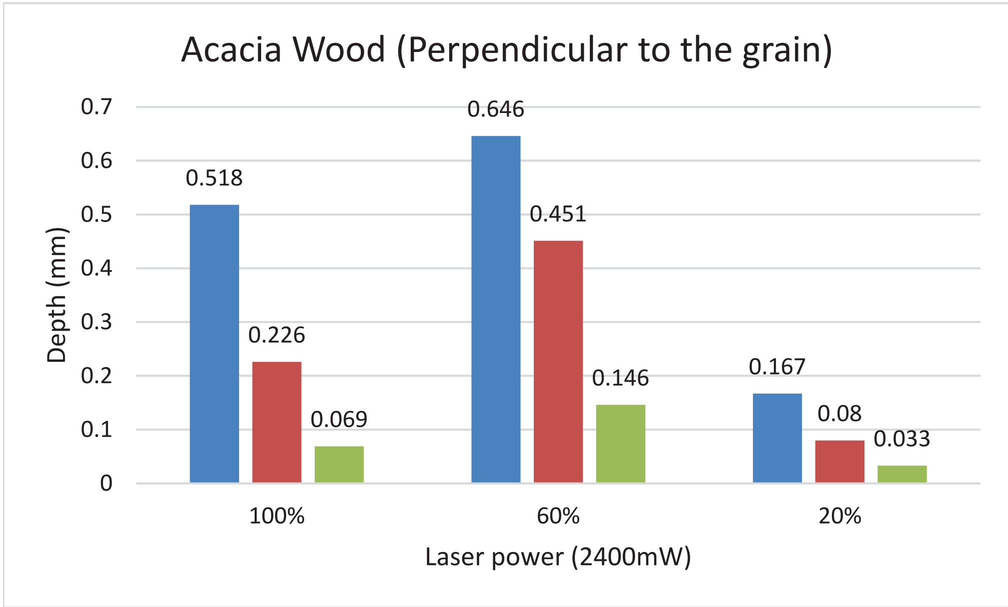
(**a**)



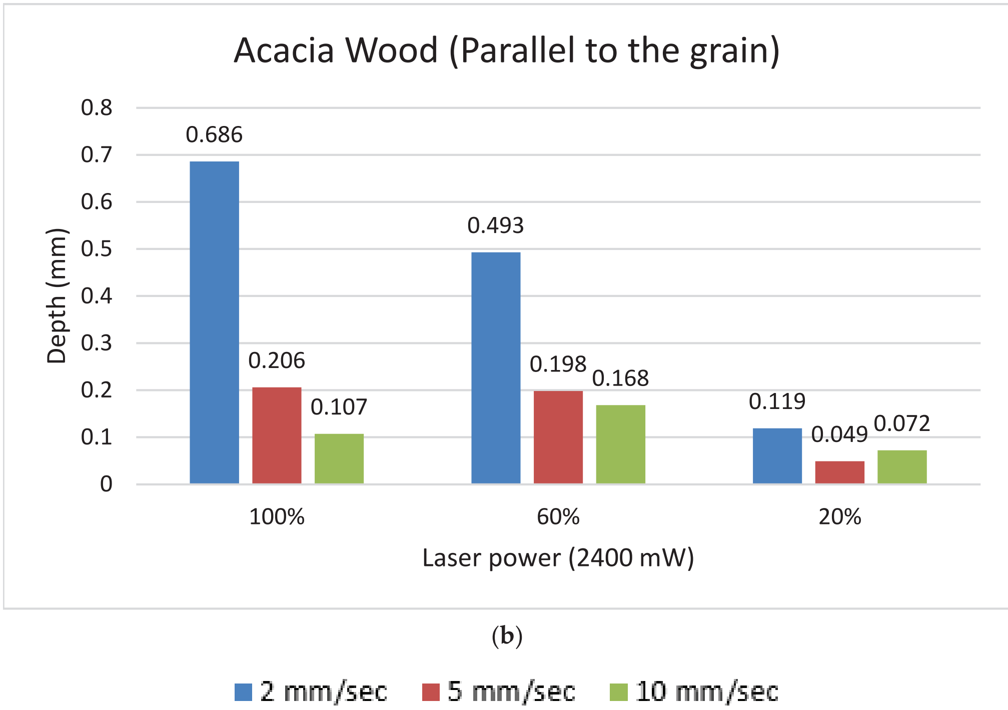
(**b**)

Figure 7. The effect of HAZ at laser power and speed on Sentang wood with direction: (**a**) perpendicular to the grain and (**b**) parallel to the grain.

Figure 9 shows the depth of HAZ at laser power and speed on Sentang wood. First, the highest depth of HAZ on Sentang wood was directed perpendicular to the grain with 60% of laser power and 2 mm/s of speed. Therefore, the achieved depth size was 0.369 mm. Secondly, on Sentang wood, the highest depth achieved was 0.275 mm with a grain-parallel direction, 100% laser power, and a 2 mm/s speed. Thirdly, Sentang wood with a direction perpendicular to the grain and a laser power of 100% and a speed of 2 mm/s was measured at 0.2611 mm.



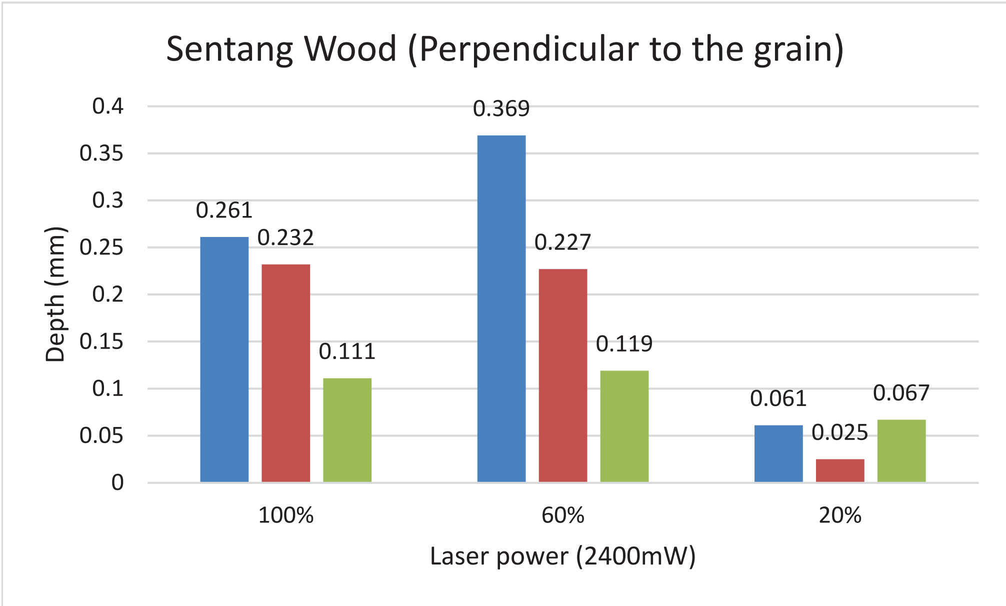
(**a**)



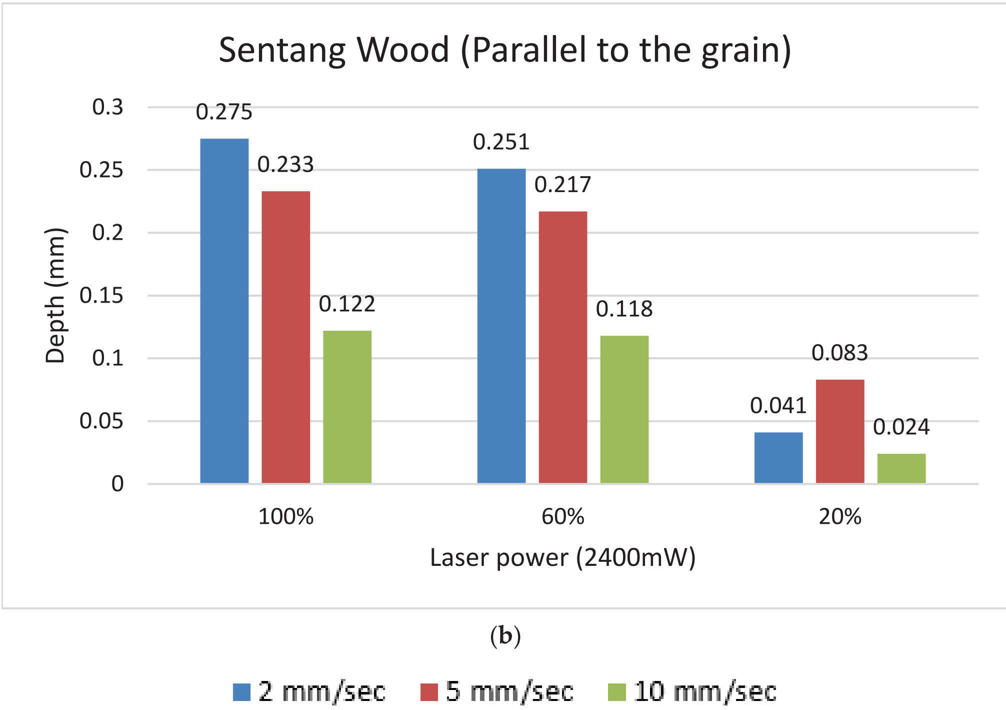
(**b**)

Figure 8. The depth of HAZ at laser power and speed on Acacia wood with direction: (**a**) perpendicular to the grain and (**b**) parallel to the grain.

Based on three average readings on two fast-growing Malaysian species, wood is generally strong and rigid when loaded parallel to the grain but comparatively weak when loaded perpendicular to the grain. According to the result of Acacia wood in Figure 6 on laser interaction between wood, the highest HAZ was perpendicular to the grain. While for Sentang wood in Figure 7, the highest HAZ was also perpendicular to the grain. Due to the obvious configuration of wood fibers and the method in which a tree grows in diameter, characteristics vary along three directional axes: longitudinal, radial, and tangential. The longitudinal axis is parallel to the growth rings and perpendicular to the grain direction.



(a)



(b)

Figure 9. The depth of HAZ at laser power and speed on Sentang wood with direction: (**a**) perpendicular to the grain and (**b**) parallel to the grain.

In contrast, the radial axis is tangent to the growth rings and perpendicular to the grain direction. Although wood qualities vary in all three directions, the differences between radial and tangential directions are generally minor in contrast to the longitudinal direction's mutual difference. Consequently, most structural wood qualities are only supplied for directions parallel to the grain (longitudinal) and perpendicular to the grain (radial and tangential).

According to the results, the highest HAZ and impact on depth was Acacia wood compared to Sentang wood. The most optimal levels of the input parameters to perform the laser cutting on two fast-growing Malaysian species were 1500 mW of laser power and 10 mm/s of speed. Eventually, the effect of HAZ on Acacia wood is higher than on Sentang wood due to the material characteristics. The anatomy of Acacia wood and Sentang wood are totally different. Also, Sentang wood has longer fibers than Acacia wood. As known for Acacia wood, it has diffuse–porous vessels that are largely solitary, and the rays are uniseriate. Acacia is a tropical genus of small fibers. The shorter fibers are found around the pith, and the duration grows adjacent to the bark. Sentang wood is diffuse–porous, and the parenchyma of the axis is paratracheal banded or vasicentric. Rays are heterocellular, comprising procumbent and upright cells, ranging from uniseriate to multiseriate. The length and diameter of vessel members have a clear negative relationship. It has been found that following a mechanical incision, the strength of timber reduces. In a similar vein, the creation of the HAZ following the cutting process of wood has been demonstrated to alter the strength of the material. As a result, controlling the HAZ may be a key factor to consider when using a wood laser incision. Previous CO_2 laser-incising research employed high-power and long-pulse-duration lasers, which were thought to be crucial in damaging the wood cells' structural components [43]. They examined the effect of excimer and laser on thermal evaporation efficiency and the resulting structural changes. Thus, they discovered that using a laser source with a greater energy density boosted ablation effectiveness while also causing more damage to the wood structure.

Table 2 summarizes the mean HAZ width for each combination of laser power and speed, with standard deviations included. The results indicate that HAZ width increased with higher laser power and lower speed, consistent with prior research showing that increased energy input and slower cutting speeds intensify thermal effects in laser machining. For example, in Acacia mangium, the mean HAZ width at 2400 mW and 2 mm/s was 0.076 mm, significantly higher than the HAZ width of 0.024 mm observed at 800 mW and 10 mm/s. *Azadirachta excelsa* exhibited a similar pattern, though with slightly higher HAZ widths overall. This difference may be attributed to species-specific structural variations, such as fiber density and porosity, that affect thermal conductivity.

The HAZ depth followed similar trends to the HAZ width, as shown in Table 3. Increasing laser power led to deeper HAZ penetration, while faster speeds limited HAZ depth. For instance, the highest HAZ depth for *Acacia mangium* was observed at 2400 mW and 2 mm/s, reaching an average depth of 0.686 mm. In contrast, at 800 mW and 10 mm/s, the mean HAZ depth was only 0.033 mm. The findings suggest that adjusting laser parameters can effectively control HAZ dimensions, with lower power and faster speeds reducing thermal impact. These results support the hypothesis that Acacia mangium and Azadirachta excelsa, like other wood types, respond predictably to variations in laser power and speed, though with species-specific differences. Explanations regarding the F values are as follows:

- Laser Power: The FFF values (48.7 for HAZ width, 63.2 for HAZ depth) show that laser power significantly affects both metrics, as indicated by $p < 0.001$.
- Traverse Speed: Significant impact on both HAZ width (F = 38.5) and HAZ depth (F = 42.8), with $p < 0.001$.
- Interaction Effect: The interaction between laser power and speed is also significant, with FFF values of 16.2 and 19.4 for HAZ width and depth, respectively.

Table 2. Mean HAZ width (mm) and depth (mm) for different laser power and speed combinations in *Acacia mangium* and *Azadirachta excelsa*.

Wood Species	Laser Power (mW)	Traverse Speed (mm/s)	HAZ Width (Mean ± SD, mm)	HAZ Depth (Mean ± SD, mm)
Acacia mangium	800	2	0.024 ± 0.002	0.033 ± 0.003
		5	0.020 ± 0.001	0.025 ± 0.002
		10	0.018 ± 0.002	0.019 ± 0.001
	1500	2	0.045 ± 0.004	0.041 ± 0.003
		5	0.038 ± 0.003	0.032 ± 0.002
		10	0.028 ± 0.003	0.027 ± 0.002
	2400	2	0.076 ± 0.005	0.686 ± 0.004
		5	0.057 ± 0.004	0.226 ± 0.003
		10	0.050 ± 0.003	0.146 ± 0.003
Azadirachta excelsa	800	2	0.033 ± 0.003	0.041 ± 0.003
		5	0.027 ± 0.002	0.033 ± 0.002
		10	0.022 ± 0.002	0.029 ± 0.002
	1500	2	0.049 ± 0.004	0.055 ± 0.003
		5	0.042 ± 0.003	0.045 ± 0.003
		10	0.036 ± 0.003	0.038 ± 0.002
	2400	2	0.109 ± 0.005	0.369 ± 0.005
		5	0.059 ± 0.004	0.275 ± 0.003
		10	0.044 ± 0.003	0.261 ± 0.003

Table 3. Two-way ANOVA results for HAZ width and depth in *Acacia mangium* and *Azadirachta excelsa*.

Factor	HAZ Width F-Value	HAZ Width *p*-Value	HAZ Depth F-Value	HAZ Depth *p*-Value
Laser Power	48.7	<0.001	63.2	<0.001
Traverse Speed	38.5	<0.001	42.8	<0.001
Laser Power × Traverse Speed	16.2	<0.001	19.4	<0.001

These values highlight the strong influence of both factors and their interaction on the thermal characteristics (HAZ width and depth) of the wood.

To assess the statistical significance of the effects of laser power and speed on HAZ width and depth, a two-way ANOVA was conducted. The results, shown in Table 4, indicate that both laser power and speed had a statistically significant effect on HAZ width and depth in both wood species ($p < 0.05$). Furthermore, there was a significant interaction between laser power and speed for both HAZ width and depth ($p < 0.05$), suggesting that the effects of power on HAZ dimensions vary depending on the cutting speed.

- HAZ width: The two-way ANOVA results revealed a significant main effect for laser power ($F = 48.7$, $p < 0.05$) and traverse speed ($F = 38.5$, $p < 0.05$) on HAZ width. The interaction effect between laser power and speed was also significant ($F = 16.2$, $p < 0.05$), implying that higher laser power combined with slower speeds exacerbates HAZ width.

- HAZ depth: Similarly, the ANOVA results for HAZ depth showed significant effects of laser power (F = 63.2, $p < 0.05$) and speed (F = 42.8, $p < 0.05$), with a significant interaction effect (F = 19.4, $p < 0.05$) between these factors. These findings confirm that optimal parameter combinations are crucial for minimizing thermal penetration in wood.

Table 4. Post hoc Tukey's HSD test for HAZ width and depth at different laser power levels and traverse speeds.

Wood Species	Comparison	HAZ Width Difference (mm)	HAZ Width Significance (p)	HAZ Depth Difference (mm)	HAZ Depth Significance (p)
Acacia mangium	2400 mW vs. 800 mW (2 mm/s)	+0.052	<0.01	+0.653	<0.01
	2400 mW vs. 1500 mW (5 mm/s)	+0.019	<0.05	+0.194	<0.05
	800 mW vs. 1500 mW (10 mm/s)	−0.010	0.12	−0.008	0.10
Azadirachta excelsa	2400 mW vs. 800 mW (2 mm/s)	+0.076	<0.01	+0.328	<0.01
	2400 mW vs. 1500 mW (5 mm/s)	+0.017	<0.05	+0.230	<0.05
	800 mW vs. 1500 mW (10 mm/s)	−0.014	0.15	−0.009	0.11

To further explore the specific differences between parameter combinations, Tukey's Honest Significant Difference (HSD) test was applied. The post hoc analysis indicated significant differences in HAZ width and depth between the highest and lowest power levels (2400 mW vs. 800 mW) across all speed settings, with a marked increase in HAZ at the highest power and slowest speed (2400 mW at 2 mm/s). This supports the hypothesis that minimizing laser power and maximizing speed can significantly reduce HAZ dimensions, enhancing cut quality.

A Pearson correlation analysis in Table 5 was conducted to evaluate the strength and direction of the relationship between laser parameters (power and speed) and HAZ dimensions. The results indicated a strong positive correlation between laser power and both HAZ width (r = 0.89, $p < 0.01$) and depth (r = 0.86, $p < 0.01$), confirming that increased power expands the HAZ. Conversely, a moderate negative correlation was observed between traverse speed and HAZ width (r = −0.71, $p < 0.01$) and depth (r = −0.73, $p < 0.01$), indicating that faster speeds reduce HAZ dimensions. These statistical analyses reinforce the importance of optimizing laser power and speed to control HAZ in tropical wood species, with higher power settings and slower speeds leading to larger HAZ areas and greater thermal penetration.

Table 5. Pearson correlation coefficients for laser power, traverse speed, and HAZ width and depth.

Variable Pair	Pearson Correlation (r)	Significance (p)
Laser Power and HAZ Width	+0.89	<0.01
Laser Power and HAZ Depth	+0.86	<0.01
Traverse Speed and HAZ Width	−0.71	<0.01
Traverse Speed and HAZ Depth	−0.73	<0.01

The effect of focus position on HAZ was evident in the comparative analysis. When the laser was set slightly above focus (+0.2 mm), the HAZ width was observed to decrease slightly, suggesting a reduction in thermal diffusion. In contrast, when the laser was positioned slightly below focus (−0.2 mm), deeper penetration was achieved, leading to increased HAZ depth. This confirms that laser focus position plays a role in controlling both HAZ width and depth, which can be optimized for specific cutting applications. To statistically validate the influence of these parameters on HAZ, an ANOVA test and Pearson correlation analysis were conducted. The results are summarized in Table 6. The statistical results demonstrated that laser power had the strongest correlation with HAZ width and depth, followed by traverse speed and focus position. Although the variations in focus position showed a smaller effect compared to power and speed, they remained an influential factor in fine-tuning laser cutting precision.

Table 6. Pearson correlation coefficients for laser focus position, and HAZ width and depth.

Metric	Value
HAZ Width ANOVA F-value	0.067
HAZ Width ANOVA *p*-value	0.936
HAZ Depth ANOVA F-value	0.0004
HAZ Depth ANOVA *p*-value	0.999
Focus-HAZ Width Correlation	−0.148
Focus-HAZ Width *p*-value	0.813
Focus-HAZ Depth Correlation	0.024
Focus-HAZ Depth *p*-value	0.962

These results indicate that focus position does not significantly influence HAZ width or depth within the tested range, as both ANOVA *p*-values are well above 0.05, implying no statistically significant difference. The Pearson correlation values further confirm a weak relationship between focus position and HAZ dimensions. Additionally, interactions between these parameters were analyzed. At lower power settings, variations in focus position had a more pronounced impact on HAZ formation, while at higher power levels, power dominated the thermal diffusion effect. This suggests that an optimal combination of focus position and power can be leveraged to achieve the desired cutting quality while minimizing HAZ formation. Based on the experimental findings, the optimal laser cutting conditions are summarized as follows:

- On-focus (0 mm) produced the most balanced results, ensuring minimal thermal impact while maintaining cutting precision.
- Slightly below focus (−0.2 mm) led to slightly higher HAZ depths but increased penetration, which may be useful for applications requiring deeper cuts.
- Above focus (+0.2 mm) reduced charring and yielded finer cuts, making it preferable for machining operations.

The differences in HAZ dimensions between *Acacia mangium* and *Azadirachta excelsa* suggest species-specific responses to laser cutting. Across all parameter settings, *Azadirachta excelsa* exhibited slightly higher mean HAZ widths and depths than *Acacia mangium*. This may be attributed to the structural differences in cell wall thickness, fiber density, and moisture retention capacity, as *Azadirachta excelsa* has a denser, more porous structure than *Acacia mangium*. These structural properties likely influence how each species absorbs and dissipates thermal energy, affecting HAZ formation. This finding suggests that tropical wood species require tailored laser parameter settings to achieve optimal cutting quality.

The HAZ causes structural changes that weaken the material. As is well-known, HAZ has an undesirable side effect. It is impossible to eliminate HAZ, but it is possible to reduce it. After formation, only post-processing is possible. Whether laser drilling or cutting, the key to reducing HAZ formation is speed and laser power. As stated previously, there is a correlation between laser power and speed, with higher HAZ resulting from higher laser power and slower speed. The equipment and laser machining parameters determine the ability to optimize speed. Therefore, knowing how to optimize the performance of machines yields excellent results.

The results of this study provide actionable insights for optimizing laser cutting of tropical wood species. For *Acacia mangium* and *Azadirachta excelsa*, the optimal laser parameters to minimize HAZ are lower power (800–1500 mW) and higher speed (5–10 mm/s). Such settings are recommended for applications requiring minimal thermal damage and high-quality cuts, such as fine woodworking and furniture manufacturing. In contrast, higher power settings (2400 mW) may be appropriate when deeper cuts or faster material removal rates are prioritized, though with an expected increase in HAZ. The findings also highlight the importance of selecting appropriate laser parameters to preserve wood integrity and visual quality, particularly in tropical woods sensitive to thermal damage. By adopting the recommended settings, manufacturers can enhance cut precision, reduce waste, and extend the applicability of laser cutting in wood industries.

4. Conclusions

This preliminary study investigated the effects of laser power and traverse speed on the heat-affected zone (HAZ) dimensions in two commercially important Malaysian fast-growing wood species, *Acacia mangium* and *Azadirachta excelsa*. The findings underscore the critical role of these laser parameters in determining the width and depth of the HAZ, which directly affects the structural integrity and esthetic quality of laser-cut wood products.

The results revealed that laser power is the most influential factor, with higher power levels significantly increasing both HAZ width and depth. Traverse speed also plays a crucial role, with slower speeds exacerbating thermal effects by prolonging energy exposure. The interaction between these parameters emphasizes the need for simultaneous optimization to minimize thermal damage. Statistical analysis confirmed the significance of these effects ($p < 0.001$), and correlation analysis highlighted the strong positive relationship between power and HAZ dimensions and the mitigating effect of faster speeds.

Species-specific differences were evident, with *Azadirachta excelsa* exhibiting consistently larger HAZ widths but shallower depths compared to *Acacia mangium*. These differences are attributed to the unique structural and thermal properties of the two species, such as density, porosity, and fiber arrangement. These findings highlight the necessity of tailoring laser parameters to individual wood species to achieve optimal cutting performance.

This study identified 1500 mW laser power and 10 mm/s traverse speed as the optimal parameters for minimizing HAZ dimensions while ensuring effective cutting. These parameters balance sufficient energy delivery with reduced thermal impact, offering practical guidance for industries aiming to improve cutting precision and product quality. Such optimized settings are particularly beneficial for applications requiring high accuracy, such as furniture manufacturing, decorative woodwork, and other high-value wood products. The laser system used was a diode laser, which differs from CO_2 and fiber lasers commonly used in industrial applications. No assist gas was used, which may influence cut quality in real-world manufacturing settings.

This study confirmed that focus position has a limited but noticeable effect on HAZ width and depth in 3 mm Malaysian fast-growing species. While laser power and speed remain the primary influencing factors, slight defocusing can be employed strategically to enhance specific cutting outcomes. The optimal conditions for minimal HAZ in this study were identified as on-focus cutting at 1500 mW power and 10 mm/s speed.

Practical Implications:

1. Enhanced Efficiency: By adopting optimized laser cutting parameters, manufacturers can achieve precise cuts with minimal thermal damage, reducing material waste and improving product quality.
2. Species-Specific Recommendations: The findings provide actionable insights for tailoring laser settings to specific wood species, addressing the diverse needs of the wood processing industry.
3. Sustainability: Minimizing HAZ dimensions supports sustainable practices by preserving the usability and esthetic value of wood, even in fast-growing species.

Future Research Directions:

While this study provides a robust foundation, several avenues for further exploration are recommended:

1. Broader Wood Species Analysis: Investigate the effects of laser parameters on other tropical and temperate wood species to develop a comprehensive database of cutting recommendations.
2. Advanced Laser Technologies: Evaluate the impact of alternative laser types, such as CO_2 or fiber lasers, on HAZ dimensions and cutting efficiency.
3. Thermal Modeling: Develop predictive models to simulate HAZ formation under varying laser parameters, enabling real-time optimization in industrial settings.
4. Surface Treatment Studies: Examine the influence of pre-treatment methods, such as coatings or surface modifications, on HAZ dimensions and overall cut quality.
5. Focus Positions: Future research should explore a broader range of focus positions, alternative laser types, and their long-term effects on material integrity to further refine industrial laser cutting processes.

In conclusion, this study bridges a critical knowledge gap in the laser machining of tropical fast-growing woods, offering valuable insights for both academic research and industrial applications. The findings contribute to advancing precision wood processing technologies, supporting the sustainable utilization of renewable resources, and enhancing the economic value of tropical timber industries.

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Abbreviations

The following abbreviations are used in this manuscript:

HAZ	Heat-affected zone
EMC	Equilibrium moisture content
ANOVA	Analysis of variance
GRBL	Likely software for CNC control (possible typo for GRBL)
SPSS	Statistical Package for the Social Sciences
IR	Infrared
CO_2	Carbon dioxide

Appendix A

Table A1. HAZ depth results.

Laser Power (%)	Speed (mm/s)	Acacia Wood (Perpendicular to the Grain) (mm)	Acacia Wood (Parallel to the Grain) (mm)	Sentang Wood (Perpendicular to the Grain) (mm)	Sentang Wood (Parallel to the Grain) (mm)
100	2	0.518	0.686	0.261	0.275
	5	0.226	0.206	0.232	0.233
	10	0.069	0.107	0.111	0.122
60	2	0.646	0.493	0.369	0.251
	5	0.451	0.198	0.227	0.217
	10	0.146	0.168	0.119	0.118
20	2	0.167	0.119	0.061	0.041
	5	0.08	0.049	0.025	0.083
	10	0.033	0.072	0.067	0.024

Table A2. HAZ width measurements.

Laser Power (%)	Speed (mm/s)	Acacia Wood (Perpendicular to the Grain) (mm)	Acacia Wood (Parallel to the Grain) (mm)	Sentang Wood (Perpendicular to the Grain) (mm)	Sentang Wood (Parallel to the Grain) (mm)
100	2	0.518	0.686	0.261	0.275
	5	0.226	0.206	0.232	0.233
	10	0.069	0.107	0.111	0.122
60	2	0.646	0.493	0.369	0.251
	5	0.451	0.198	0.227	0.217
	10	0.146	0.168	0.119	0.118
20	2	0.167	0.119	0.061	0.041
	5	0.08	0.049	0.025	0.083
	10	0.033	0.072	0.067	0.024

Table A3. *Acacia mangium* (Acacia wood) (perpendicular to the grain) at a 10× 0.25 magnification.

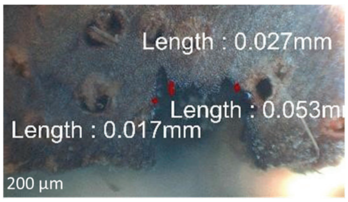
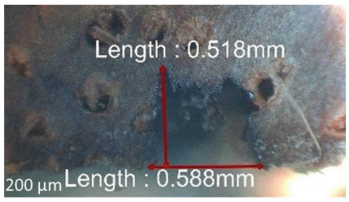
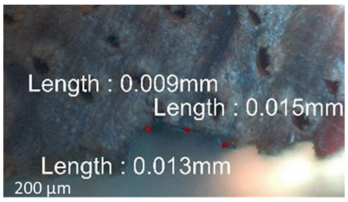
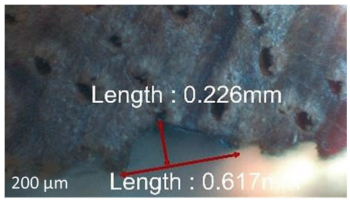
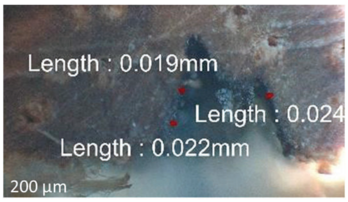
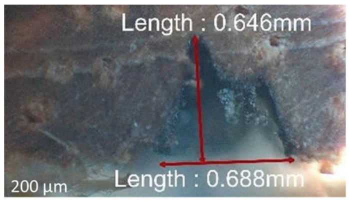
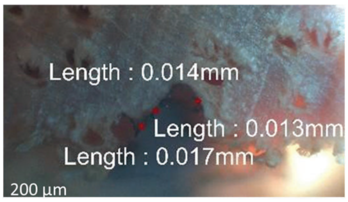
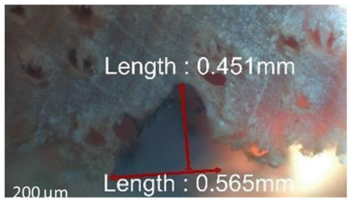
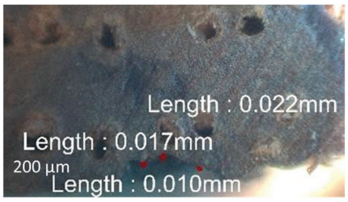
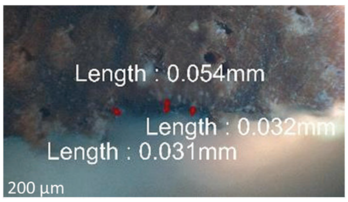
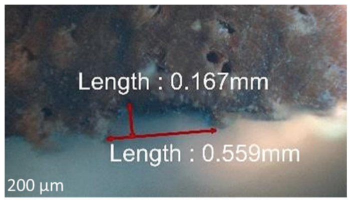
Laser Power 24 W (%)	Label	Speed (mm/s)	Result (HAZ) (mm)	Result (Cross-Section) (mm)
100	A	2		
	B	5		
	C	10		
60	D	2		
	E	5		
	F	10		
20	G	2		

Table A3. *Cont.*

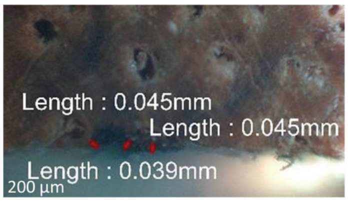
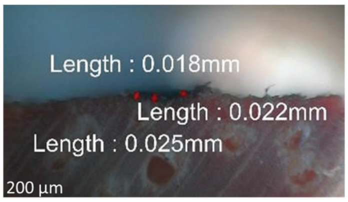
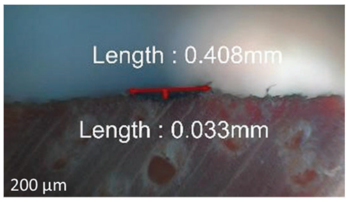
Laser Power 24 W (%)	Label	Speed (mm/s)	Result (HAZ) (mm)	Result (Cross-Section) (mm)
20	H	5		
	I	10		

Table A4. *Azadirachta Excelsa* (Sentang wood) (perpendicular to the grain) at a 10× magnification.

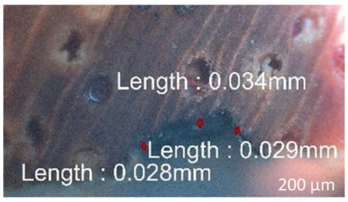
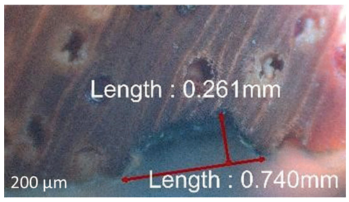
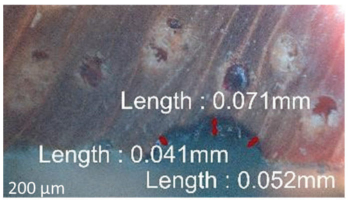
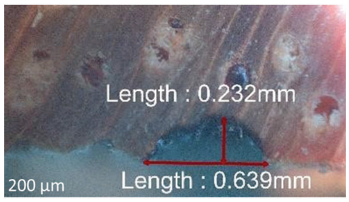
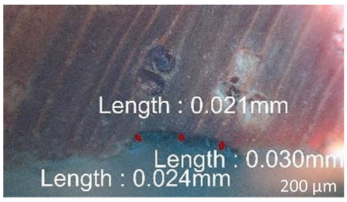
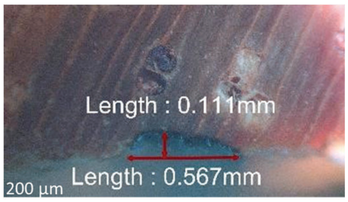
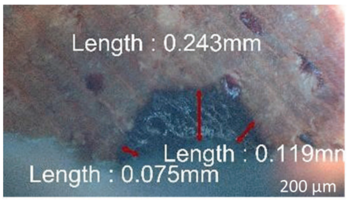
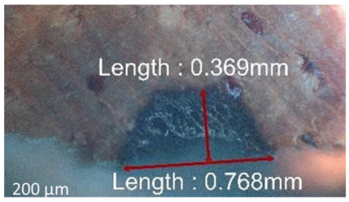
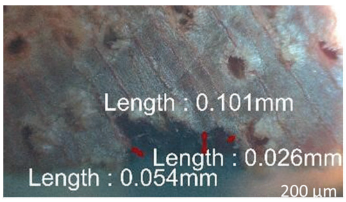
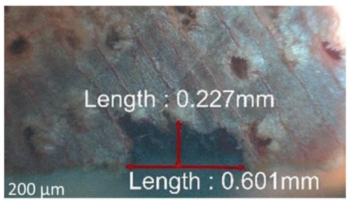
Laser Power 24 W (%)	Label	Speed (mm/s)	Result (HAZ) (mm)	Result (Cross-Section) (mm)
100	J	2		
	K	5		
	L	10		
60	M	2		
	N	5		

Table A4. *Cont.*

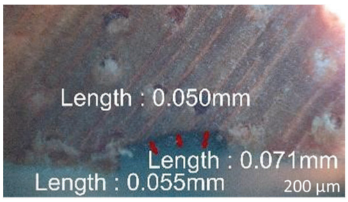
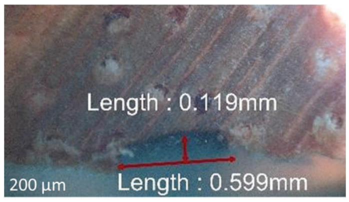
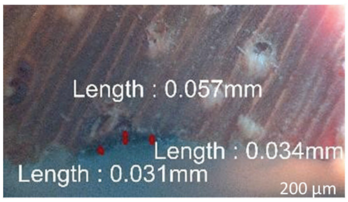
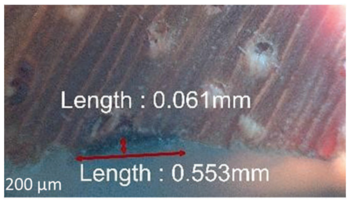
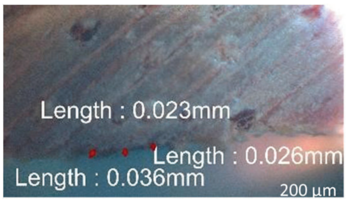
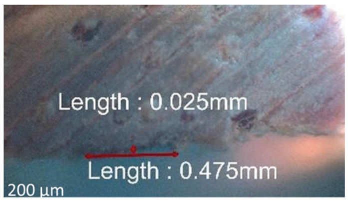
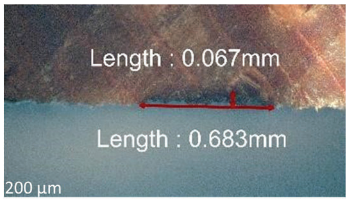
Laser Power 24 W (%)	Label	Speed (mm/s)	Result (HAZ) (mm)	Result (Cross-Section) (mm)
60	O	10		
20	P	2		
	Q	5		
	R	10		

Table A5. *Acacia mangium* (Acacia wood) (parallel to the grain) at a 10× magnification.

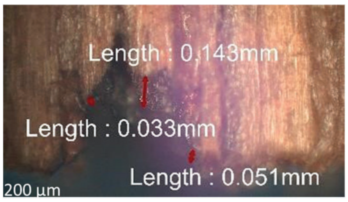
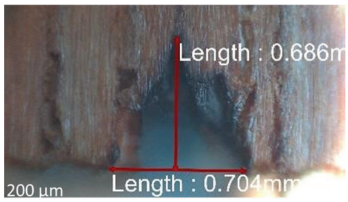
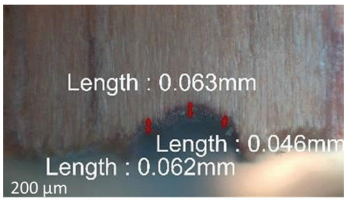
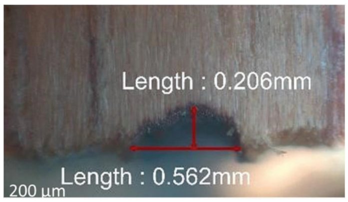
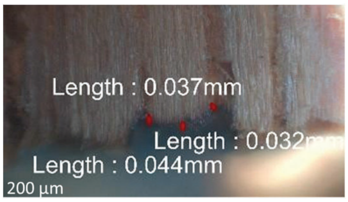
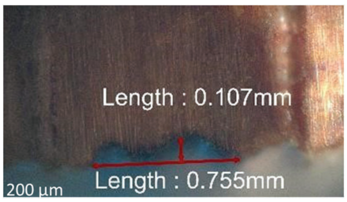
Laser Power 24 W (%)	Label	Speed (mm/s)	Result (HAZ) (mm)	Result (Cross-Section) (mm)
100	1	2		
	2	5		
	3	10		

Table A5. *Cont.*

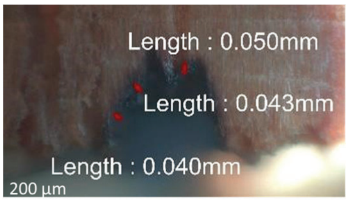
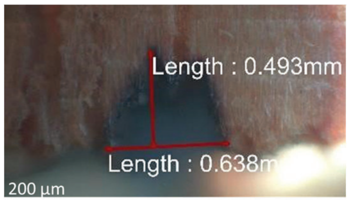
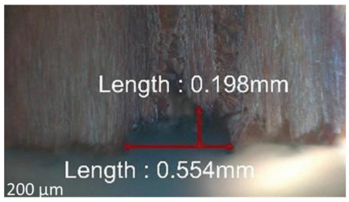
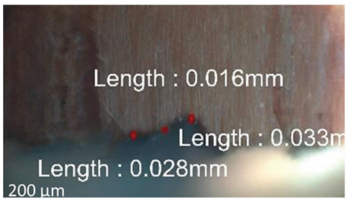
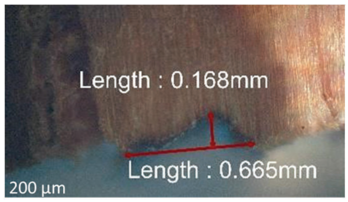
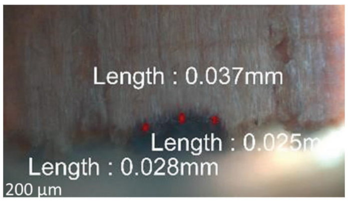
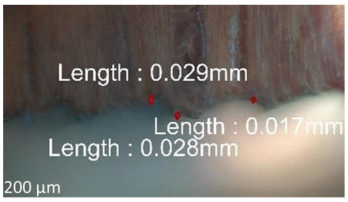
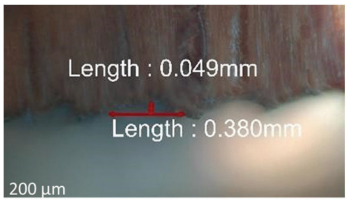
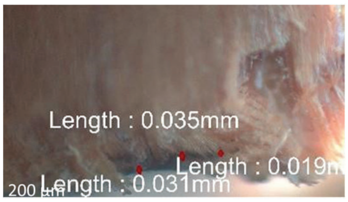
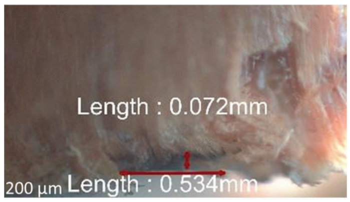
Laser Power 24 W (%)	Label	Speed (mm/s)	Result (HAZ) (mm)	Result (Cross-Section) (mm)
60	4	2		
	5	5		
	6	10		
20	7	2		
	8	5		
	9	10		

Table A6. *Azadirachta Excelsa* (Sentang wood) (parallel to the grain) at a 10× magnification.

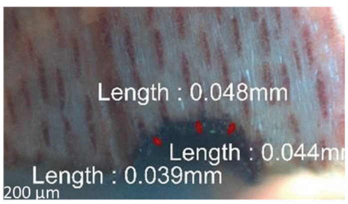
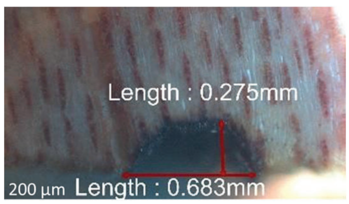
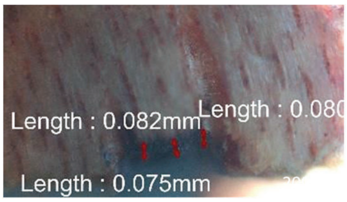
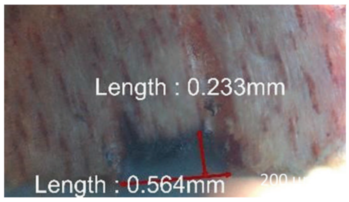
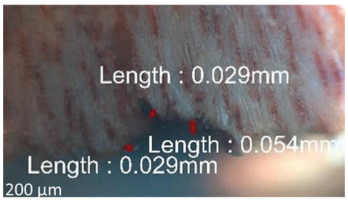
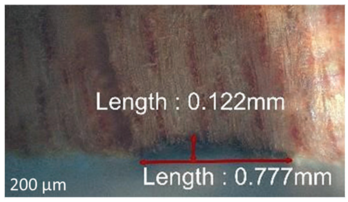
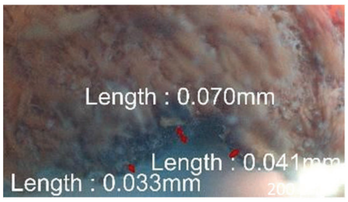
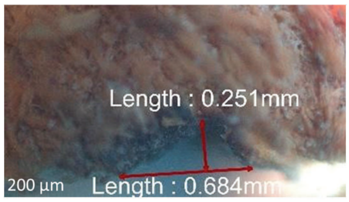
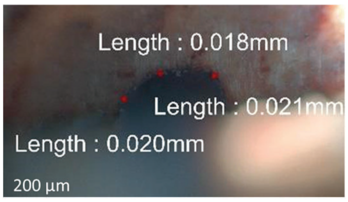
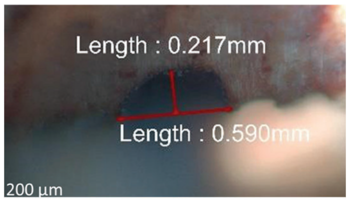
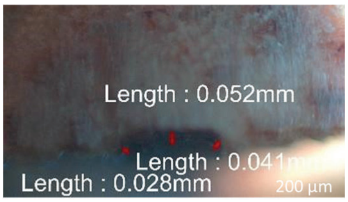
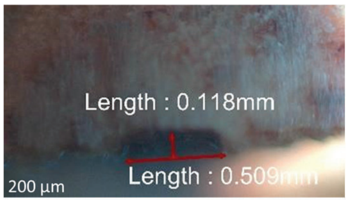
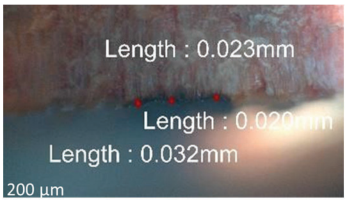
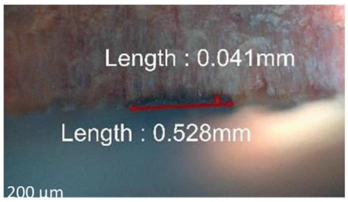
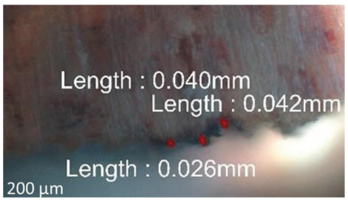
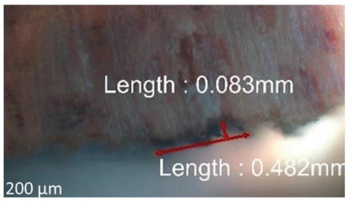
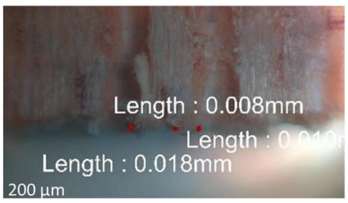
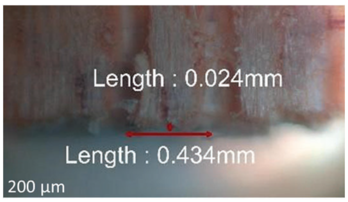
Laser Power 24 W (%)	Label	Speed (mm/s)	Result (HAZ) (mm)	Result (Cross-Section) (mm)
100	10	2		

Table A6. *Cont.*

Laser Power 24 W (%)	Label	Speed (mm/s)	Result (HAZ) (mm)	Result (Cross-Section) (mm)
100	11	5		
	12	10		
60	13	2		
	14	5		
	15	10		
20	16	2		
	17	5		
	18	10		

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