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RESEARCH OF COMPUTERIZED NUMERICAL CONTROL LASER PROCESSING QUALITIES OF SOME WOOD SPECIES USED IN THE FURNITURE INDUSTRY

Cebrail Açık[1,♠]

https://orcid.org/0000-0002-1094-6946

ABSTRACT

In recent years, laser material processing technology has become quite widespread. The quality of laser processing of wood materials is very important in terms of not causing secondary processes in the production process. In this study, computerized numerical control laser cutting qualities of some wood species that are frequently used in industrial product manufacturing were investigated. In the study, 80 % irradiation and 10 mm/sec laser cutting speed were applied to the test samples in a computerized numerical control laser machine with a 130 W carbon dioxide gas cylinder. In the case of laser cutting of 5 different wood species in the direction vertical to and parallel to the fibers, the average of the upper and lower kerf width, the difference in the width of the upper and lower kerf, the average of the width of the heat-affected zone, the width of the heat-affected zone were evaluated. In line with the findings, the effects of wood species differences on laser cutting quality in terms of material consumption, precision machining, and smoothness of cutting geometry were investigated. As a result, the highest quality cutting values were obtained from the laser cutting of the bamboo massif in terms of wood species, in the direction vertical to the fibers of the wood materials.

Keywords: CO_2 laser, computerized numerical control, laser cut quality, laser cutting, woodworking.

INTRODUCTİON

In the modern era, laser cutting is considered the cutting-edge cutting technology due to its high efficiency and ability to cut complex shapes at a very high speed. Laser cutting is one of the successful methods in the processing of many bioengineering materials. For the laser cutting process, it is especially important to reveal the responses of heterogeneous materials. (Sharma and Kumar 2015). Over the years, various speciess of lasers have been developed in research centers around the world, including gas, rod, fiber, disk and semiconductor lasers. Laser technology is currently used in the automotive, shipbuilding, aerospace, armament and energy industries for processes such as welding, hardfacing, melting, surface heat treatment, brazing, drilling, engraving, cutting and more. Therefore, laser light has many applications in the processing of various materials. The laser was discovered in the 1960s and cutting wooden elements began in the 1970s. Laser light is used for primary woodworking cutting in woodworking marking, engraving, surface cleaning automated systems. Lasers are widely used in the furniture industry (for example, in the manufacture of inlay elements), the toy industry, and the manufacture of decorations and ornaments. However, despite the advanced technology, lasers also have some disadvantages that limit their use in the woodworking industry. CO_2 laser light is absorbed by cellulose and lignin, the two main components of wood, and as a result, laser energy is converted into heat. Given the low thermal conductivity of wood, hot gases that cause charcoal deposits on the surface of the treated material damage the wood texture. The thickness of the carbonized layer depends on the physical properties and size of the workpiece, the processing direction (vertical and parallel to the fibers) and some laser operation parameters (Aniszewska *et al*. 2020). Deeper understanding of the characteristic behavior of wood is essential for predicting its mechanical response, and even more so for manufacturing design if biomaterials

[1]Onikişubat District Directorate of National Education. Kahramanmaraş, Türkiye.

[♠]Corresponding author: cebrail46@hotmail.com

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are used. In the formation of wood, the cell walls of wood fibers are structured in different layers. The primary wall consists of randomly oriented and loosely packed cellulose microfibrils. In the secondary cell wall, the microfibrils are highly oriented and parallel to each other. The middle layer of the secondary cell wall makes up most of the volume of the wood cell wall (Jakoba *et al*. 2017). The mechanical cutting process of wood is based on the principle of weakening and destroying the structure between the fibers. Cutting, planing, profiling, drilling, etc. in machining. Waste sawdust is generated after cutting, as in operations. In mechanical cutting, the structure of all cutting edges is based on the wedge principle. The wedge principle is based on the principle of increasing the effect of the force by collecting the mechanical force applied to any object in a small area (the cutting edge). The principle of laser cutting is based on increasing the burning effect of the force by collecting the light force applied to any object by stimulated radiation emission in a small area. That is, a sharp blade in mechanical cutting represents a fully concentrated (thinned) laser beam in laser cutting. Likewise, as in mechanical cutting, laser cutting is based on the principle of destroying (burning) by weakening the structure between the fibers. Laser cutting is more like saw cutting in mechanical cutting. However, instead of natural or chemically intact sawdust, the laser beam removes the sawdust in the cutting notch by evaporating it by chemical conversion (carbonization) (Cherif *et al.* 1990). In recent years, laser technology has been at the forefront of material processing. It can be considered that in the near future it will probably replace traditional techniques such as sawing (Gaff *et al.* 2020).

Human contact woodworking, which has been very common in the process until today, has recently started to leave its place to information and technology with the increase of mechanization, together with computer-controlled machines. As a result, with the computerized numerical control (CNC) machine technology, the manpower in production decreased and it started to leave its place to the processing of information. With the spread of laser technology, non-contact, precision and chipless production methods have become quite common. Although the laser entered the wood industry later, it spread rapidly and only laser machines for woodworking were produced. These developments have made academic studies on laser wood processing a necessity (Guo *et al.* 2021). On the other hand, since laser processing parameters are a versatile process, it is essential to characterize the wood mechanism in-depth and it is imperative to discover the appropriate processing combination to achieve higher yields (Aniszewska *et al.* 2020).

Studies in the literature on wood cutting in CNC laser machines with carbon dioxide gas tube, which are the most widely used in the wood industry, were examined. In these studies, the cellular structures of the surfaces cut with fiber laser and CO_2 laser were compared to compare the kerfs made with saws and the cutting surfaces made with laser beams adjusted to different power levels and movement speeds (Yusoff *et al.* 2008), Malaysia's light hard woods Nyatoh (*Palaquium* spp*.),* ınvestigation of the effects of laser power, nozzle distance or focal point position, nozzle size, auxiliary gas pressure, auxiliary gas speciess and cutting speed parameters on cut quality on Semangkok (*Scaphium* spp.), Meranti (*Shorea* spp.) (Cherif 1990), Ihlamur, Investigation of material notch width in soft maple, cherry, black walnut and hard maple wood cutting with 3000 W CO_2 laser (Yusoff 2006), examining the change of notch width in different laser power and speed parameters of some Malaysian wood species (Ibrahim and Kesevaan 2018), focal height of wood polymer composite material, determination of the most suitable cutting parameters of laser cutting speed and power (Eltawahni *et al.* 2013), Determination of optimum cutting parameters of focal length, cutting speed and power for laser cutting under cutting conditions (Merchant 1995), investigation of the effect of laser gas and air pressure on laser cutting in woodworking (Barnekov *et al*. 1986), beam power, mode, polarization and stability, optics in woodworking with laser. The directions of the focal point, the feed rate, the gas blast support system and the effects of the workpiece thickness, material density and moisture content (Kubovsky *et al.* 2020), the cutting speed of the laser power for laser processing and the number of rings per year, the cutting notch at the upper and lower points of the notch width. effect (Teivonen 2016), determination of laser engraving properties of some wood and wood-based composite materials using different laser power and speed combinations (Xu *et al*. 2017), power, speed and nozzle height parameters in laser cutting, bamboo tree cutting in the vertical and parallel directions to the fibers width and depth (Eltawahni *et al*. 2011), power, speed and nozzle height parameters in laser cutting, different thickness The effect of cutting fiberboard material on the kerf width (Liu *et al.* 2020), the effects of cutting thin wood materials with or without gas support on laser cutting at different powers and speeds (Açık and Tutuş 2023), the processing performance of different speciess of wood materials in terms of laser cutting depth (Ürgüplü and Köksal 2015) research has been done on the subject.

The quality of the laser cutting process is generally examined under three main headings: material parameters, laser system parameters and operation parameters. Material parameters include many features such as density, anatomical structure, chemical structure, thermal conductivity, optical properties, color properties, surface roughness and thickness of the cut material. Laser system parameters include beam wavelength, maximum laser power output, laser beam quality. Operation parameters include laser power, cutting speed, focusing distance of the lens, tracking of the focal point to the workpiece surface, pressure and species of auxiliary gas, nozzle diameter and distance adjustment of the nozzle to the workpiece surface. Operation parameters can be changed depending on material species and thickness. However, some characteristic parameters of the laser system and all the parameters of the material can't be changed by the operator (Sharma and Kumar 2015). In laser cutting, the most complex and influential parameter on various output qualities such as heat affected zone and kerf is the material parameter (Açık and Tutuş 2022).

When the findings and explanations in the literature studies are evaluated, it is seen that the majority of the researches are done on the operation parameters. It has been observed that the limited number of studies on wood material parameters are mostly singular in terms of the species of wood used or the investigated feature (such as the width of the upper kerf). The connection between the difference in wood species and the elements that make up the cutting output, which is important for the users, with the criteria that make up the cutting quality has not been adequately explained with a holistic approach. In this study, the density, cutting direction and characteristic structure difference of the materials obtained from 5 different wood species, which are frequently used in industrial production, the upper and lower kerf widths that determine the CNC laser cutting quality of the material, and the heat affected areas of these kerfs, material consumption, precision machining, The effects of cutting geometry on laser cutting quality in terms of smoothness were evaluated with a holistic numeral method and tried to be explained with common results. It is aimed to support the adaptation of wood product designers and manufacturers to the rapidly developing smart industrial production systems in the world.

MATERİALS AND METHODS

Materials

A total of 5 different tree species were used in the study. The densities of wood species in the air-dry state at 12 % moisture level are 657 kg/m³ in beech (*Fagus silvatica* L.), 595 kg/m³ in walnut (*Juglans nigra*), 557 kg/m³ in bamboo (*Bambusoideae*), 533 kg/m³ in sycamore (*Platanus orientalis*) and poplar (*Populus* Spp.) as 384 kg/m³. Experimental samples were prepared in the dimensions of 6 mm x 30 mm x 30 mm. Measurements were taken from different points by making cuts in the same test sample 3 times in parallel and vertical directions to the fibers. Experimental samples are shown in Figure 1a below, and laser cutting positions are shown in Figure 1b. In the study, a 10,6 µm wavelength CNC laser processing machine with a 130 W carbon dioxide gas cylinder, water cooled, 1,5 mm nozzle diameter, 2 mm thick and 20 mm diameter focusing lens was used. In addition, an optical microscope was used to determine kerf widths and measurements of heat affected zones. The materials were treated with 80 grit sandpaper and brought to the same surface roughness.

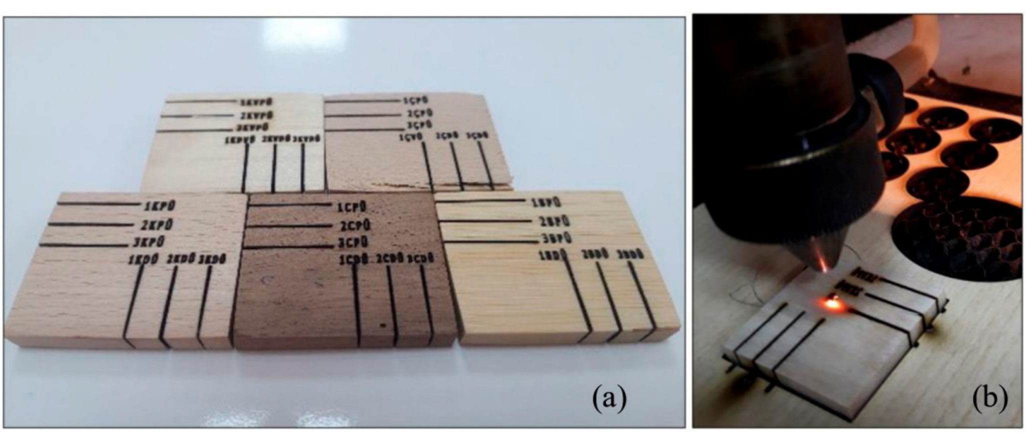

Figure 1: (a) Experiment samples, (b) laser cutting.

Methods

In the study, the limitations in machine processing functions and the thickness of the samples to be cut were taken into account. It is aimed to work only on material parameters by applying 80 % irradiation and cutting with 10 mm/s speed in a CNC laser machine with 130 W CO_2 gas cylinder. Due to the function of the lens used for the cutting process, the beam focusing distance of 2 inches (50,8 mm) is focused in the middle of the thickness of the test sample to be cut. To determine the cut quality of the test sample, the upper kerf width (WKU), the lower kerf width (WKD), the width of the upper heat affected zone (WHAZU), the width of the lower heat affected zone (WHAZD), focusing length (FL), cut parallel to the fibers (P), cut vertical to the fibers (V) and test sample thickness (T) are shown in Figure 2a below. and the measurements of the samples with an optical microscope are shown in Figure 2b.

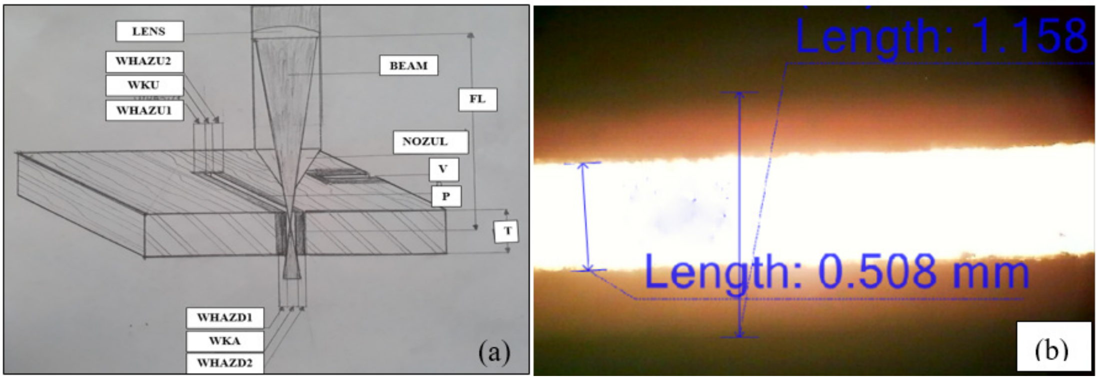

Figure 2: (a) The experimental setup Laser cuttings, (b) measurement method.

In calculating the width of the heat affected zone in the measurements, half of the remaining value was taken by subtracting the kerf width from the end-to-end width of the two heat affected zones on both sides of the kerf (WHAZ= WHAZ-WK/2). The intersection parallel to the fibers is the intersection in which the laser beam axis is vertical to the fibers and the direction of nozzle movement is parallel to the fibers. Vertical to the fibers is the intersection where the laser beam axis and the direction of movement of the nozzle are vertical to the fibers. In determining the laser cutting quality;

1- Average of upper and lower kerf width,

2- Upper and lower kerf width difference,

3- The average width of the heat-affected zone,

4- The difference in the width of the heat affected zone,

5- It was determined according to the average and difference values of the cutting data parallel to and vertical to the fibers. The lower average or difference values of wood species were evaluated as having higher quality cutting properties. Average values determine energy and material consumption, precision machining quality. The difference values determine the smoothness of the cutting geometry. Correlation analysis was performed to determine the relationship of wood species independent variable with kerf width and heat affected zone width dependent variables. One-way analysis of variance was performed to determine the differences between groups in variables that gave significant results. In statistical evaluations, negative (negative) effects should be considered as higher quality, since lower values are desired in terms of laser cutting quality.

RESULTS AND DİSCUSSİONS

Cut parallel to the fibers

Upper kerf width (WKU), lower kerf width (WKD), average of upper and lower kerf widths (WKm), difference of upper and lower kerf widths (WKd), heat affected upper zone width (WHAZU) obtained by laser cutting wood samples parallel to the fibers, lower heat affected zone width (WHAZD), mean upper and lower heat affected zone widths (WHAZm), difference between upper and lower heat affected zone widths (WHAZd), together with the densities of the materials are shown in Table 1 below.

Table 1: Cutting results of materials parallel to the fibers.

Tree Species	Density (kg/m^3)	WK (mm)				WHAZ (mm)			
		WKU	WKD	WKm	WKd	WHAZU	WHAZD	WHAZm	WHAZd
Beech	657	0,524	0,407	0,466	0,117	0,319	0,259	0,289	0,060
Walnut	595	0,487	0,329	0,408	0,158	0,330	0,254	0,292	0,038
Bamboo	557	0,375	0,434	0,405	0,059	0,247	0,342	0,295	0,095
Sycamore	533	0,534	0,363	0,449	0,171	0,268	0,263	0,266	0,005
Poplar	384	0,569	0,591	0,580	0,022	0,368	0,235	0,302	0,133
Smallest	384	0,375	0,329	0,405	0,022	0,247	0,235	0,266	0,005
Biggest	657	0,569	0,591	0,580	0,171	0,368	0,342	0,302	0,133
Average	545	0,498	0,425	0,461	0,105	0,306	0,271	0,289	0,066

In laser cutting of wood species parallel to the fibers, bamboo solid species gave the best quality cut in terms of kerf smallness (narrow), while poplar solid species gave the lowest quality cut with 30,1 % more kerf width than bamboo. In terms of the difference or equality (geometry) of the lower and upper kerf, the poplar massif gave the best quality result with the smallest value, while the sycamore massif gave the lowest quality result with a 29,1 % larger value than the poplar. In laser cutting of wood species parallel to the fibers, in terms of the mean heat affected zone (HAZ) width, the solid sycamore species gave the best quality cut, while the poplar solid species gave the lowest quality cut with 11,9% higher than the sycamore tree. In terms of lower and upper HAZ difference or equality, the solid sycamore species gave the best quality cut, while the poplar solid species gave the lowest quality cut with 96,2 % greater value than the sycamore tree.

According to the average values of all solid materials, it was determined that the width of the upper kerf was 17,1 % greater than the width of the lower kerf. The upper HAZ width, on the other hand, was found to have 12,9 % more value than the lower HAZ width. According to these results, a direct proportional relationship was determined between the upper and lower kerf widths and the HAZ widths. In other studies, it has been explained that the upper kerf width of MDF wood composite material (Eltawahni *et al.* 2011) and plywood material is greater than the lower kerf width (Ibrahim and Kesevaan 2018). In another study, it was found that the width of the upper kerf is greater than the width of the lower kerf in the parallel section of the spruce (*Pices abies L.*) tree at different machine parameters, and the difference between them is 55 %, and the width of the lower HAZ is 25,8 % more than the width of the upper HAZ explained (Barnekov *et al.* 1986). Although the results in the literature and the results of this study overlap with beech, sycamore tree and walnut wood species in terms of lower and upper kerf widths, they do not overlap with poplar and bamboo species. In terms of the width of the lower and upper HAZ, it only overlaps with the bamboo species.

The trend of mean upper and lower kerf and HAZ widths in relation to the densities of wood species is shown in Figure 3a below. In the determination of laser cutting quality, when the materials with less kerf width and HAZ width, and which make less difference between the upper and lower cutting regions of these two factors, are evaluated as having higher quality cutting properties, no relationship was found between density and quality. It has been determined that bamboo solid material gives the best quality result in cutting parallel to the fibers among wood species. The trend of upper and lower kerf and HAZ differences is shown in Figure 3b. An inversely proportional relationship was obtained between the kerf and HAZ geometry of the materials. There was no relationship between material densities and kerf widths, but an inverse relationship was found between

HAZ widths. That is, as the kerf geometry deteriorates, the HAZ geometry becomes smoother. However, this relationship is not valid for the sycamore massif.

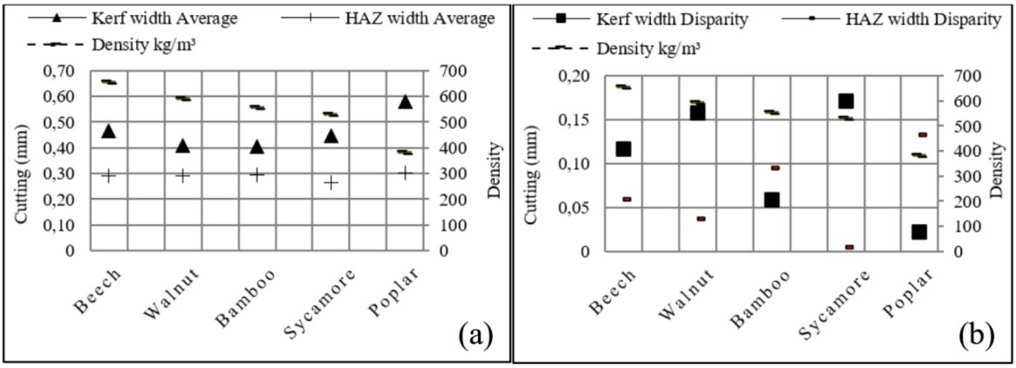

Figure 3: Cutting results of wood materials parallel to the fibers, (a) Relationship between density kerf width and heat affected zone width, (b) Density cut geometry relationship.

Cut vertical to the fibers

Upper kerf width (WKU), lower kerf width (WKD), average of upper and lower kerf widths (WKm), difference of upper and lower kerf widths (WKd), heat affected upper zone width (WHAZU) obtained by laser cutting wood samples vertical to the fibers, lower heat affected zone width (WHAZD), mean upper and lower heat affected zone widths (WHAZm), difference between upper and lower heat affected zone widths (WHAZd), together with the densities of the materials are shown in Table 2.

Table 2: Cutting results of materials vertical to the fibers.

Tree Species	Density (kg/m^3)	WK (mm)				WHAZ (mm)			
		WKU	WKD	WKm	WKd	WHAZU	WHAZD	WHAZm	WHAZd
Beech	657	0,389	0,253	0,321	0,136	0,256	0,165	0,211	0,091
Walnut	595	0,266	0,314	0,290	0,024	0,171	0,181	0,176	0,010
Bamboo	557	0,297	0,307	0,302	0,010	0,297	0,309	0,303	0,012
Sycamore	533	0,431	0,435	0,433	0,004	0,232	0,294	0,263	0,062
Poplar	384	0,516	0,594	0,555	0,078	0,270	0,352	0,311	0,082
Smallest	384	0,266	0,253	0,290	0,004	0,171	0,165	0,176	0,010
Biggest	657	0,516	0,594	0,555	0,136	0,297	0,352	0,311	0,091
Average	545	0,380	0,381	0,380	0,050	0,245	0,260	0,253	0,051

In laser cutting of wood species vertical to the fibers, in terms of the average kerf width, the walnut solid species gave the best quality cut, while the poplar solid species gave the lowest quality cut with a 47,7 % larger value than walnut. In terms of the difference between the lower and upper kerf, the sycamore massif gave the best quality result, while the beech massif gave the lowest quality result with 97 % greater value than the sycamore tree. In laser cutting of wood species vertical to the fibers, in terms of the average HAZ width, the walnut solid species gave the best quality cut, while the poplar solid species gave the lowest quality cut with 43,4 % higher than walnut. In terms of lower and upper HAZ equality or difference, walnut solid species gave the best quality cut, while beech species gave the lowest quality cut with 89 % greater value than walnut. According to the average values of all solid materials, no difference was determined between the upper kerf width and the lower kerf width. It has been determined that the width of the lower heat-affected zone is 6,1 % more than the width of the upper heat-affected zone. The trend of mean lower and upper kerf and HAZ widths in relation to the densities of wood species is shown in Figure 4a below. An inversely proportional relationship was found between material densities and kerf widths. In other words, high-density materials gave narrower and higher quality kerf results. However, this relationship is not valid for the walnut massif. In determining the laser cutting quality, when the materials with less kerf width and HAZ width, and which make less difference between the upper and lower cutting regions of these two factors, are evaluated as having higher quality cutting properties, it is seen that bamboo solid material is among wood speciess both in cutting parallel to fibers and in cutting. It has been determined that it gives the best quality result in cutting vertical to the fibers. The reason for this is considered to be due to the structural anisotropy of bamboo, which consists of parallel and regular fiber bundles with consistent textures and no lateral contact (Xu *et al.* 2017). The trend of lower and upper kerf and HAZ differences is shown in Figure 4b direct proportional relationship was obtained between the lower and upper kerf width difference of the materials and the lower and upper HAZ difference. In other words, as the kerf geometry improved, the HAZ geometry also improved. However, this relationship was not valid for the sycamore massif.

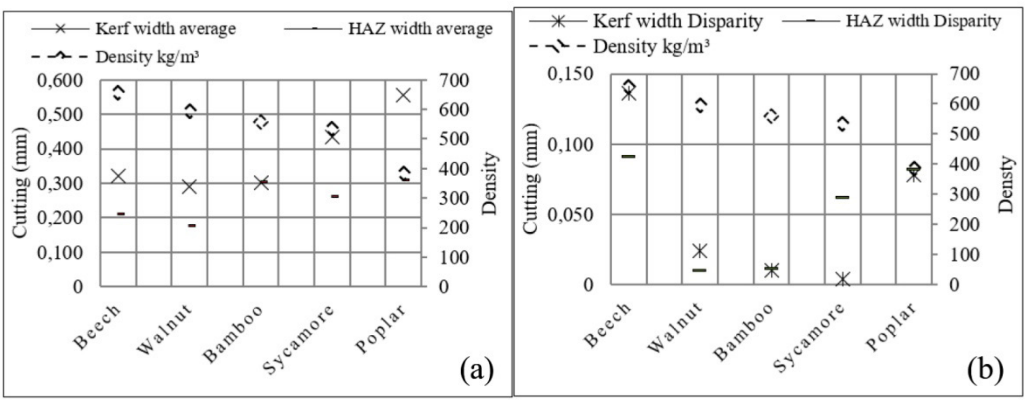

Figure 4: Laser cutting results of materials vertical to the fibers, (a) Relationship between density kerf width and heat affected zone width, (b) Density cut geometry relationship.

Laser cutting results parallel to and vertical to the fibers

The kerf widths (WK) obtained in laser cutting of wood samples, parallel to the fibers in Table 1 and vertical to the fibers in Table 2, mean (MKm) and differences (MKd) of the kerf width averages (MK) obtained in the cut, and the materials parallel to the fibers in Table 1 and Table 2. The differences (DK), average (DKm) and differences (DKd) of kerf widths in cutting vertical to the fibers in Table 2, as well as the averages of heat affected zone widths (WHAZ) obtained in laser cutting of wood samples, parallel to the fibers in Table 1 and to the fibers in Table 2 Average (MHAZm) and differences (MHAZd) of heat affected zone width averages (MHAZ) in vertical cut, mean (DHAZm) and differences (DHAZd) of heat affected zone width differences (DHAZ) of materials in parallel to fibers in Table 1 and vertical to fibers in Table 2 are shown in Table 3 below.

Table 3: Laser cutting results parallel to and vertical to the fibers.

Tree Species	Density (kg/m³)	WK				WHAZ			
		MK		DK		MHAZ		DHAZ	
		MKm	MKd	DKm	DKd	MHAZm	MHAZd	DHAZm	DHAZd
Beech	657	0,072	0,145	0,009	0,019	0,039	0,078	0,015	0,031
Walnut	595	0,059	0,118	0,067	0,134	0,058	0,116	0,014	0,028
Bamboo	557	0,051	0,103	0,024	0,014	0,004	0,008	0,041	0,083
Sycamore	533	0,008	0,016	0,065	0,167	0,001	0,003	0,028	0,057
Poplar	384	0,012	0,025	0,028	0,056	0,004	0,009	0,025	0,051
Smallest	384	Sycamore	Sycamore	Beech	Bamboo	Sycamore	Sycamore	Walnut	Walnut
Biggest	657	Beech	Beech	Walnut	Sycamore	Walnut	Walnut	Bamboo	Bamboo

When the cutting of wood species parallel to and vertical to the fibers is compared, the best quality laser cutting result in terms of kerf width was obtained from sycamore tree and the lowest quality cut from beech massif. In terms of kerf geometry, the best quality cut was obtained in beech and bamboo, and the lowest quality cut was obtained in walnut and sycamore solid speciess. In terms of HAZ width, the highest quality laser cutting result was obtained in sycamore tree and the lowest quality cutting result was obtained in walnut in wood species. In terms of HAZ geometry, the best quality cut was obtained in walnut, and the lowest quality cut was obtained in bamboo solid species. Below is the microscope image of the upper kerf cut parallel to the fibers of the bamboo massif in Figure 5a. In Figure 5b, the image of the upper kerf cut perpendicular to the fibers is shown. When the total values in Table 1 and Table 2 are compared, in laser cutting vertical to the fibers of wood species, 17,5 % higher quality laser cutting results were obtained in terms of average kerf width and 52,3 % in terms of lower and upper kerf width equality compared to cutting parallel to the fibers. In laser cutting of wood species vertical to the fibers, 12,4 % higher quality laser cutting results were obtained in terms of the average HAZ width and 22,7 % in terms of the geometry of the lower and upper HAZ widths compared to the cutting parallel to the fibers. Thus, in laser cutting vertical to the fibers, a higher quality laser cutting result was obtained in all parameters compared to cutting parallel to the fibers. This is because during laser cutting of materials with high thermal conductivity, heat starts to spread rapidly from the cutting zone to the material. Therefore, the high cutting power is weakened at the main cutting point. This theory also applies to wood material. In wood materials, the thermal conductivity in the direction parallel to the fibers is approximately 2,5 times higher than the direction vertical to the fibers. During a laser cut vertical to the fibers, the kerf and HAZ width measurement axis are formed in the direction parallel to the fibers. Further spreading of the heat in the direction parallel to the fibers weakens the heat effect at the cut point. The weakening of the heat effect creates less burning and carbonization. In this case, a narrower and less burnt quality cut with kerf and HAZ width is obtained in the vertical cut to the fibers (the kerf width measuring axis extending in the direction parallel to the fibers) (Açık and Tutuş 2022). In another study, it was explained that the low thermal conductivity of wood compared to other engineering materials is negatively affected by hot gases that cause coal deposits on the surface of the laser-treated material and damage its texture (Aniszewska *et al.* 2020).

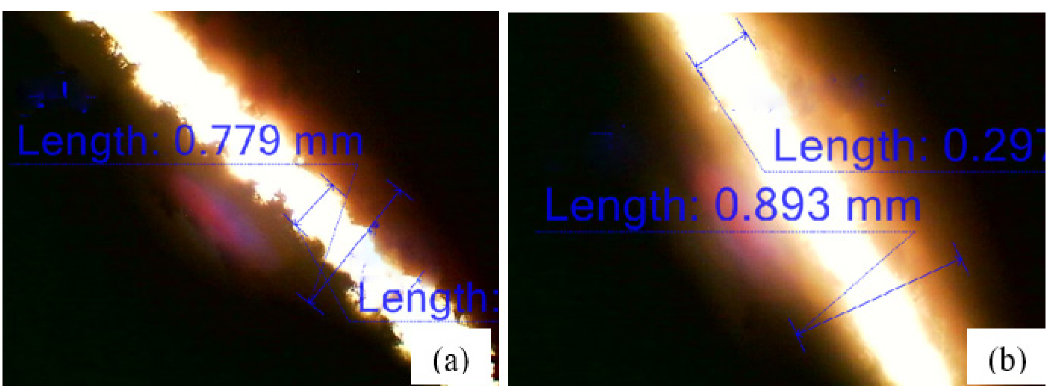

Figure 5: Laser cut image of bamboo massif, (a) Parallel cut to fibers (b) Vertical cut to fibers.

Statistical analysis

Pearson correlation analysis was performed to statistically determine the relationship between the laser cut values obtained from the wood test samples and the wood species. Densities of the materials were defined as the nominal value of the wood species in the statistics program, and the numbers 1 for the parallel direction and 2 for the vertical direction were defined for the nominal value of the cutting direction. Statistically, negative effects should be considered as a result of better quality cutting, as it expresses the desired smaller values in laser cutting outputs. The results obtained are given in Table 4.

As seen in Table 4 above, according to the results of the correlation analysis, no significant relationship was found between wood species and cutting directions in laser cutting of tree species. Negative and significantly high correlation was obtained between the mean kerf width (WKm) and the wood species. The wood species variable affected the change in laser kerf width by 52 % (r^2=0,515). In other words, as the density of the wood species increased, quality results with narrower kerf width were obtained compared to the statistical results. No significant results were obtained in the kerf width difference (WKd), which is important for wood species and cutting geometry. Negative and significantly moderate relationship was obtained between the mean of heat affected area (WHAZm) and wood species. The wood species variable affected the change in laser HAZ width by 19 % (r^2=0,189). In other words, as the density of the wood species increased, quality results with narrower HAZ width were obtained compared to the statistical results. No significant results were obtained in the heat affected zone width difference (WHAZd), which is important for wood species and cutting geometry.

Table 4: Relationship between variables and laser cutting width.

		Species	Direction	WKm	WKd	WHAZm	WHAZd
Species	Pearson Correlation(r)	1	0	-0,718*	0,162	-0,435*	-0,207
	Sig. (p)	-	1	0	0,393	0,016	0,272
	N	30	30	30	30	30	30
Direction	Pearson Correlation(r)	0	1	-0,422*	-0,366*	-0,389*	-0,240
	Sig. (p)	1	-	0,020	0,047	0,034	0,201
	N	30	30	30	30	30	30
WKm	Pearson Correlation(r)	-0,718*	-0,422*	1	0,077	0,555*	0,492*
	Sig. (p)	0	0,020	-	0,686	0,001	0,006
	N	30	30	30	30	30	30
WKd	Pearson Correlation(r)	0,162	-0,366*	0,077	1	0,148	-0,018
	Sig. (p)	0,393	0,047	0,686	-	0,435	0,926
	N	30	30	30	30	30	30
WHAZm	Pearson Correlation(r)	-0,435*	-0,389*	0,555*	0,148	1	0,203
	Sig. (p)	0,016	0,034	0,001	0,435	-	0,281
	N	30	30	30	30	30	30
WHAZd	Pearson Correlation(r)	-0,207	-0,240	0,492*	-,018	0,203	1
	Sig. (p)	0,272	0,201	0,006	0,926	0,281	-
	N	30	30	30	30	30	30

* $p < 0,05$, $0,710 < r < 0,990$ high level of association, $0,300 < r < 0,700$ medium level of association $0,010 < r < 0,290$ low level of association.

Negative and significant moderate correlation was obtained between the laser cutting direction and both the mean kerf width and the difference in kerf width. The cutting direction variable affected the change in laser kerf width averages by 18 % (r^2=0,178) and the kerf width difference by 13 % (r^2=0,133). In other words, according to the statistical results, quality cutting results with both narrower kerf width and smoother geometry were obtained from cutting parallel to the fibers in the direction of cutting vertical to the fibers. Negative and significantly moderate relationship was obtained between the cutting direction and the mean of the HAZ. The laser cutting direction variable affected the change in HAZ width at the level of 15 % (r^2=0,151). In other words, according to the statistical results, quality results with a narrower HAZ width were obtained in vertical to the fibers than in parallel cutting. However, this relationship did not give significant results in the difference of HAZ width, which is important for the cut geometry.

According to the statistical results, wide or narrow kerf widths did not affect the kerf geometry, according to the total values in all variables. Kerf width affected HAZ width by 31 % (r^2=0,308) and HAZ geometry by 24 % (r^2=0,242) moderately positively and significantly. In other words, the increase in kerf width both increased the HAZ width average and increased the HAZ geometric difference, resulting in a lower quality cut. In the laser cutting of wood massifs, one-way analysis of variance Duncan test was performed to determine the groups that made a difference and that did not, in the variables where significant differences occurred as a result of the above correlation analysis. The statistical results obtained are given in Table 5.

Table 5: Laser cutting group relationships of wood species.

Groups	WKm				WHAZm			
	n	*m	*sd	*g	*n*	m	sd	g
Walnut	6	0,349	0,068	a	6	0,237	0,071	a
Bamboo	6	0,353	0,065	a	6	0,299	0,020	bc
Beech	6	0,393	0,080	ab	6	0,250	0,044	ab
Sycamore	6	0,441	0,027	b	6	0,264	0,024	ab
Poplar	6	0,567	0,020	c	6	0,306	0,031	c

*m (mean), sd (standard deviation), g (homogeneity).

According to Table 5 above, there was no significant difference between walnut, bamboo and beech groups, as well as beech and plane tree groups in laser cutting depending on the mean kerf width (WKm) of wood species. The poplar massif formed a different group from all other wood species. There was no significant difference between walnut, beech and sycamore groups, between beech, sycamore and bamboo groups, and between sycamore, bamboo and beech groups in laser cutting depending on the heat affected zone width averages (WHAZm) of wood species. It is seen that the density properties are effective in group formation of wood species depending on kerf width averages (WKm). Since there are two groups parallel and vertical to the fibers in the direction of laser cutting, analysis of variance was not performed. The interaction graph of the laser cut kerf width of wood species groups, which gave meaningful results in the analysis, is given in Figure 6a, and the interaction graph of the laser cut HAZ width of the wood species groups is given in Figure 6b below. There is a parallelism between the kerf width trend of wood species groups and the HAZ width trends. However, this parallelism does not apply to the bamboo massif.

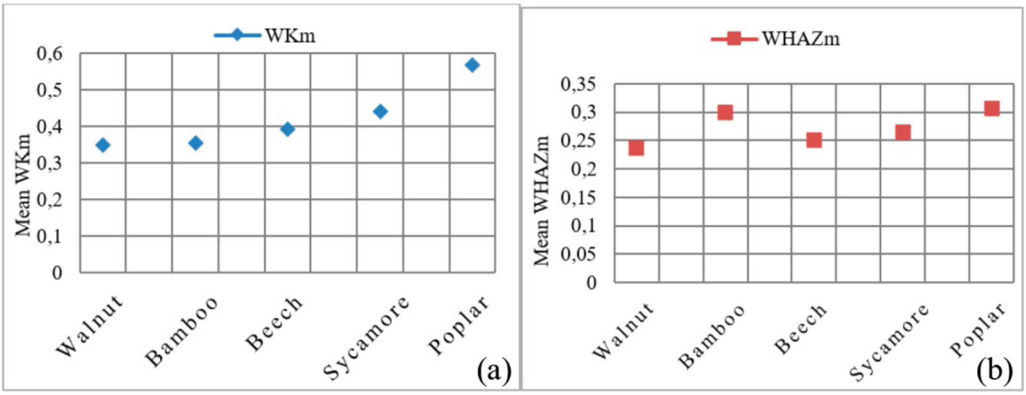

Figure 6: (a) Relationship between kerf width of wood species groups, (b) Relationship between HAZ width of wood species groups.

CONCLUSİONS

Among the 5 wood species, bamboo solid material gave the best quality laser cutting results both in the direction vertical to the fibers and in the direction parallel to the fibers in terms of both the kerf quality and the quality of the heat affected area.

Statistically, while the density of wood species increased the cut quality in terms of precision cut, energy and material consumption, it did not affect the cut geometry quality. In this sense, the least difference in terms of homogeneity with other species in terms of cutting quality was obtained in laser cutting of the beech massif, and the highest difference was obtained from the results of laser cutting of the poplar massif.

In all laser cutting quality criteria, higher quality cutting results were obtained in vertical to the fibers than in parallel cutting. The laser cutting direction variable affected the cutting quality of the poplar massif at least.

The quality of the kerf widths also affected the quality of the heat affected zone in the same direction. It did not affect the cutting geometry.

The lower cutting regions of wood species gave better cutting results than the upper cutting regions in terms of both kerf quality and HAZ quality.

AUTHORSHİP CONTRİBUTİONS

C. A.: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

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