

COMPARING THE EFFECTS OF ANATOMICAL STRUCTURAL DIFFERENCES IN DIFFERENT WOOD SPECIES ON THE INDUSTRIAL PROCESSING CAPABILITIES OF COMPUTER CONTROLLED LASERS



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ABSTRACT

This study aims to compare the effects of anatomical structural differences in different tree species on the industrial processing capabilities of CNC lasers. For this purpose, solid wood materials were laser-cut at a speed of 10 mm/s and laser-engraved at a feed rate of 200 mm/s using a 130-watt carbon dioxide-filled glass tube CNC laser machine. The effects of the anatomical structures of six different solid wood materials (heartwood, sapwood, early wood, and late wood) on laser cutting and laser engraving were investigated. The macroscopic anatomical structure of the wood was examined in terms of ease of direct application in production. As a result, for all six different solid wood materials, it was found that early wood sections were easier to process than late wood sections in both laser cutting and laser engraving. The differences in laser processing performance between early and late wood were found to be statistically significant. The positive or negative effects of heart, sapwood, and heartwood anatomical sections on both laser cutting and laser engraving were not found to be statistically significant for all tree species. However, these effects were evaluated proportionally among all tree species. Overall, the heartwood and sapwood of solid wood species showed approximately the same laser cutting performance, with heart exhibiting lower laser cutting performance. On the other hand, the sapwood of solid wood species generally showed better laser engraving performance than both heart and heartwood, while heart and heartwood showed approximately the same laser engraving performance. Consequently, it was concluded that laser operators would be more accurate to separately evaluate the positive or negative effects of anatomical cross-sections of heartwood and sapwood on both laser cutting and laser engraving for each wood species, based on numerical data.

Keywords: Anatomical differences in wood, CNC laser, industrial production, laser wood processing, laser wood carving.

INTRODUCTION

Woodworking, a traditional craft involving various tools, has long been a valuable material. While handiwork is important, adapting to technology has become inevitable to withstand competition in the market. As a result, computer numerical control (CNC) machine technology has reduced human intervention in production, replacing hand craftsmanship with information processing and technology. This situation has made academic research and development essential for the continued sustainability of the sector (Açık 2022).

Each different wood structural layer yields different results in laser processing even with the same machine and process parameters. Therefore, in laser wood product manufacturing, the most complex parameter

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Received: 09.08.2024 Accepted: 28.07.2026

compared to machine and process parameters is the material parameter. Below are some properties that should be known in laser processing of wood materials.

Density, the laser cutting depth in wood material decreased as the material density increased. This can be explained by the fact that the denser the material, the greater the amount of material occupying the same volume. Therefore, more energy is needed to remove a large amount of material. Moisture, higher moisture content means the wood contains more water, this results in a slower burning effect, i.e., less burning. On the other hand, lower moisture content means the wood contains less water, and this results in a greater burning effect. Also, in wood with higher moisture content, a large amount of energy provided by the laser beam is consumed to absorb and evaporate the water molecules in the wood. The remaining small amount of energy is then used to cut the wood. In addition, the thermal conductivity of the wood increases with increasing moisture content, resulting in less energy concentration at the beam's point of incidence. Therefore, more power is required to cut wet wood than to cut dry wood. Cutting direction, some of the laser beam energy absorbed by the wood is lost by the transfer of heat to the material. Because the thermal conductivity of wood along the fiber is significantly greater than across the fiber, less conduction loss occurs from a heat source moving in the direction of the fiber than from a heat source moving perpendicular to the fiber. Also, the local density along the fiber is smaller than that perpendicular to the fiber. Therefore, deeper cuts are obtained when cutting along the fiber. Thermal and optical properties: Materials with a polished surface, such as aluminum, have very poor cutability due to their high reflectivity (Alici 2006). While metals can reflect more than 90% of laser energy, losses are relatively small for wood. After energy is absorbed, more losses occur due to heat transfer to the mass. Because wood has a much lower thermal conductivity than metals, very little energy is lost through conduction. However, in wood composites that have been polished by surface treatments or coated with synthetic glossy materials, the gloss may weaken the laser cutting process (Açık 2022). Some anatomical parts of solid material that are important for laser processing are shown below in two dimensions in Figure 1.

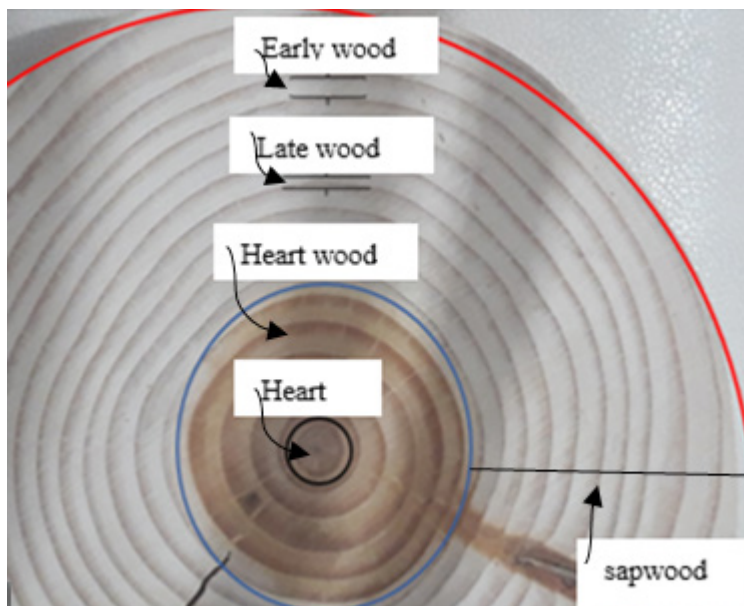


Figure 1: Some anatomical parts of wood material (Açık 2022).

The laser cutting process is more similar to chip cutting in mechanical cutting. However, instead of removing waste chips with their natural structure intact, it removes chips from the cutting notch by vaporizing them through chemical transformation. Because of these similarities, factors such as feed rate, material density, and cutting power in cutting parameters can have the same effect in both cutting processes. However, since energy absorption, thermal conductivity, density, and anatomical heterogeneity in cellular structure are much more influential factors in laser material removal, formulating these effects requires scientific experiments (Açık 2022).

Laser engraving is the principle of continuous laser cutting of the notch width in a cut. A study by Barnekov *et al.* (1986) states that the theory of laser wood cutting consists of a combination of elements such as the ability of laser light to cut wood, light absorption, conversion of light energy into heat, distribution of heat transfer during the process, and evaporation rate in the radiation zone. The same effects that occur in laser cutting also apply to engraving. However, factors such as material heating due to repeated processing alter the ratio of these effects. Therefore, formulating the ratios of these effects again requires scientific experiments.

Laser processing performance has been shown to depend on thermophysical properties, wood density, and energy transfer during material removal, indicating that substrate characteristics strongly influence machining quality (Cherif, 1990; Merchant, 1995; Li *et al.*, 2018; Aık and Tutuř, 2023). However, existing studies have largely focused on machining parameters or individual wood species, providing limited evidence on how macroscopic anatomical regions influence laser cutting and engraving across different species. This limitation justifies the comparative experimental approach adopted in the present study.

On the other hand, in laser engraving, not only cutting but also color changes on the engraved surface come into play. Studies have emphasized the importance of color changes in terms of visual impact. It has also been noted that differences in the chemical structure of wood are significant factors in laser engraving, requiring more precise experimental studies (Katik and Kubovsky, 2011; Teivonen, 2016; Gurau *et al.* 2017; Petru and Lunguleasa, 2017; Kubovsky *et al.* 2020; Guo *et al.* 2021).

In this study, the effects of anatomical structure on laser processing were investigated by comparing three coniferous and three deciduous trees. The goal is to achieve efficient operation and visually appealing results in both laser cutting and especially laser engraving. Similar studies have investigated the effects of structural differences within each tree species on laser wood processing. However, since there is a wide variety of trees in the industry, generating data for each tree has not been sufficient to solve the problem. In this study, the results of anatomical structural differences in numerous different tree species were compared, attempting to create a common platform as much as possible.

MATERIAL AND METHOD

Material

In the study, a total of 6 different tree species, 3 types of deciduous trees and 3 types of coniferous trees were used. From the straight trunks of the trees, 100 cm long logs were obtained from the chest level and were used. The information on the wood types and properties from which the solid wood test pieces used in the study were taken are shown in Table 1 below.

Table 1: Tree types and properties used in the study.

Tree Species	Air Dry Density (kg/m ³)	Moisture (%)	Log diameter (cm)
Beech (<i>Fagus sylvatica</i>)	652	12	25
Fir (<i>Abies cilicica</i>)	601	12	23
Walnut (<i>Juglans nigra</i>)	619	12	28
Cedar (<i>Cedrus libani</i>)	567	12	25
Yellow pine (<i>Pinus sylvestris</i>)	441	12	24
Poplar (<i>Populus canadensis</i>)	393	12	26

CNC laser machine features and fixed processing parameters used in the study are shown in Table 2 below, and its picture is shown in Figure 2. In addition, a digital caliper with 0,1 mm resolution and 0,2 mm measurement accuracy, as well as a digital magnifying glass (5X) were used for cutting and engraving depth measurements. The laser with CO₂ gas, whose radiation is best absorbed by the wood material and which is the most widely used in the wood industry, was preferred.

Table 2: Features of the laser machine used in the study.

Brand	Ayka	Work table	600x900 mm
Nozzle type	Cylindrical flat head	Cooling system	Su
Cutting position	Non-angular, straight	Gas type	CO ₂
Nozzle diameter	1,5 mm	Axis speed	mm/s
Nozzle height	5 mm	Wavelength	10,6 μm
Laser output power	130 Watt	Software	Laserwork V6

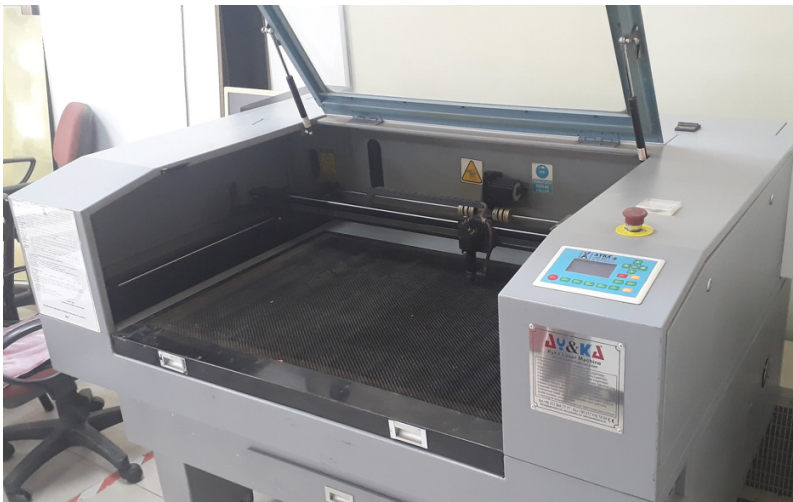


Figure 2: The laser machine used in the study.

Method

The laser cutting effect was investigated by applying 100 % watt power and 10 mm/s speed to the heart, late and early wood in the heartwood region, and late and early wood parts in the sapwood region of solid materials. Heartwood and sapwood cutting depths were determined according to the early and late wood averages of these regions. The test sample was cut perpendicular to the fibers on the radial surface passing through the heart. For the laser cutting of the anatomical structures of solid materials, a solid example of yellow pine (*Pinus sylvestris* L.) is shown in Figure 3 below.

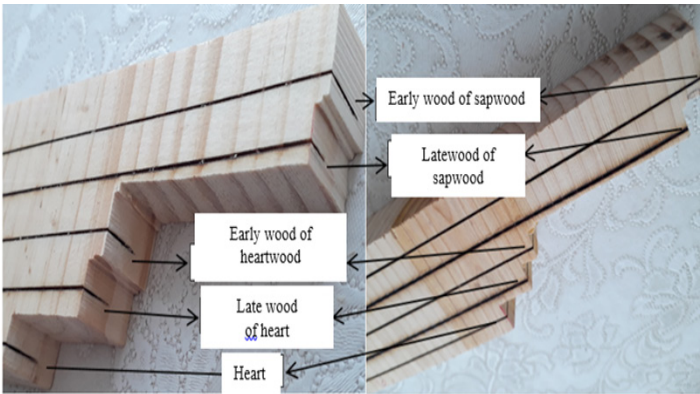


Figure 3: Laser cutting examples of anatomical structures of wood solid materials.

Laser engraving depth was investigated by applying 200 mm/s speed and 100 % watt power to the heart, late and early wood in the heartwood region, and late and early wood parts in the sapwood region of solid materials. The test samples were etched on the radial surface passing through the heart. Digging depths of heartwood and sapwood were decided according to the early and late wood averages of these regions. An example of a yellow pine (*Pinus sylvestris* L.) wood is shown in Figure 4.



Figure 4: Laser engraving examples of anatomical structures of wood solid materials.

Table 3 below shows the number of samples and experimental replicates evaluated for wood test samples, genus, each tree species, and different anatomical regions (heart, heartwood, sapwood, earlywood, and latewood), as well as the number of measurements per sample. Values for heartwood and sapwood were calculated as the average of the latewood and earlywood measurement values for these regions.

Table 3: Number of Experimental Samples and Experimental Data Measurement Procedure

Wood Species		CN	EN	Heart		Heartwood				Sapwood			
						Latewood		Earlywood		Latewood		Earlywood	
				CMN	EMN	CMN	EMN	CMN	EMN	CMN	EMN	CMN	EMN
Sapwood	Beech	3	3	3	3	3	3	3	3	3	3	3	3
	Walnut	3	3	3	3	3	3	3	3	3	3	3	3
	Poplar	3	3	3	3	3	3	3	3	3	3	3	3
softwood	Fir	3	3	3	3	3	3	3	3	3	3	3	3
	Cedar	3	3	3	3	3	3	3	3	3	3	3	3
	Yellow pine	3	3	3	3	3	3	3	3	3	3	3	3

CN: Cutting Sample Number, EN: Engraving Sample Number, CMN: Cutting Measurement Number, EMN: Engraving Measurement Number

RESULTS AND DISCUSSION

Findings of CNC laser cutting process of anatomical structures of wooden

Solid materials obtained from three sapwood and three softwood species have 100 % power and laser cutting depths were investigated by applying a speed of 10 mm/s. Findings regarding the laser cutting depths of the anatomical structures of solid materials are shown in Table 4.

Table 4: Laser cutting depths of anatomical structures of solid materials.

Wood Species		Heart		Heartwood				Sapwood			
				Latewood		Earlywood		Latewood		Earlywood	
		X	SD	X	SD	X	SD	X	SD	X	SD
Sapwood	Beech	3,73	0,60	7,30	0,90	8,56	0,89	8,86	0,66	9,50	0,40
	Walnut	5,76	0,80	6,40	0,70	6,43	0,58	5,40	0,52	5,93	0,75
	Poplar	10,90	1,80	11,90	0,85	11,63	0,32	11,13	2,41	10,96	1,84
softwood	Fir	10,60	1,70	11,50	1,10	11,70	1,20	9,36	0,80	11,30	0,50
	Cedar	8,56	1,70	8,33	1,70	9,20	1,20	7,83	2	9,30	1,30
	Yellow pine	11,33	0,60	8,46	0,50	11,30	0,50	7,30	1	13,30	0,30

SD: Standard deviation.

According to Table 4 above, the laser cutting depth in the heart of wood solid materials was determined as the lowest at 3,73 mm in the beech wood, and the highest at 11,33 mm in the yellow pine (*Pinus sylvestris* L.) wood. In both the heartwood part and the sapwood part (according to the average of early and late wood), laser cutting depth was decided as the lowest in the walnut wood and the highest in the poplar wood. These results suggest that the expectation that a value for an anatomical structure in one tree species should be high or low in other anatomical regions across different tree species may be incorrect.

Laser cutting depths of heart, late wood of heartwood (HLW), early wood of heartwood (HEW), late wood of sapwood (SLW) and early wood of sapwood (SEW) laser cutting depths of each solid material are given in Figure 5.

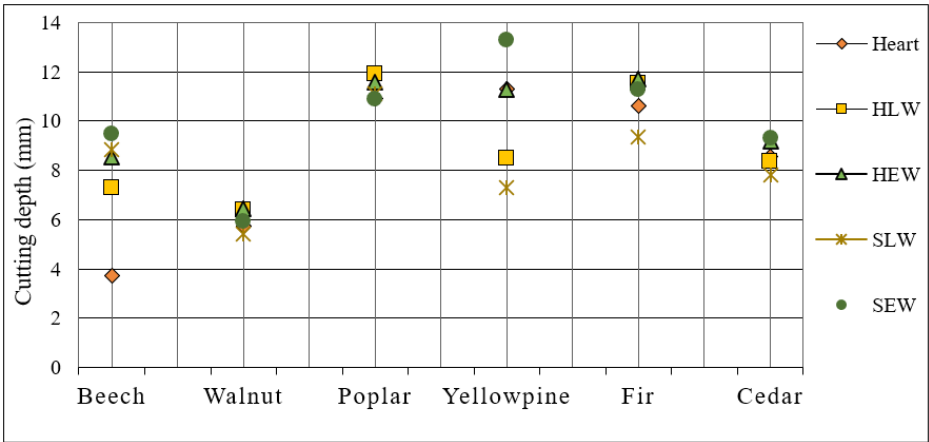


Figure 5: Laser cutting depths of anatomical structures of solid materials.

In Figure 5 in laser cutting of wood materials, it is seen that the laser cutting capabilities of all anatomical parts of walnut, poplar and cedar species are close to each other and that there are wood types that show stable behavior in laser cutting. The heart of the beech massive material differed considerably from other regions. Due to this variable feature, special attention should be paid to the heart of the beech wood in laser cutting applications. It was determined that the difference between the cutting depth of the early and late wood parts in the yellow pine (*Pinus sylvestris* L.) solid material was 25 % in the heartwood and 45 % in the sapwood. Because the values are quite different from each other, it can be said that the yellow pine (*Pinus sylvestris* L.) wood is the one that exhibits the most unstable behavior in the laser-cutting process among the wooden used in the experiment. This is because it is evaluated as the very high rate of earlywood tracheids.

Multivariate linear regression analysis was performed to determine the effect of wood type, anatomical region (heartwood, sapwood), and annual ring variables on laser cutting, depending on the anatomical structure of solid materials. Since the effect of the anatomical region variable on the cutting depth was statistically insignificant ($p=0,681$), it was not included in the analysis. Analysis results of tree species and annual ring variables are shown in Table 5 below.

Table 5: Regression analysis results of anatomical structures of solid materials.

Variables	Beta(β)	*Beta(β)	Partial Correlation (pr)	Significance
Control constant	5,857	-	-	0,000
Wood Type	0,434	0,319	0,331	0,005
Annual ring	1,283	0,276	0,276	0,014

* It is standardized.

According to the analysis results in Table 5 above, the tree species positively and significantly affected the cutting depth with an effect size of 11 % ($pr^2=0,109$), while the annual ring variable affected the cutting depth positively and significantly with an effect size of 8 % ($pr^2=0,084$). It was found that the regression analysis model was 95 % reliable ($p<0,05$), and 15 % ($R^2_{adjusted}=0,154$) of the variation in cutting depth was explained by the independent variables.

Since the data did not meet the normal distribution assumptions in descriptive statistics, nonparametric testing was performed in laser cutting related to the anatomical structure of solid materials. The Kruskal-Wallis test was used for tree species group differences in order to determine the groups that made a difference and that did not. The Mann-Whitney U test was performed as there were only two groups in the annual ring variable. Group comparisons are given in Table 6 below.

Table 6: Groups of laser cutting of anatomical structures of solid materials.

Variables	Paired Groups	Group Mean Differences	Adjusted Significance	N	Groups	Homogeneity groups
Wood Type	Walnut-Beech	17,900	0,908	15	Walnut	a
	Walnut-Cedar	-26,033	0,095	15	Beech	ab
	Walnut- Yellow pine	-45,100	0	15	Poplar	d
	Walnut-Fir	-52,100	0	15	Fir	cd
	Walnut-Poplar	-56,267	0	15	Cedar	abc
	Beech-Cedar	-8,133	1	15	Yellow pine	bcd
	Beech- Yellow pine	-27,200	0,065			
	Beech-Fir	-34,200	0,005			
	Beech-Poplar	-38,367	0,001			
	Cedar- Yellow pine	-19,067	0,684			
	Cedar- Fir	26,067	0,094			
	Cedar-Poplar	30,233	0,023			
	Yellow pine -Fir	7	1			
	Yellow pine -Poplar	11,167	1			
	Fir-Poplar	4,167	1			
Annual ring	Early-Late Wood	11,66	0,018	36	Earlywood	a
				36	Latewood	b

As a result of the Kruskal-Wallis test, according to the data in the group mean differences in Table 6 above, a statistically significant difference was obtained between the poplar and walnut, beech and cedar tree species groups, between the walnut and yellow pine (*Pinus sylvestris* L.) and fir groups, and also between the beech and fir groups has been done. No significant difference was found between other tree species groups. In addition, as a result of the Mann-Whitney U test, a statistically significant difference was obtained between the early wood and late wood groups. The tree species in Figure 6a and the significant relationships of the early and late wood variables in Figure 6b with the group averages are given below. Yellow pine and cedar showed the least difference from other groups in terms of anatomical structure among the tree species variable groups, in terms of homogeneity.

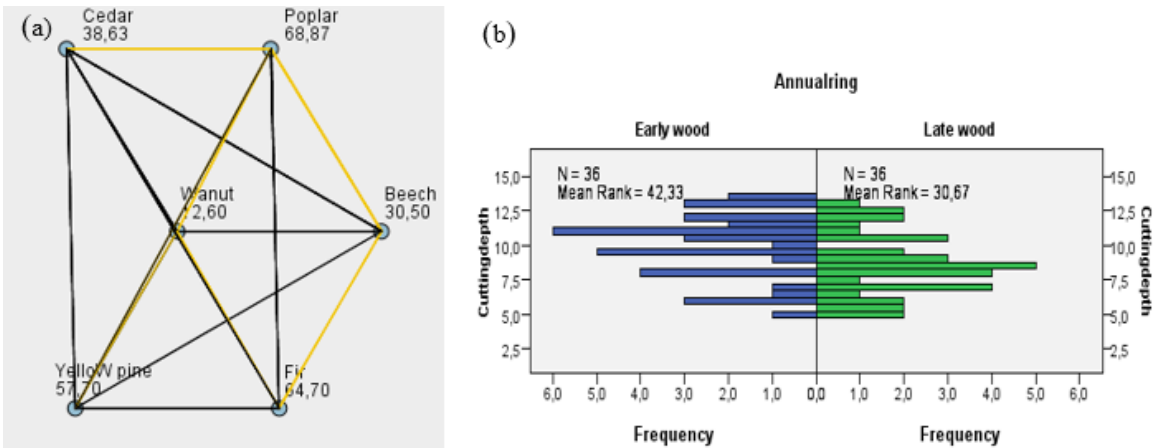


Figure 6: Group relations of laser cutting according to the anatomical structure (a) wood type, (b) annual ring.

Findings of CNC laser engraving of anatomical structures of wooden

Solid materials obtained from three sapwood and three softwood species are divided into heartwood, sapwood, late wood, and early wood parts, 100 watts power and 200 mm/s laser engraving capabilities were investigated. Findings regarding the laser engraving depths of the anatomical structures of solid materials are shown in Table 7 below.

Table 7: Laser engraving depths of anatomical structures of solid materials.

Wood Species		Heart		Heartwood				Sapwood			
				Latewood		Earlywood		Late wood		Earlywood	
		X	SD	X	SD	X	SD	X	SD	X	SD
Sapwood	Beech	1,30	0,17	1,30	0,17	1,40	0,17	1,20	0,20	1,30	0,20
	Walnut	1,56	0,15	1,10	0,10	1,20	0,36	1,30	0,46	1,46	0,10
	Poplar	1,96	0,28	2	0,26	2,73	0,25	1,63	0,28	2,80	0,20
Coniferous wood	Fir	1,46	0,15	1	0	1,93	0,20	1,10	0,10	2,13	0,15
	Cedar	1,53	0,20	1,03	0,25	1,73	0,05	1,13	0,23	2,33	0,15
	Yellow pine	2,06	0,30	1	0,20	2,76	0,40	1,03	0,20	2,96	0,25

SD: Standard deviation.

According to Table 6 above, the laser engraving depth in the heart of wood solid materials was found to be the lowest at 1,30 mm in the beech wood and the highest at 2,06 mm in the yellow pine (*Pinus sylvestris* L.) wood. The laser engraving depth was the lowest in the walnut wood and the highest in the poplar wood, both in the heartwood part and the sapwood part (according to the average of early and late wood) of solid materials.

Laser engraving depths of the anatomical structures of wood materials for each heartwood, late wood of heartwood (HLW), early wood of heartwood (HEW), late wood of sapwood (SLW) and early wood of sapwood (SEW), laser engraving depths are shown below in Figure 7.

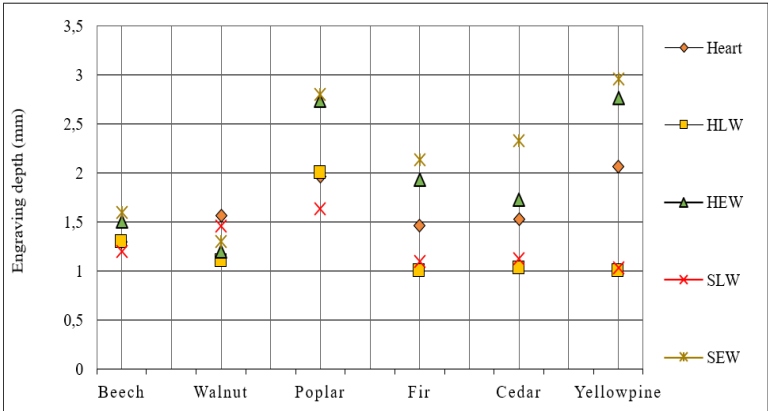


Figure 7: Laser engraving depths of the anatomical structures of the materials.

According to Figure 7, even though the scraping depth of the heart part of the walnut wood material is higher than the other parts, it was decided that the variation differences were in the range of 0,5 mm in all scraped floors. Especially in the heartwood region, approximately 10 % digging depth differences were detected between the early and late wooden. In general, it can be said that it has a scraping ground that can be considered layerless.

Multivariate linear regression analysis was performed to determine the effect of tree type, anatomical region (heartwood, sapwood), and annual ring structure variables on laser engraving depth in laser engraving of solid materials depending on the anatomical structure. Since the effect of the anatomical region variable on the scraping depth was statistically insignificant ($p=0,540$), it was not included in the analysis. Analysis results of tree species and annual ring variables are shown in Table 8 below.

Table 8: Regression analysis results of laser engraving depth of solid materials.

Variables	Beta(β)	*Beta(β)	Partial Correlation (pr)	Significance
Control constant	0,039	-	-	0,865
Wood Type	0,107	0,273	0,343	0,003
Annual ring	0,811	0,605	0,629	0

* It is standardized.

According to the analysis results in Table 8 above, the tree species variable positively and significantly affected the incising depth with an effect size of 12 % ($pr^2=0,117$) and the annual ring variable with an effect size of 40 % ($pr^2=0,395$). It was found that the regression analysis model was reliable at the 95 % level ($p<0,05$), and 43 % ($R^2_{adjusted}=0,425$) of the variation in the engraving depth was explained by the independent variables.

In laser engraving of the anatomical structure of solid materials, nonparametric testing was performed because the data did not meet the normal distribution assumptions in descriptive statistics. There was no significant difference between the groups belonging to the anatomical region (heart, heartwood, sapwood) ($p=0,458$) variable. Kruskal-Wallis test was performed for group differences in tree species where significant differences occurred. The Mann-Whitney U test was performed as the annual ring variable was only two

groups. Group comparisons are given in Table 9 below.

Table 9: Laser engraving group comparisons of the anatomical structures of solid materials.

Variables	Paired Groups	Group Mean Differences	Adjusted Significance	N	Groups	Homogeneity groups
Wood Type	Walnut-Beech	17,900	0,908	15	Walnut	a
	Walnut- Cedar	-26,033	0,095	15	Beech	ab
	Walnut-Yellow Pine	-45,100	0	15	Poplar	d
	Walnut-Fir	-52,100	0	15	fir	cd
	Walnut-Poplar	-56,267	0	15	Cedar	abc
	Beech- Cedar	-8,133	1	15	Yellow pine	bcd
	Beech- Yellow Pine	-27,200	0,065			
	Beech-Fir	-34,200	0,005			
	Beech-Poplar	-38,667	0,001			
	Cedar- Yellow Pine	-19,067	0,684			
	Cedar-Fir	-26,067	0,094			
	Cedar-Poplar	30,233	0,023			
	Yellow Pine-Fir	7,000	1			
	Yellow Pine-Poplar	11,167	1			
	Fir-Poplar	4,167	1			
Annual Ring	Early-Late wood	25,76	0	36	Earlywood	a
				36	Latewood	b

As a result of the Kruskal-Wallis test, according to the data in the group mean differences in Table 9 above, cedar and yellow pine (*Pinus sylvestris* L.) did not make a statistical difference with other tree groups. A significant difference was found between poplar and walnut, fir, and beech. In addition, as a result of the Mann-Whitney U test, a statistically significant difference was obtained between the early wood and late wood groups. The tree species in Figure 8a and the annual ring variables in Figure 8b together with the group means are given below. Among the tree species variable groups, yellow pine (*Pinus sylvestris* L.) and cedar trees showed the least difference in terms of anatomical structure.

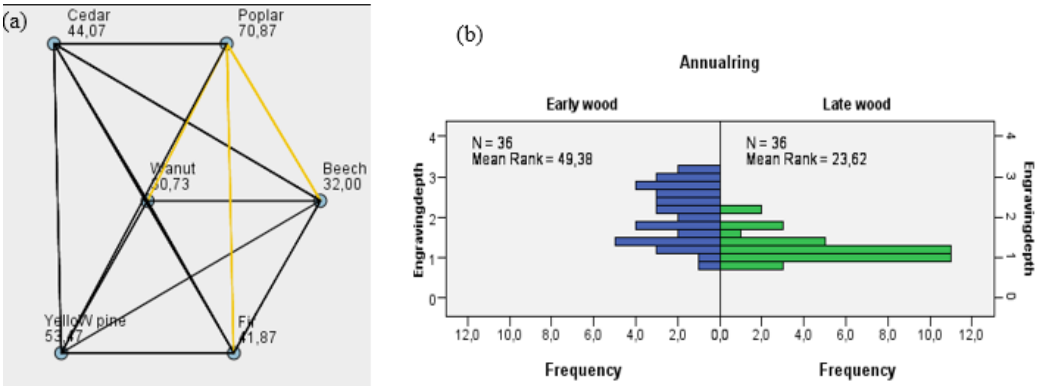


Figure 8: Group relations of laser engraving according to the anatomical structure (a) wood type, (b) annual ring.

Below is a radial section of walnut trees in Figure 9a, beech trees in Figure 9b, poplar trees in Figure 9c, fir trees in Figure 9d, cedar trees in Figure 9e and Scots pine trees in Figure 9f surface is displayed. When the laser scanning image of the walnut wood is evaluated macroscopically, it is seen that the heart part and sapwood part have a more layered scraping ground than the heartwood part. It has been observed that the color of the incised background is gradually darker from the core to the shell. The summer wooden have formed a color tone in the form of dark broad stripes, albeit slightly.

The difference in cutting depth of spring and summer wooden in the sapwood region of beech solid material is more pronounced than in the heartwood region. However, it can be said that it has a flat scraping ground in general since the difference in the depth of scraping for spring and summer wooden is about 8 %. When the laser scanning image of the beech wood is evaluated macroscopically, it is seen that the heart and heartwood parts have a flatter scraping ground than the sapwood part. It has been observed that the color of the incised background is gradually getting lighter from the core to the shell. The summer wood parts formed an image in thin and clear lines.

It has been determined that the laser engraving depths of the spring and summer wood parts of the poplar solid material differ up to 35 % in both the heartwood and sapwood regions. For this reason, it can be said that the poplar wood has the least flat scraping ground in laser engraving among the sapwood wooden used in the experiment. When the laser scanning image of the poplar wood was evaluated macroscopically, it was observed that the color darkened in the core, and the sapwood and heartwood parts had approximately the same color tone. It is seen that the summer wood forms prominent protrusions and lighter-colored lines on all the incised floors.

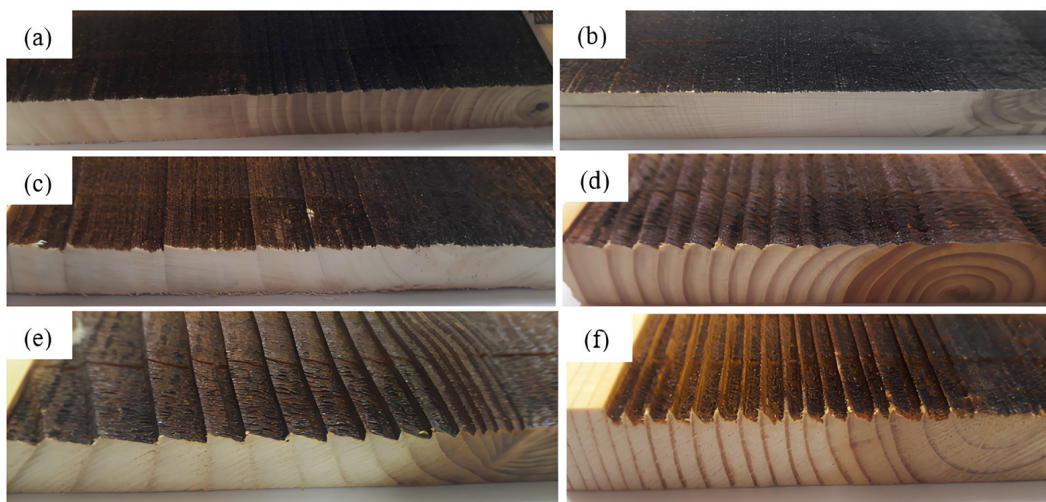


Figure 9: Laser engraving images of (a) walnut, (b) beech, (c) poplar, (d) fir, (e) cedar, (f) yellow pine solid materials.

It has been decided that the cutting depth of the core of the fir solid material is close to the averages of the spring and summer wooden in the heartwood and summer wood. It has been determined that the laser engraving depth of the sapwood region is approximately 10 % higher than that of the heartwood region. It was decided that while there were about 80 % differences in cutting depth between the spring and summer wooden in the heartwood region, this ratio reached 100 % in the sapwood region. When the laser scanning image of the fir wood is evaluated macroscopically, it has a sawtooth-like indentation in the cross-section and a corrugated appearance in the radial section. Contrary to the leafy tree species, it was observed that the color of the incised ground gradually became darker from the core to the bark. Spring and summer wooden have created a color tone with light-dark thick lines in an orderly and aesthetic way.

The cutting depth of the core of the cedar solid material was found close to the average of the heartwood and sapwood regions. The laser engraving depth of the sapwood region was found to be approximately 20 % greater than that of the heartwood region. It was determined that while there were approximately 70 % digging depth differences between the spring and summer wooden in the heartwood region, this ratio reached 100 % in the sapwood region. When the laser scanning image of the cedar massive is evaluated macroscopically, it has

a sawtooth-like indentation in the cross-section and a corrugated appearance in the radial section. Contrary to the leafy tree species, it was observed that the color of the incised ground gradually became darker from the core to the bark. In this respect, it resembles the fir wood. Spring and summer wooden have created a color tone with light-dark thick lines in an orderly and aesthetic way.

It has been determined that the cutting depth of the core of the yellow pine (*Pinus sylvestris* L.) solid material is close to the average of the heartwood and sapwood regions. It has been determined that the laser engraving depth of the sapwood region is approximately 5 % higher than the heartwood region. While the scraping depth difference between spring and summer wooden was about 270 % in the heartwood region, this difference increased up to 300 % in the sapwood region. With this structure, it can be said that among the softwood wooden used in the experiment, the yellow pine (*Pinus sylvestris* L.) wood is the most disadvantageous material in laser engraving due to its indented appearances like sawtooth in cross section and corrugated appearance in radial section. When the laser scanning image of the yellow pine (*Pinus sylvestris* L.) wood is evaluated macroscopically, it has a sawtooth-like indentation in the cross-section and a corrugated appearance in the radial section. It has been observed that the color of the scraping ground is dark in the core, light in the heartwood, and slightly darkening again towards the bark. Spring and summer wooden have created a color tone with light-dark thick lines in an orderly and aesthetic way.

CONCLUSIONS

This study addresses a previously limited knowledge area by presenting comparative experimental evidence that macroscopic anatomical regions significantly influence CNC laser machining performance in different wood species. While studies have previously examined the laser machining performance of different anatomical regions of any given wood species, they have not established a common platform for understanding how these results would affect other wood species. To develop a solution to this problem, the laser cutting and engraving characteristics of anatomical regions of heart, heartwood, sapwood, late wood, and early wood were investigated by applying 100 watts of power to solid wood materials such as beech, fir, walnut, cedar, Scots pine (*Pinus sylvestris* L.), and poplar at a speed of 10 mm/s and 200 mm/s respectively.

The results showed that the heartwood and sapwood portions of solid wood species generally exhibited the same laser cutting performance, while the heart showed lower laser cutting performance. Furthermore, early wood portions showed approximately 15% better laser cutting performance compared to late wood portions. The differences in laser cutting values for different anatomical regions were less pronounced in walnut, poplar, and cedar, while they were more pronounced in fir, Scots pine (*Pinus sylvestris* L.), and beech.

Overall, the sapwood of solid wood species exhibited deeper laser engraving performance compared to heart and heartwood. Both heartwood and heart showed approximately the same engraving depth. Additionally, early wood sections showed approximately 38% better laser engraving depth performance compared to late wood sections. Laser engraving depths in different anatomical regions were less effective in walnut and beech, while more effective in fir, Scots pine (*Pinus sylvestris* L.), cedar, and poplar.

In the analysis conducted to determine the effect of wood species, anatomical region (heart, heartwood, sapwood), and annual ring variables on laser cutting and engraving depth, statistically significant results were obtained in wood species and annual ring variables depending on the anatomical structure of solid materials.

Since deciduous wood exhibits more stable behavior in laser processing due to its lower late wood ratio compared to softwood, sapwood should be used in wood product designs where homogeneous output is important. This study demonstrates that the variation in laser processing capability value for an anatomical structure in one tree species compared to other anatomical regions does not necessarily mean that the same trend will be observed in different tree species. In this study, the results of anatomical structural differences in numerous different tree species were compared, attempting to create a common platform as much as possible.

Authorship Contributions

C. A.: Conceptualization, methodology, software, data curation, writing-original draft preparation, investigation, writing-reviewing and editing. A. T.: Software, validation, visualization, supervision.

Acknowledgments

This study was supported by the Kahramanmaraş Sütçü İmam University Scientific Research Fund as part of the doctoral thesis entitled “Investigation and Application of CNC Laser Manufacturing Parameters in Industrial Wood Product Design”. Projects (Project No: 2019/5-10D).

Conflict Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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