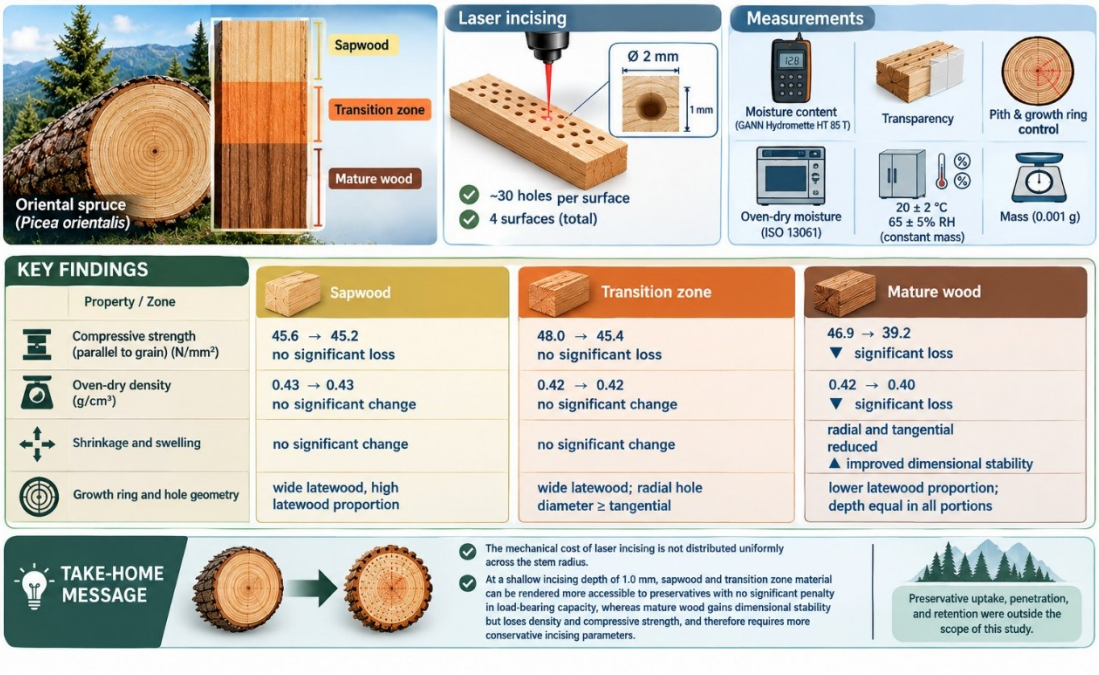
Effects of Laser Incising on Compressive Strength and Physical Properties of Sapwood, Transition Zone, and Mature Wood of Oriental Spruce (*Picea orientalis*)

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GRAPHICAL ABSTRACT



Effects of Laser Incising on Compressive Strength and Physical Properties of Sapwood, Transition Zone, and Mature Wood of Oriental Spruce (*Picea orientalis*)

Davut Bakır ,* and Abdullah Aydın

Oriental spruce (*Picea orientalis* (L.) Peterm.), a refractory species of low natural durability, requires adequate impregnation to attain a longer service life in high-risk end uses (use classes 3 and 4). Improving the permeability of such species through laser-incising pretreatment is therefore important, provided that the physical and mechanical properties of the different wood portions (sapwood, transition zone, and mature wood) are not adversely affected. In this study, the weight loss, density, moisture content, shrinkage and swelling, and compressive strength parallel to the grain of these wood portions were evaluated after laser incising. The depth and diameter of the incised holes and the growth-ring characteristics were also examined. The sapwood and transition-zone samples had greater latewood layer width and higher latewood proportion than the mature wood. Laser incising reduced radial and tangential shrinkage and swelling in mature wood. Compressive strength parallel to the grain of the mature wood was lower in the laser-incised samples than in the controls. In the transition zone, the radial hole diameter was higher than the tangential diameter.

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Keywords: Laser incising; Oriental spruce; Different wood portions; Physical properties; Compressive strength parallel to the grain

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INTRODUCTION

The high permeability of wood from different tree species and different wood regions within the same species (sapwood, transition zone, heartwood or mature wood, and juvenile wood) is of considerable importance for achieving effective penetration of preservative solutions into the wood structure. This guarantees an even distribution of treatment chemicals, achieving optimal retention levels. In this article, the term heartwood is used for the inner region of the stem where it is clearly differentiated from the sapwood, typically by a distinct colour change, whereas in species such as spruce and fir, in which no such colour boundary is formed, the corresponding inner region is referred to as mature wood; juvenile wood, by contrast, denotes the wood laid down during the first years of cambial activity around the pith and may therefore lie within either region. Although sapwood from many tree species can be successfully impregnated, the preservative treatment of heartwood using conventional impregnation methods is considerably more difficult due to several anatomical and chemical barriers. However, the mechanisms responsible for this low permeability differ between softwoods and hardwoods. In softwoods, the reduced treatability of heartwood is primarily attributed to pit aspiration and to the thickening and closure of pit membranes caused by incrustation with compounds such as lignans, whereas in hardwoods it is

more commonly associated with the occlusion of vessels by tyloses and with the deposition of extractives and other occluding substances (Wang and DeGroot 1996; Matsumura *et al*. 1999; Messner *et al.* 2003; Panigrahi *et al.* 2018; Thybring *et al.* 2022).

Oriental spruce, one of the native tree species of Türkiye, is classified as a low-durability species and as a refractory-to-treatment wood species with respect to permeability. Not only its mature wood but also its sapwood, which would generally be expected to exhibit higher permeability, is difficult to impregnate (Bakır *et al*. 2022). Therefore, improving the permeability of refractory wood species is of substantial importance for the forestry sector. One of the approaches employed in the forest products industry to enhance the permeability of both refractory wood species and their heartwood portions is the application of various pretreatments. During impregnation processes, some pretreatments improve internal fluid flow in low-permeability wood (Nath *et al*. 2020a,b; Bakır 2022a). To achieve the minimum retention and penetration requirements in refractory wood species, various incising pretreatments are recommended prior to preservative treatment (Islam *et al*. 2007).

Previous studies on laser incising have primarily focused on increasing wood permeability (Ruddick 1991; Voulgaridis *et al*. 2014; Bakır 2022a, 2023; Winandy *et al*. 2022), the effects of laser irradiation on wood anatomical characteristics (Wang *et al*. 2013; Nath *et al*. 2020a, 2022; Bakır 2023), the influence of laser incising on the strength properties of wood (Suzuki *et al*. 1996; Morrell *et al*. 1998; Kortsalioudakis *et al*. 2015; Sharapov *et al*. 2019; Arulvel *et al*. 2023), enhancement of wood drying rates through laser-incising pretreatment (Simpson 1987), the effects of laser processing parameters on wood properties (Nath *et al*. 2022), the impact of laser incising on durability and leaching resistance (Bakır 2026), and the chemical characterization of wood tissues affected by laser-induced thermal modification (Barcikowski *et al*. 2006; Wang *et al*. 2013; Kúdela *et al*. 2023).

In a previous study investigating the effects of different pretreatment methods (mechanical incising, laser incising, and biological incising) on the physical and mechanical properties of refractory Oriental spruce and European larch (*Larix decidua* Mill.) sapwood specimens (Bakır 2022b), the effects of these pretreatments on density, mass loss, dimensional stability, and compressive strength parallel to the grain were found to vary depending on the wood species. For example, while laser and biological incising significantly reduced the compressive strength parallel to the grain of Oriental spruce and European larch sapwood specimens, mechanical incising did not cause any significant reduction in strength. These findings suggest that mechanical pretreatment should be prioritized for refractory wood species intended for applications in which strength properties are of critical importance. Furthermore, laser incising, which produced favorable improvements in dimensional stability, appears to be a more suitable pretreatment for wood products intended for applications where dimensional stability is a primary concern. The study also demonstrated that laser incising caused greater mass loss in European larch sapwood than in Oriental spruce sapwood and was more effective in reducing wood density in European larch than in Oriental spruce (Bakır 2022b). The findings of such previous studies, which were conducted exclusively on sapwood specimens, indicate that pretreatments applied to different tree species or different wood regions within the same species may exert varying effects on the physical and mechanical properties of the resulting wood materials. This observation constitutes the primary motivation and focus of the present study.

Although numerous recent studies have investigated micro-scale technological approaches (*e.g.*, mechanical incising, laser incising, microwave treatment) and

biotechnological approaches (*e.g.*, bacteria, enzymes, wood-decaying fungi, and sap-stain fungi) for enhancing wood permeability, and despite the substantial body of literature devoted to improving the treatability of refractory wood species, no study has been identified that specifically examines the effects of laser incising on the physical and mechanical properties of different wood regions of spruce. Therefore, the present study aimed to evaluate the effectiveness of laser incising in improving the dimensional stability and compressive strength parallel to the grain of sapwood, transition zone, and mature wood of Oriental spruce. In addition, growth-ring characteristics of these wood regions and the relationships between wood type and the depth and diameter of laser-drilled cavities formed on radial and tangential surfaces were comparatively investigated. All experimental findings were analyzed and discussed in a comparative framework to provide a comprehensive assessment of the response of different wood regions to laser incising.

EXPERIMENTAL

Test Materials

Defect-free wood specimens representing different wood portions of Oriental spruce, namely sapwood, transition zone, and mature wood, were used in this study. The specimens were obtained from a single Oriental spruce tree (*Picea orientalis* (L.) Peterm.) growing in Artvin Province, located in the Eastern Black Sea Region of Türkiye. The tree was approximately 122 ± 5 years old and had a diameter at breast height (DBH) of 40 cm.

The tree was felled using a chainsaw, leaving approximately 30 cm of the stem base embedded in the soil. The north-south orientation of the tree was marked prior to felling. Breast height was not assumed as a nominal value; prior to felling, a height of 1.30 m was measured on the standing tree from ground level on the uphill side using a steel measuring tape, and the sampling position was marked on the stem. A single 5-cm-thick disc was then removed from this marked breast-height position and was used only to determine the age of the tree and its growth-ring characteristics, and to identify the boundaries of the sapwood, transition zone, and mature wood regions. The test specimens themselves were not cut from this disc; they were prepared from radial strips obtained from the sapwood, transition zone, and mature wood regions of a single log taken from the same Oriental spruce tree. Radial strips containing the pith were cut from this disc along the north-south axis. The surfaces of the strips were sanded to obtain smooth measurement planes, and growth-ring widths were measured in both the northern and southern directions with a precision of 0.01 mm using an Eklund-Brinell microscope. The widths of both earlywood and latewood layers were determined from the bark toward the pith. Subsequently, the procedures described below were carried out to identify the sapwood, transition zone, and mature wood regions within the stem of Oriental spruce.

Identification of Juvenile Wood, Mature Wood, Transition Zone, and Sapwood

The transition from juvenile wood formation to mature wood generally occurs between ages 5- and 20-years (Wolcott *et al*. 1987; Wang and Stewart 2012). Based on this information, growth rings were counted from the pith outward using an Eklund-Brinell microscope. Specimens corresponding to the first 20 growth rings, representing juvenile wood, were excluded from the study because juvenile wood does not fully

exhibit the characteristic properties of the species and generally possesses inferior quality characteristics (Bakır 2019).

The distinction between sapwood, transition zone, and mature wood was performed using a moisture meter (GANN Hydromette HT 85 T), which enables moisture measurements at predetermined intervals on the transverse surface of the wood. Measurements were taken on the freshly cut transverse surface of the log, starting from the outermost region adjacent to the bark and proceeding inward to the pith at intervals of approximately 40 to 50 mm along the radius. No fixed absolute moisture threshold was adopted; the boundaries were instead located from the shape of the resulting radial moisture profile. The outer region adjacent to the bark gave the highest readings and was assigned to sapwood; the readings then decreased moderately over an intermediate band, which was assigned to the transition zone, and they fell markedly in the inner region, which was assigned to mature wood. Because these resistance-type readings were used only as a relative indicator for locating the boundaries between the wood portions, and not as absolute moisture values, the reduced accuracy of resistance-type measurements on transverse surfaces did not affect the data reported in this study; all moisture contents given in the Results were determined gravimetrically by the oven-dry method. Measurement on the transverse surface was necessary because the objective was to map the moisture gradient along the radius, which cannot be obtained from a radial or tangential face. The electrodes were driven to a constant depth at every measuring position, and identical species and temperature corrections were applied throughout. In addition, thin sections cut from this disc were examined against transmitted light, and the differences in transparency were used to distinguish sapwood, transition zone, and mature wood regions (Fig. 3), following the method described by Sandberg (2009) and Bakır (2019).

Wood specimens utilized in the present study were subsequently prepared from the identified sapwood, transition zone, and mature wood regions (Fig. 3). All specimens were cut to dimensions of 100 mm × 25 mm × 25 mm (length × width × thickness). A total of 54 specimens were used, comprising 18 sapwood specimens, 18 transition-zone specimens, and 18 mature-wood specimens. In the radial direction, the transition zone was defined as the band lying immediately inward of the sapwood and immediately outward of the mature wood; it therefore corresponds to the intermediate band across which both the moisture readings and the translucency of the disc changed progressively from sapwood values to mature wood values, rather than to a sharp boundary line (Fig. 3). Counted from the pith, growth rings 1 to 20 were classified as juvenile wood and excluded from the study, rings 21 to 63 were assigned to mature wood, rings 64 to 77 to the transition zone, and rings 78 to 122 to sapwood. The transition zone was thus appreciably narrower than the two adjacent regions, comprising 14 growth rings compared with 43 rings for mature wood and 45 rings for sapwood. This is also reflected in the sampling: The sapwood and mature wood regions were each wide enough to yield two radial strips of 25 mm × 25 mm, whereas only a single strip could be obtained from the transition zone (Fig. 3b). All transition-zone specimens were consequently taken from this single band and from corresponding growth-ring positions along the stem, so that they represent the full radial width of the zone rather than a selected part of it. All specimens were sawn with consideration of the radial and tangential anatomical directions.

Laser Incising Pretreatment

Laser incisions were produced on all four longitudinal surfaces of each Oriental spruce specimen derived from different wood portions, that is, on both radial surfaces

and both tangential surfaces (four incised faces per specimen); the two transverse (cross-sectional) end surfaces were not incised. The incisions were produced using a CO_2 laser system (VLS6.60, Universal Laser Systems, Scottsdale, AZ, USA). Throughout this article, the terms "drilling" and "laser incising" refer exclusively to the non-contact removal of wood material by the focused laser beam: the beam heats the wood locally to the point of pyrolysis and vaporisation, and the resulting ablation of the wood substance leaves an open hole of defined diameter and depth in the surface. No mechanical drill bit, needle, or other cutting tool was used at any stage of the treatment, and the hole geometry is therefore governed by the beam and process parameters rather than by the dimensions of a tool. The laser incising was conducted at a power output of 60 W, a speed setting of 4.0, and a focal distance of 30 mm. The same incision pattern was applied to all specimens, as illustrated in Fig. 1b.

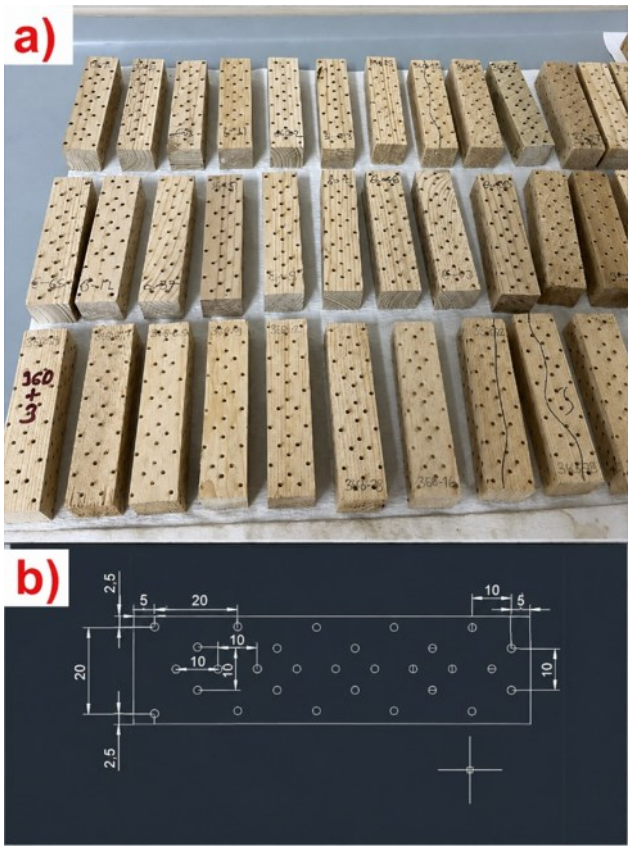


Fig. 1. Laser-incised wood specimens (a), and schematic representation of the spacing between incisions produced in the lateral and longitudinal directions according to the laser-incising pattern (b). The same pattern was applied to all four longitudinal surfaces of each specimen, that is, to both radial and both tangential surfaces; the transverse end surfaces were not incised.

The incision density was established at 10.000 incisions/m² for the laser-incising process (Fig. 1b). All incisions were produced with a depth of 1.0 mm and a diameter of 2.5 mm (Fig. 1a), following the methodology reported by Islam *et al.* (2008). This depth was selected deliberately rather than being limited by the capability of the equipment. Laser incising is a surface pretreatment intended to create a network of discrete openings that increases the accessibility of the outer wood tissue to fluids, and not a perforation of the cross-section, so that the intended effect is generated in the region immediately beneath the treated surface. Because the incisions were applied to

all four longitudinal surfaces of each 25 mm cube, the treated zone extends inward from every lateral face, and the proportion of the specimen affected by the treatment is therefore considerably greater than the nominal depth on a single face would suggest. The choice was further guided by earlier experimental evidence obtained on the same species. In a previous study in which laser incisions were produced to a depth of 10 mm in Caucasian spruce and European larch specimens, the compressive strength parallel to the grain was reduced significantly, and the reduction was attributed to the removal of load-bearing material and to the thermal damage extending deep into the cross-section (Bakır 2022b). Because the present study was designed to isolate the response of the three wood portions to an identical laser treatment, a depth that would itself dominate the strength response was avoided; at 1.0 mm the ablated volume remains small, as confirmed by the measured weight-loss values, and the mechanical integrity of the specimens is preserved. Restricting the depth to 1.0 mm additionally ensured that an identical setting could be reproduced in all three wood portions; the penetration depths measured stereomicroscopically did not differ significantly among sapwood, transition zone, and mature wood (Table 3), confirming that the comparison among portions was made under equivalent geometrical conditions. The laser incising was carried out on specimens in the air-dry condition. Prior to treatment, all specimens, irrespective of wood portion, were conditioned at 20 ± 2 °C and 65 ± 5% relative humidity until constant mass was attained, so that each specimen had reached moisture equilibrium with the same surrounding environment before being incised; the corresponding moisture contents are reported in Table 2. Any remaining difference in moisture content between the wood portions in this equilibrium state reflects a genuine difference in the hygroscopic behavior of sapwood, transition zone, and mature wood rather than a difference in specimen preparation, and it is discussed as such in the Results and Discussion section.

Weight loss was determined gravimetrically. The specimens were dried in an oven at 60 °C for three days until constant mass was reached and were then weighed to the nearest 0.01 g to establish the reference mass prior to laser incising. After this reference weighing, the specimens were reconditioned at 20 ± 2 °C and 65 ± 5% relative humidity until they had regained the air-dry state and constant mass was again attained, and the laser incising was performed only after this equilibrium had been reached. The oven-drying step therefore served solely to provide a moisture-free reference mass for the gravimetric calculation and did not represent the condition of the specimens at the time of treatment. Following laser incising, the identical drying and weighing procedure was repeated to obtain the corresponding reference mass after treatment. A drying temperature of 60 °C was selected in preference to the conventional 103 ± 2 °C in order to avoid any thermal degradation or loss of volatile constituents during the drying stage itself. Because both weighings were performed on specimens in the same dry condition, the calculated weight loss is independent of any difference in moisture content; it reflects the mass removed by ablation together with any mass lost through thermal degradation and volatilization of wood constituents within the heat-affected zone generated by the laser. The percentage weight loss resulting from the laser incising was calculated using Eq. 1:

$$WL(\%) = \frac{W_0 - W_1}{W_0} \times 100 \quad (1)$$

where WL is weight loss of the specimen (%); W_0 denotes oven-dry weight of the specimen before treatment (g); and W_1 is oven-dry weight of the specimen after treatment (g).

Stereomicroscopic Evaluation of the Laser-Incised Holes

The purpose of these evaluations was to characterize the geometry of the individual laser-incised holes and to determine whether this geometry differed among the sapwood, transition zone, and mature wood portions. The radial and tangential surfaces of the specimens (100 mm × 25 mm × 25 mm) were used for these examinations and measurements. The evaluations were performed at low magnification on the intact specimen surfaces, on features that are visible to the unaided eye; the stereomicroscope was used solely to magnify these features and to allow calibrated dimensional measurement of them. No sectioning or cell-level (light or electron microscopy) examination of the wood tissue was carried out, and the term "macroscopic" is therefore used here in this sense throughout the text. These evaluations were conducted using images captured with a BAB Bscamera digital camera mounted on a BAB Image Analysing Systems BAB-STR80 stereomicroscope. The acquired images were analyzed using the BsCap image-processing software (Fig. 2).

To ensure an accurate assessment of the effects of laser incising on different wood portions of Oriental spruce, the macroscopic analyses and the determination of physical and mechanical properties were performed on the same specimens. For this purpose, three parameters were measured on the laser-incised specimens selected for this evaluation: (i) the penetration depth of the incised holes, (ii) their tangential diameter, and (iii) their radial diameter, determined on both the radial and the tangential surfaces. These measurements were used to compare the response of the sapwood, transition zone, and mature wood portions to the identical laser-incising treatment, and the resulting mean values were evaluated statistically together with the weight loss, density, dimensional stability, and compressive strength data obtained from the same specimens.

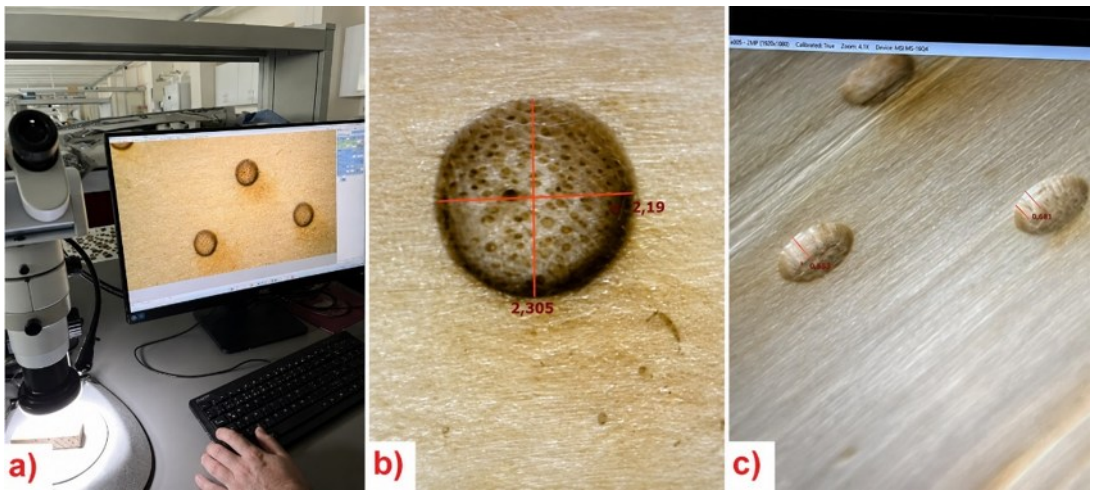


Fig. 2. Measurement of the tangential/radial diameters (b) and penetration depths (c) of laser-incised holes on the radial and tangential surfaces of the specimens using a stereomicroscope (a)

Physical and Mechanical Properties

The effects of laser incising were evaluated on the density, moisture content, compressive strength parallel to the grain, and dimensional stability, including swelling and shrinkage behavior, of the Oriental spruce specimens obtained from the different wood portions.

Specimens with dimensions of 30 mm × 20 mm × 20 mm (longitudinal × radial × tangential) were prepared from the original samples (100 mm × 25 mm × 25 mm) and used for the determination of physical and mechanical properties. The reduction of the cross-section from 25 mm × 25 mm to 20 mm × 20 mm was not carried out symmetrically. Material was removed from two adjacent faces only, 5 mm being cut from one radial and one tangential surface, so that the opposite radial and tangential surfaces were left in the condition in which they had been laser incised. Each test specimen therefore retained two intact incised surfaces, together with the incisions themselves and the thermally affected material surrounding them, and the physical and mechanical properties reported below were determined on specimens in which the treated zone was preserved rather than machined away.

Swelling and shrinkage measurements were performed using a digital caliper with an accuracy of 0.01 mm at three predetermined and marked locations on each specimen before and after water immersion. Swelling and shrinkage values were determined in accordance with TS ISO 13061-16 (2021) and TS ISO 13061-14 (2021), respectively.

Density was determined stereometrically in accordance with TS ISO 13061-2 (2021), both at a moisture content of 12% (D_{12}) and in the oven-dry condition (D_0). For each specimen the mass was determined to the nearest 0.01 g and the volume was calculated from the external dimensions, each of which was measured to the nearest 0.01 mm with a digital caliper at three marked positions along the specimen. The same procedure was applied before and after laser incising, and the marked measuring positions ensured that the dimensions were recorded at identical locations in both measurements, so that any dimensional change caused by the treatment would be captured. Because the volume was obtained stereometrically from the external dimensions, the voids created by the incisions are included in the calculated volume; the reported values therefore represent apparent density. Compressive strength parallel to the grain was determined in accordance with TS ISO 13061-17 (2019).

Statistical Analyses

Statistical analyses were conducted using analysis of variance (ANOVA) to evaluate differences among the experimental groups. When significant differences were detected, mean comparisons were performed using Tukey's honestly significant difference (HSD) test at a 95% confidence level. All statistical analyses, including ANOVA and Tukey's HSD tests, were carried out using JMP statistical software version 5.0.1a (JMP 2002; SAS Institute Inc., Cary, NC, USA).

RESULTS AND DISCUSSION

Determination of Wood Regions for Specimen Sampling

Sapwood, transition zone, and mature wood were identified based on differences in transparency and moisture content.

Radial strips with cross-sectional dimensions of 25 mm × 25 mm were subsequently prepared so that they corresponded to the same growth rings along the stem. Taking into account the saw kerf loss of approximately 0.3 mm during cutting, only two strips could be obtained from each of the sapwood and mature wood regions. In contrast, because of its limited radial extent, only one strip could be obtained from the transition zone (Fig. 3).

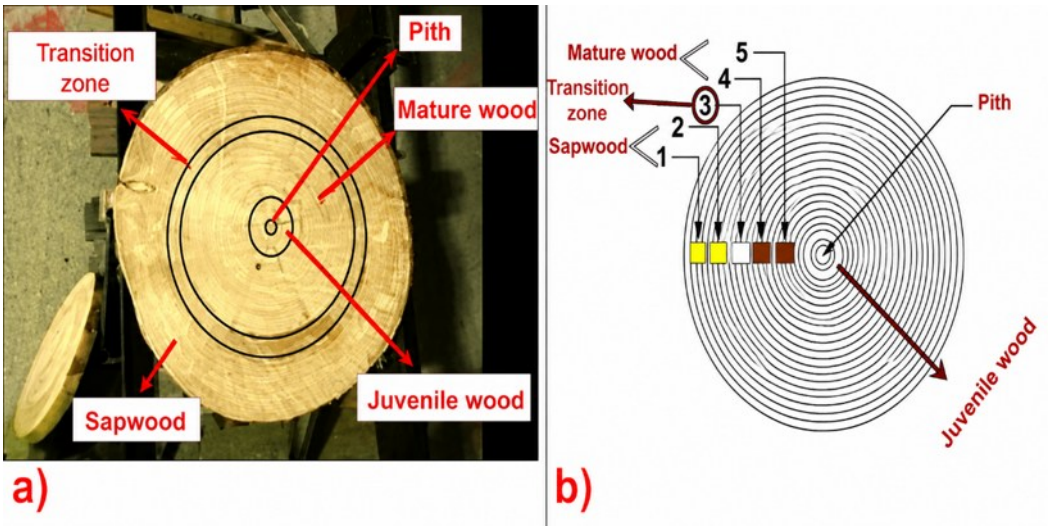


Fig. 3. Identification of sapwood, transition zone, and mature wood in Oriental spruce. (a) Thin sections cut from the breast-height disc and examined against a light source to reveal differences in transparency; (b) Determination of sapwood, transition zone, and mature wood regions along the stem for specimen sampling based on differences in transparency and moisture content

Determination of Growth-Ring Characteristics

The growth-ring width, latewood width, and latewood proportion of the sapwood, transition zone, and mature wood specimens were determined and are presented in Table 1. Although no significant difference was observed between the growth-ring widths of the transition-zone and mature wood specimens, a significant difference was found between these wood portions and the sapwood specimens (Table 1). Similarly, no significant difference was detected between the sapwood and transition-zone specimens in terms of latewood width and latewood proportion; however, both wood portions differed significantly from the mature wood specimens.

As shown in Table 1, the growth-ring widths of the transition-zone and mature wood specimens were greater than those of the sapwood specimens. In contrast, the sapwood and transition-zone specimens exhibited higher latewood widths and greater latewood proportions than the mature wood specimens. These findings may help explain why laser incising caused a more pronounced reduction in density in specimens obtained from mature wood than in those obtained from sapwood. Nath *et al*. (2020a) reported that the presence and distribution of earlywood and latewood layers significantly influence the drilling characteristics, that is, the geometry and quality of the holes ablated by the beam, during CO_2 laser processing. Furthermore, Nath *et al*. (2020b) demonstrated that material removal resulting from surface melting and ablation during CO_2-TEA (Transversely Excited Atmospheric) laser machining of pine wood was greater in the low-density earlywood layer than in the denser latewood layer. The same authors also reported that lasers operating at shorter wavelengths tend to provide more efficient machining performance in high-density wood materials.

Based on the growth-ring measurements obtained in the present study, mature wood specimens contained a higher proportion of low-density earlywood than sapwood specimens. Consequently, the greater amount of earlywood within mature wood may have increased the susceptibility of these specimens to laser-induced ablation and material removal. This phenomenon is therefore proposed as a possible contributing factor to the greater reduction in density observed in mature wood following laser

incising; because the mechanism was not evaluated directly in this study, it should be regarded as a plausible explanation rather than a demonstrated cause.

Because the three wood portions differ systematically in both their anatomical organization and their chemical composition, a brief account of these differences is warranted here, since they underlie the differing responses to laser incising reported in the following sections. Anatomically, the most relevant distinction in a softwood such as Oriental spruce concerns the proportion and the dimensions of the earlywood and latewood tracheids. Earlywood tracheids possess wide lumina and thin cell walls, whereas latewood tracheids are narrow-lumened and thick-walled, so that the proportion of latewood largely governs the density of a growth ring (Gindl 2001). The measurements presented in Table 1 show that this proportion decreased from the sapwood (29.8%) through the transition zone (23.0%) to the mature wood (16.4%), while the growth-ring width increased in the same direction, from 1.24 to 1.71 mm. The mature wood examined here therefore consisted predominantly of wide, thin-walled earlywood tracheids, whereas the transition zone occupied an intermediate position between the two extremes. Because the coupling of laser energy into the material is governed largely by the density and the cell-wall thickness of the tissue encountered, this radial gradient provides a direct anatomical basis for expecting the ablation response to differ among the three portions.

Table 1. Growth-Ring Characteristics of the Different Wood Portions of Oriental Spruce

Growth-Ring Characteristics	Wood Portion	Measurements
Growth-ring width (mm)	Sapwood	1.24 (0.39)^{c}
	Transition zone	1.52 (0.67)^{ab}
	Mature wood	1.71 (0.97)^{a}
Latewood width (mm)	Sapwood	0.37 (0.09)^{a}
	Transition zone	0.35 (0.08)^{ab}
	Mature wood	0.28 (0.08)^{c}
The proportion (%) of latewood in a growth-ring	Sapwood	29.84 (7.07)^{a}
	Transition zone	23.03 (3.62)^{ab}
	Mature wood	16.37 (3.97)^{c}

Values are arithmetic means, and the figures in parentheses are the corresponding standard deviations. The superscript letters denote homogeneous groups obtained from Tukey's HSD multiple comparison test at a significance level of $p \leq 0.05$. The comparison was performed separately within each growth-ring characteristic, that is, among the sapwood, transition zone, and mature wood values of that characteristic. Mean values sharing at least one common letter do not differ significantly from one another, whereas mean values sharing no common letter differ significantly. The letters are assigned in descending order of the mean value, so that the group designated "a" has the highest mean for that characteristic.

The three portions also differ in their physiological status and consequently in their chemical composition. Sapwood retains living parenchyma cells and its conducting function. It is characterized by a low extractive content and by bordered pits that remain largely unaspirated. The formation of mature, non-conducting wood is accompanied by the death of the parenchyma cells, by the aspiration and incrustation of the bordered pits, and by the deposition of phenolic extractives and resinous substances within the cell walls and lumina (Bamber 1976; Taylor *et al*. 2002). The transition zone is the region in which these processes are actively taking place, and it therefore contains tissue at an intermediate and highly variable stage of conversion, so that its anatomical and chemical heterogeneity is greater than that of either adjacent

region. These compositional differences are directly relevant to laser processing, because extractives and resinous compounds volatilize and decompose at lower temperatures than the structural cell-wall polymers, and their presence consequently influences the extent of thermal degradation, carbonization, and volatile loss in the immediate vicinity of the incisions. In Norway spruce, moreover, the transition zone has been shown to possess a chemical composition that is distinct from that of either adjacent region, containing less lignin and fewer lipophilic extractives than both the heartwood and the sapwood (Bertaud and Holmbom 2004). Because lignin is the most thermally stable of the structural cell-wall polymers, a matrix that is comparatively poor in lignin and correspondingly rich in polysaccharides may be expected to degrade at lower temperatures, and this offers a plausible explanation for the more pronounced thermal response inferred for the transition-zone specimens in the present study.

It must be emphasized, however, that no chemical analysis was carried out in the present study. Neither the extractive content nor the lignin, cellulose, and hemicellulose proportions of the three wood portions were determined, and the condition of the bordered pits was not examined. The account given above is drawn from the established literature on the radial variation of wood structure and composition, and it is presented in order to provide the anatomical and compositional context within which the measured differences may be interpreted, rather than as evidence obtained in this study. Quantifying the extractive content, the proportions of the principal cell-wall polymers, and the condition of the pit membranes in each wood portion, both before and after laser incising, would be required in order to establish the extent to which chemical degradation differs among the portions, and this is identified here as a priority for further work.

Determination of Weight Loss

The results regarding differences in weight loss (%) observed in Oriental spruce specimens from different wood portions following laser incising were evaluated. No statistically significant differences were found among the weight losses recorded for sapwood, transition zone, and mature wood specimens following laser incising (Table 2). As shown, the percentage weight loss caused by laser incising was comparable across the different wood portions.

In contrast, a noteworthy finding was that although no significant differences existed among the air-dry and oven-dry density values of the different wood portions prior to laser incising, density values measured after laser incising were statistically higher in sapwood than in mature wood specimens. Considering the relationship between density and its governing parameters,

$$\rho = \frac{m}{v} \tag{2}$$

where ρ is density (g/cm³), m is mass (g), and v is volume (cm³), a reduction in density may result from a decrease in mass, an increase in volume, or a combination of both factors. It should be clarified that the air-dry (D_{12}) and oven-dry (D_0) densities were not compared with each other. Each of these two densities was determined under its own fixed moisture condition, and the effect of laser incising was assessed by comparing the values obtained before and after treatment within the same moisture condition (D_{12} before versus D_{12} after, and D_0 before versus D_0 after). The moisture loss and the associated shrinkage that occur when wood passes from the air-dry to the oven-dry state therefore do not enter into the comparisons discussed below.

As shown in Table 2, the absence of significant differences in weight loss

among the wood portions suggests that the pronounced density reduction observed in mature wood specimens may not be solely attributable to mass loss. Rather, it suggests that a change in the effective volume of the specimens, particularly in mature wood, may also have contributed to the density reduction. It should be emphasized that no increase in specimen volume was measured directly in the present study: the dimensional measurements taken before and after laser incising revealed no statistically significant change in the external dimensions of the specimens, and the present interpretation is therefore inferred from the density and weight-loss data rather than demonstrated experimentally. On this basis it may be hypothesized that the formation of thermally affected zones around the incisions, together with the development of microcracks, altered the cellular structure of mature wood, leading to a loosening of the cell-wall architecture and increased porosity (Gilani *et al*. 2013; Cabezas-Romero *et al.* 2021). Such structural modifications would be consistent with the greater reduction in density observed in mature wood despite similar levels of mass loss among the wood portions.

The presence of a thermally affected zone is itself supported by the stereomicroscopic observations, in which a distinctly darkened, carbonized rim was visible around the perimeter of every incision (Fig. 2a, b). However, those examinations were otherwise limited to the geometry of the incised holes and did not provide direct evidence of laser-induced expansion or microcracking; confirming this mechanism would require cell-level examination, for example by light or scanning electron microscopy or by X-ray micro-computed tomography. It should further be noted that the carbonization and microcrack formation invoked below in relation to the pronounced moisture loss of the transition zone, and the structural loosening proposed here for mature wood, are not competing explanations but different manifestations of the same thermally induced modification: the wood portions differ in the property through which this modification is expressed. In the transition zone, whose initial moisture content was the highest, the effect was most evident in the moisture-related behavior, whereas in mature wood, which contained the highest proportion of low-density earlywood, it was most evident in the density response. Because neither mechanism was verified at the cellular level in this study, and because no wood-portion-specific evidence of microcracking was obtained from the stereomicroscopic examinations, both interpretations are presented as hypotheses to be tested in future work.

Determination of Moisture Content

No significant differences were detected between the moisture contents of the control and laser-incised specimens in either the sapwood or mature wood groups. However, a statistically significant difference was found between the control transition-zone specimens and the laser-incised transition-zone specimens (Table 2).

As can be seen in Table 2, the moisture content of transition-zone specimens decreased significantly following laser incising compared with the untreated controls. Furthermore, and somewhat unexpectedly, the moisture content of the transition-zone control specimens was higher than that of both sapwood and mature wood control specimens.

Knedlová *et al*. (2024) reported that wood moisture content plays a crucial role in laser machining and that its influence varies substantially among different wood species, including oak, beech, pine, spruce, alder, ash, and cherry. According to these authors, each species exhibits a characteristic response to moisture content with respect to drilling depth and surface quality. They further stated that wood moisture content

can markedly affect various machining parameters, including penetration depth, wood structure, and surface characteristics. In general, an inverse relationship between wood moisture content and laser drilling depth has been reported.

However, the results obtained in the present study indicate that although the initial moisture content of the transition zone was higher than those of the sapwood and mature wood portions before laser incising, no significant differences were observed in penetration depth among the wood portions (Table 3). This finding suggests that factors other than moisture content may have exerted a greater influence on laser penetration under the applied processing conditions. It is also plausible that the initially higher moisture content and distinctive anatomical structure of the transition zone altered the distribution of laser energy within the wood matrix. Consequently, laser incising may have promoted more extensive carbonization and microcrack formation in the transition zone, leading to greater moisture loss from this wood portion compared with sapwood and mature wood specimens (Wang *et al*. 2013; Nath *et al*. 2020a).

On the other hand, degradation of hemicelluloses is known to modify the hygroscopic behavior of wood. Reduced hygroscopicity decreases the capacity of wood to absorb and retain moisture, while water entering the wood structure evaporates more readily. These changes contribute to alterations in dimensional stability, including swelling and shrinkage behavior, and may also enhance resistance to fungal attack (Gündüz *et al*. 2009). Therefore, the substantial reduction in moisture content observed in laser-incised transition-zone specimens may also be attributed to a greater degree of hemicellulose degradation in this wood portion compared with the sapwood and mature wood specimens.

It should be emphasized that the values reported in Table 2 represent equilibrium moisture contents rather than residual moisture remaining from an earlier stage of drying. Control and laser-incised specimens alike were conditioned at 20 ± 2 °C and 65 ± 5% relative humidity until constant mass was attained, so that all specimens had come into equilibrium with an identical surrounding climate before the measurement. Under these conditions a statistically significant difference between control and treated specimens can arise only from a change in the capacity of the wood to bind water, and the significantly lower value obtained for the laser-incised transition-zone specimens therefore constitutes direct evidence that the treatment altered the moisture behavior of this wood portion.

The physical and the chemical modifications produced by the laser act on this behavior at different levels. The microcracking and the carbonized rim observed around the incisions increase the accessibility of the internal surfaces and create additional pathways for vapour transport, and thus influence primarily the rate at which moisture is taken up or released. The equilibrium moisture content, by contrast, is governed principally by the number of accessible hydroxyl groups available for water sorption within the cell wall. Degradation of hemicelluloses, which are the most hygroscopic of the cell-wall polymers, together with condensation and cross-linking reactions within the lignin network, both reduce the availability of these sorption sites and therefore offer the more plausible explanation for the lower equilibrium values recorded here.

This interpretation is consistent with the dimensional-stability data. Both the shrinkage and the swelling of mature wood specimens decreased significantly after laser incising (Table 2), and a reduction in the capacity of the cell wall to bind water is expected to be expressed simultaneously in a lower equilibrium moisture content and in a smaller dimensional response to changes in humidity. The two responses need not reach statistical significance in the same wood portion, since the dimensional response additionally reflects the loss of material and the accompanying reduction in density,

whereas the equilibrium moisture content reflects the sorption capacity of the remaining cell-wall substance alone. No chemical analysis was performed in the present study, so these mechanisms are advanced as interpretations consistent with the measured physical behavior and require verification by chemical characterization in future work.

Density Determination

The effects of laser incising on the oven-dry and air-dry density values of Oriental spruce specimens obtained from different wood portions were evaluated. Prior to laser incising, no statistically significant differences were observed between the sapwood and mature wood specimens in terms of either oven-dry or air-dry density. However, following laser incising, significant differences were detected between the density values of sapwood and mature wood specimens (Table 2).

As shown in Table 2, both oven-dry and air-dry density values of mature wood specimens were lower than those of sapwood specimens after laser incising. These results indicate that laser incising was more effective in reducing density in mature wood than in sapwood. Nath *et al*. (2020b) reported that material removal from wood surfaces during laser machining was greater in samples containing a higher proportion of low-density earlywood relative to latewood within a growth ring. The growth-ring measurements obtained in the present study support this observation, as mature wood exhibited a lower latewood proportion than sapwood, indicating a comparatively higher proportion of earlywood in mature wood specimens (Table 1).

Furthermore, mature wood of spruce generally contains higher amounts of resin and extractives than sapwood (Luxford 1953; Wu and Hu 1997; Wagner 2010). Therefore, it is reasonable to assume that some of these resins and extractive compounds were volatilized or thermally degraded during laser processing. The removal of such constituents from the wood matrix under elevated temperatures may have contributed to the greater density reduction observed in mature wood specimens following laser incising (Gündüz *et al*. 2009).

Determination of Shrinkage and Swelling

Differences in the shrinkage and swelling behavior of laser-incised Oriental spruce specimens obtained from different wood portions are presented in Table 2. No significant differences were detected between sapwood and mature wood specimens with respect to longitudinal or volumetric shrinkage and swelling, either before or after laser incising. In contrast, significant differences were observed in radial and tangential shrinkage and swelling values following laser incising (Table 2).

As shown in Table 2, radial and tangential shrinkage and swelling were higher in sapwood than in mature wood after laser incising. In other words, laser incising reduced radial and tangential dimensional changes in mature wood. This finding suggests that laser incising partially decreased the hygroscopicity of mature wood. When wood is exposed to elevated temperatures during laser processing, permanent modifications occur in its physical and chemical structure. These changes are primarily associated with the thermal degradation of hemicelluloses. As the treatment temperature increases, the extent of these modifications becomes more pronounced. Consequently, wood exhibits reduced moisture absorption, improved dimensional stability, enhanced biological durability, darker coloration, migration or loss of certain extractive compounds, reduced pH, improved thermal insulation properties, and lower density (Gündüz *et al*. 2009). The degradation of hemicelluloses also alters the hygroscopic behavior of wood. As moisture sorption decreases, water entering the wood structure is less readily absorbed and evaporates more easily. These changes

contribute to reduced shrinkage and swelling and may additionally improve resistance to fungal deterioration (Gündüz *et al*. 2009).

These results suggest that mature wood may represent the most suitable wood portion for applications where dimensional stability is of primary importance, particularly in refractory wood materials characterized by high resin and extractive contents. Consequently, mature wood from Oriental spruce may be preferable for end-use applications requiring enhanced dimensional stability following laser incising.

Determination of Compressive Strength Parallel to the Grain

The effects of laser incising on the compressive strength parallel to the grain of Oriental spruce specimens obtained from different wood portions were also evaluated. Although apparent reductions in compressive strength parallel to the grain were observed in sapwood and transition-zone specimens after laser incising, these decreases were not statistically significant. In contrast, the reduction observed in mature wood specimens was statistically significant (Table 2). As shown in Table 2, mature wood specimens subjected to laser incising exhibited lower compressive strength parallel to the grain than the corresponding untreated control specimens.

The most direct explanation for this behavior is the concurrent reduction in density. Laser incising caused significant reductions in both the oven-dry and the air-dry density of mature wood (Table 2), and compressive strength parallel to the grain is closely and positively correlated with density; the loss of load-bearing material and the local disruption of the cross-section produced by the incisions are therefore expected to reduce strength, and mature wood was the only portion in which the density reduction was statistically significant. Beyond this density effect, it may additionally be hypothesized, on the basis of the established relationship between lignin content and compressive strength parallel to the grain, that laser irradiation induced structural modifications involving lignin-rich components in mature wood. It must be emphasized, however, that no chemical analysis was performed in the present study; neither the lignin content nor any other aspect of the chemical composition of the specimens was determined before or after laser incising, and this mechanism is therefore offered as a possible additional explanation rather than as a demonstrated one. Gündüz *et al.* (2009) reported that thermal modification processes conducted at elevated temperatures improve dimensional stability and resistance to fungal degradation but are generally accompanied by reductions in mechanical properties, and the significant decrease in compressive strength observed here in mature wood is qualitatively consistent with those findings. This comparison should nevertheless be drawn with caution, because the two processes are not thermally equivalent: thermal modification exposes the entire specimen to a controlled elevated temperature for several hours, so that heat-induced chemical changes develop throughout the material, whereas laser incising delivers highly localized, short-duration heating confined to the immediate vicinity of the incisions, with steep temperature gradients and only limited thermal exposure of the surrounding wood. The extent and the nature of the chemical and structural modifications produced by the two processes may therefore differ considerably, and thermal-modification studies are cited here only as contextual support.

The depth to which the thermal modification extended into the material warrants explicit consideration, since any structural change of the kind proposed above must be confined to the region actually reached by the heat. This depth was not measured directly in the present study, and the extent of the thermally affected zone can therefore only be delimited by indirect reasoning. The darkened, carbonized rim observed

stereomicroscopically was restricted to the immediate vicinity of the hole perimeter, and the low thermal diffusivity of wood, combined with the short duration of the energy input during ablation, restricts the propagation of heat beyond the ablated boundary (Fig. 2a, b). The thermally affected material is accordingly expected to form a thin envelope extending only a fraction of a millimeter around each incision rather than to penetrate the specimen as a whole. The proposed modification of lignin-rich components should therefore be understood as a local phenomenon occurring within this envelope, and not as a modification of the bulk of the specimen.

That the affected volume is local does not, however, render it mechanically negligible. Because the incisions were produced on all four longitudinal surfaces of the 25 mm blanks, and because two of these incised surfaces were retained intact when the 20 mm × 20 mm test cross-section was prepared, a layer of the order of 1 mm along two adjacent faces corresponds to approximately one tenth of the cross-sectional area resisting the applied load. A local reduction in the load-bearing capacity of a peripheral layer of this magnitude is sufficient to influence the measured compressive strength, particularly in mature wood, in which the reduction in density was also significant. Furthermore, the validity of the comparison among the wood portions does not depend on the exact depth of the thermally affected zone, since all specimens received an identical treatment and the measured penetration depths of the incisions did not differ significantly among sapwood, transition zone, and mature wood (Table 3). The differences reported here are therefore attributable to the response of the wood portions themselves rather than to differences in the extent of the treatment. Direct determination of the depth of thermal modification, for example by scanning electron microscopy of transverse sections through the incisions, by X-ray micro-computed tomography, or by depth-resolved chemical characterization, would nevertheless permit this interpretation to be tested and is identified as a priority for future work.

Conversely, the insignificant reductions observed in the compressive strength of laser-incised sapwood and transition-zone specimens suggest that the laser incising may have primarily affected wood constituents that play a relatively minor role in load-bearing performance. However, confirmation of this hypothesis requires further investigation. To better understand the mechanisms responsible for these changes, additional microscopic studies examining the effects of laser irradiation on wood anatomical structures, together with chemical analyses such as lignin characterization and carbohydrate composition analyses, are required.

The limited reductions in density and compressive strength observed in laser-incised sapwood and transition-zone specimens have important practical implications. For applications in which mechanical performance is critical, wood materials obtained from the sapwood and transition-zone portions of refractory Oriental spruce may be preferable to mature wood when laser incising is employed. Such wood portions appear to maintain their structural integrity more effectively while still benefiting from the enhanced permeability provided by laser incising.

The influence of the incising depth itself becomes apparent when the present results are compared with those of an earlier study conducted on the same species. Bakır (2022b) produced laser incisions to a depth of 10 mm in Caucasian spruce and European larch sapwood samples and reported a significant reduction in compressive strength parallel to the grain, which was attributed to the removal of a substantial proportion of the load-bearing cross-section and to the extension of the heat-affected zone deep into the material.

Table 2. Weight Loss, Physical Properties, and Mechanical Properties of Oriental Spruce Specimens from Different Wood Portions Before and After Laser Incising

Wood Portion	Pretreatment	WL (%)	MC (%)	CS (N/mm^2)	D_0 (g/cm^3)	D_{12} (g/cm^3)	Tangential Shrinkage (%)	Radial Shrinkage (%)	Longitud-inal Shrink-age (%)	Volumetric Shrinkage (%)	Tangential Swelling (%)	Radial Swelling (%)	Longitudinal Swelling (%)	Volumetric Swelling (%)
Sap-wood	Control	----	8.33 (0.07)^{bc}	45.61 (0.86)^{a}	0.43 (0.04)^{a}	0.46 (0.04)^{a}	4.61 (0.27)^{ab}	7.74 (0.33)^{ab}	0.81 (0.29)^{a}	12.70 (0.64)^{a}	4.83 (0.34)^{ab}	8.39 (0.39)^{ab}	0.82 (0.28)^{a}	14.56 (0.85)^{a}
	Laser incised	5.37 (0.12)^{a}	8.14 (0.08)^{c}	45.22 (0.86)^{a}	0.43 (0.03)^{a}	0.46 (0.04)^{a}	4.95 (0.30)^{a}	8.29 (0.35)^{a}	1.28 (0.32)^{a}	13.93 (0.67)^{a}	5.23 (0.37)^{a}	9.05 (0.41)^{a}	1.31 (0.30)^{a}	16.28 (0.93)^{a}
Transition zone	Control	----	8.85 (0.09)^{a}	47.99 (0.86)^{a}	0.42 (0.04)^{ab}	0.46 (0.04)^{a}	4.86 (0.30)^{ab}	8.27 (0.33)^{a}	0.60 (0.29)^{a}	13.25 (0.61)^{a}	5.11 (0.35)^{ab}	9.02 (0.44)^{a}	0.60 (0.29)^{a}	15.28 (0.85)^{a}
	Laser incised	5.47 (0.11)^{a}	8.18 (0.07)^{bc}	45.38 (0.86)^{a}	0.42 (0.04)^{ab}	0.45 (0.03)^{ab}	4.64 (0.28)^{ab}	7.93 (0.32)^{ab}	0.95 (0.28)^{a}	13.03 (0.76)^{a}	4.87 (0.32)^{ab}	8.62 (0.43)^{ab}	0.96 (0.29)^{a}	15.01 (0.85)^{a}
Mature wood	Control	----	8.45 (0.09)^{b}	46.94 (0.86)^{a}	0.42 (0.04)^{ab}	0.45 (0.04)^{ab}	4.60 (0.30)^{ab}	7.22 (0.33)^{ab}	1.49 (0.29)^{a}	12.80 (0.64)^{a}	4.83 (0.35)^{ab}	7.80 (0.37)^{ab}	1.53 (0.29)^{a}	14.74 (0.95)^{a}
	Laser incised	5.73 (0.12)^{a}	8.20 (0.07)^{bc}	39.18 (0.85)^{b}	0.40 (0.03)^{b}	0.42 (0.03)^{b}	3.64 (0.27)^{b}	6.71 (0.32)^{b}	1.30 (0.28)^{a}	11.25 (0.66)^{a}	3.79 (0.33)^{b}	7.20 (0.39)^{b}	1.33 (0.29)^{a}	12.77 (0.85)^{a}

WL was calculated from the masses of the same specimens determined before and after laser incising under identical conditioning conditions; in both cases the specimens were dried at 60 °C for three days to constant mass before weighing, so the reported values are independent of moisture content. WL therefore represents the material removed by laser ablation together with any mass lost through thermal degradation and volatilization of wood constituents within the heat-affected zone.

WL: Weight loss; MC: Moisture content; CS: Compressive strength; D_0: Oven-dry density; D_{12}: Air-dry density

Values are arithmetic means, and the figures in parentheses are the corresponding standard deviations. The superscript letters denote homogeneous groups obtained from Tukey's HSD multiple comparison test at a significance level of $p \leq 0.05$. The comparison was performed separately within each column, across all six combinations of wood portion and treatment. Mean values sharing at least one common letter do not differ significantly from one another, whereas mean values sharing no common letter differ significantly. The letters are assigned in descending order of the mean value, so that the group designated "a" has the highest mean within that column.

In the present study, in which the incising depth was restricted to 1.0 mm, the reduction in compressive strength remained statistically insignificant in the sapwood and transition-zone specimens, and a significant reduction was confined to mature wood (Table 2). Considered together, the two studies indicate that the incising depth governs the extent to which the mechanical performance of the material is compromised: at a depth of 10 mm the geometry of the treatment dominates the strength response, whereas at 1.0 mm the response remains sufficiently moderate for the intrinsic differences among the wood portions to be resolved. This distinction is of practical relevance, because the purpose of incising is to enhance permeability with the smallest attainable loss of strength, and the present findings indicate that this balance is more favorable at shallow incising depths, particularly for sapwood and transition-zone material.

Evaluation of Variations in Hole Diameter and Penetration Depth as a Function of Wood Portion Following Laser Incising

No significant differences were observed in the penetration depths of laser-incised holes among the specimens obtained from the different wood portions, regardless of whether the measurements were performed on the radial or tangential surfaces. Likewise, no significant differences were found between the tangential and radial diameter values measured on the radial and tangential surfaces of sapwood and mature wood specimens. In contrast, a statistically significant difference was detected between the tangential and radial hole diameters measured on the radial and tangential surfaces of specimens obtained from the transition zone (Table 3).

As shown in Table 3, radial diameter values were greater than tangential diameter values in the specimens obtained from the transition zone, regardless of whether the measurements were conducted on the radial or tangential surfaces. This phenomenon was not observed in specimens obtained from sapwood or mature wood. In addition, the tangential diameter values measured on the tangential surfaces of transition-zone specimens were lower than those recorded for mature wood specimens.

Besides these dimensional measurements, the stereomicroscopic examination revealed a visible alteration of the wood surface immediately surrounding the incisions. In all specimens, irrespective of the wood portion, the perimeter of each hole was bordered by a distinctly darkened, brown to black zone forming a narrow ring around the opening, and this discoloration was clearly discernible against the surrounding untreated wood (Fig. 2a, b). Such darkening is the macroscopic expression of the carbonization that accompanies the localized thermal exposure of the wood during laser ablation, and it therefore constitutes direct visual evidence that a thermally affected zone was generated around the incisions. The darkened ring was confined to the immediate vicinity of the hole perimeter, which is consistent with the short duration and the highly localized nature of the energy input. The width of this zone was not quantified, because the measurements in this study were directed at the geometry of the holes themselves, and no systematic difference in the extent of the discoloration among sapwood, transition zone, and mature wood could be established from the images obtained. Neither microcracking nor changes at the cell-wall level could be resolved at the magnification employed, since these features lie below the resolution of stereomicroscopic examination of intact surfaces.

When wood anatomy, laser-wood interactions, and the physical characteristics of the material are considered together, the larger radial diameters observed in transition-zone specimens may be attributed to the anatomical heterogeneity of this region, which contains characteristics of both sapwood and mature wood tissues (Wang *et al*. 2021; Savero *et al*.

2024). Since the transition zone represents an intermediate region in which the anatomical and physiological characteristics of sapwood gradually change toward those of mature wood, it is reasonable to expect more pronounced anisotropic behavior during laser processing in this portion of the stem. Furthermore, the more pronounced density variation in the radial direction may have influenced laser energy absorption, resulting in greater thermal degradation and ablation in regions containing a relatively higher proportion of latewood (Nath *et al*. 2020a). Variations in the anatomical arrangement of wood tissues across the radial profile may therefore have contributed to the observed differences in hole geometry. Moreover, the anisotropic thermal conductivity of wood, which varies among the longitudinal, radial, and tangential directions (Hu *et al*. 2023; Vay and Hansmann 2026), together with directional differences in cellular structure, mechanical resistance, and hygroscopic behavior (Flity *et al*. 2023; Zhao *et al*. 2023; Vay and Hansmann 2026), may have promoted greater expansion of hole diameters in the radial direction. These factors could have altered heat distribution around the irradiated area, thereby affecting the extent of localized material removal during laser machining.

On the other hand, considering that the anatomical characteristics of different wood portions are inherently distinct, it is also plausible that the more irregular distribution of resin canals, resin content, and extractive compounds within transition-zone specimens (Qian *et al*. 2021) influenced the absorption of laser energy. Variations in the concentration and spatial distribution of these constituents may have resulted in localized temperature increases, thereby enhancing surface melting and erosive material removal (ablation) during laser processing (Nath *et al*. 2020a, 2022; Gurau *et al*. 2024). Consequently, the unique anatomical and chemical characteristics of the transition zone may have contributed to the pronounced directional differences in hole diameter observed in the present study.

Table 3. Hole Diameter and Penetration Depth Values Measured on the Radial and Tangential Surfaces of Oriental Spruce Specimens Obtained from Different Wood Portions Following Laser Incising

Wood Portion	Surfaces of Wood Samples	Penetration Depth (mm)	Tangential Hole Diameter (mm)	Radial Hole Diameter (mm)
Sapwood	Tangential surface	0.96 (0.08)^{ab}	2.29 (0.14)^{cd}	2.32 (0.07)^{bc}
	Radial surface	0.90 (0.06)^{b}	2.32 (0.16)^{bc}	2.33 (0.07)^{ab}
Transition zone	Tangential surface	0.91 (0.08)^{ab}	2.27 (0.05)^{d}	2.32 (0.07)^{bc}
	Radial surface	0.95 (0.04)^{ab}	2.31 (0.07)^{bc}	2.36 (0.07)^{a}
Mature wood	Tangential surface	0.99 (0.06)^{a}	2.31 (0.16)^{bc}	2.33 (0.08)^{ab}
	Radial surface	0.93 (0.08)^{ab}	2.33 (0.07)^{abc}	2.35 (0.07)^{ab}

Values are arithmetic means, and the figures in parentheses are the corresponding standard deviations. The superscript letters denote homogeneous groups obtained from Tukey's HSD multiple comparison test at a significance level of $p \leq 0.05$. The comparison was performed separately within each column, across all wood portions and measurement surfaces. Mean values sharing at least one common letter do not differ significantly from one another, whereas mean values sharing no common letter differ significantly. The letters are assigned in descending order of the mean value, so that the group designated "a" has the highest mean within that column.

Future studies may focus on determining which wood portions and wood species, particularly those characterized by low permeability and poor treatability, are most suitable for specific permeability-enhancement techniques. Such investigations could also identify

the most appropriate end-use applications for these materials based on their response to different permeability-improvement methods. The development of a comprehensive database integrating these findings would provide valuable guidance for the forest products industry and could ultimately serve as the basis for a practical handbook supporting material selection and treatment decisions.

Furthermore, the results obtained in the present study suggest that laser incising may lead to different degrees of degradation among the chemical constituents of various wood portions. This possibility raises the question of whether the type and quantity of degraded wood components vary according to wood portion and treatment conditions. To accurately explain and interpret these mechanisms, comprehensive anatomical and chemical investigations are required on different wood portions of refractory wood species subjected to various incising and permeability-enhancement treatments. Such studies should include detailed microscopic analyses as well as chemical characterization techniques to elucidate the relationships among wood anatomy, chemical composition, and treatment-induced property changes.

CONCLUSIONS

1. Sapwood and transition-zone specimens exhibited greater latewood width and higher latewood proportion within a growth ring than mature wood specimens. These findings suggest that the greater density reduction observed in mature wood following laser incising may be associated with its higher proportion of low-density earlywood within the growth rings compared with sapwood and transition-zone wood.
2. Laser-incising pretreatment was found to reduce radial and tangential shrinkage and swelling in mature wood. However, the compressive strength parallel to the grain of laser-incised mature wood specimens was lower than that of the corresponding control specimens.
3. For specimens obtained from the transition zone, radial hole diameters were significantly greater than tangential hole diameters on both the tangential and radial surfaces. In addition, the tangential hole diameters measured on the tangential surfaces of transition-zone specimens were lower than those measured in mature wood specimens.
4. The present study was designed to assess the effects of laser incising on the dimensional stability and the compressive strength parallel to the grain of the three wood portions, and to relate these responses to their growth-ring characteristics and to the geometry of the incised cavities. Preservative uptake, penetration, and retention were accordingly outside its scope and were not measured; these aspects are addressed in a separate study now in preparation.
5. The mechanical cost of the treatment was not distributed uniformly across the stem radius, since the significant reductions in density and in compressive strength parallel to the grain were confined to mature wood, whereas the sapwood and transition-zone specimens retained their strength. Where laser incising is employed in order to render refractory material more accessible to preservatives, sapwood and transition-zone material may therefore be treated with little penalty in load-bearing capacity, whereas mature wood requires more conservative incising parameters.

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