Effect of Air Heat Treatment on the Shrinkage and Surface Roughness of Six Korean Oak Woods

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The effect of air heat treatment was evaluated relative to the shrinkage and surface roughness of six Korean oak woods: *Quercus serrata* (*Qs*), *Quercus mongolica* (*Qm*), *Quercus acutissima* (*Qac*), *Quercus aliena* (*Qal*), *Quercus dentata* (*Qd*), and *Quercus variabilis* (*Qv*). The properties were examined using untreated and treated flat-sawn heartwood boards at 160, 180, 200, and 220 °C for 2 h. The shrinkage in the radial and tangential directions increased with increasing temperature, whereas the anisotropy coefficients decreased from 160 to 200 °C and increased at 220 °C. At all temperatures, *Qm* exhibited the smallest shrinkage, and *Qv* showed the highest shrinkage in the radial and tangential directions. The surface roughness of the oak wood decreased with increasing temperature, showing the highest average roughness (R_a) value in *Qs* at all temperatures. *Qm* and *Qac* showed the smallest R_a values at 160 to 200 °C and 220 °C, respectively. *Qm* showed the highest change in R_a value at 160 and 200 °C, while *Qv* had the highest change at 180 and 220 °C. In contrast, *Qal* consistently exhibited the smallest change in R_a at all temperatures.

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INTRODUCTION

Quercus L., in the Fagaceae family, is an abundant genera among angiosperms and economically important as a wood resource in the Northern Hemisphere (Manos *et al*. 1999), with approximately 400 species in North and Central America, Colombia, Eurasia, and northern Africa (Nixon 1997; Fang *et al*. 2011). Oak wood is characterized by wide, numerous, and prominent medullary rays, clear grains, and a high proportion of heartwood. It is economically valued owing to its unique properties, exceptional durability, and superior mechanical properties; it is hard, dense, and possesses a proportionally high strength (Mania and Tomczak 2020). Therefore, it is widely utilized in various applications, such as carpentry, construction, furniture, veneers, flooring, charcoal, firewood, and wine barrels (Santos *et al*. 2012). Additionally, oak wood is used in the production of pallets, railway ties, and timber mats (Bumgardner 2017).

In Korea, six oak species are the most abundant hardwood species: Jolcham Oak (*Quercus serrata*, *Qs)*, Mongolian Oak (*Quercus mongolica*, *Qm*), Sawtooth Oak (*Quercus acutissima, Qac*), Galcham Oak (*Quercus aliena, Qal*), Japanese Emperor Oak (*Quercus dentata, Qd*), and Oriental Cork Oak (*Quercus variabilis, Qv*). They cover approximately 1,037,650 ha or 16.3% of the forested area, with a total standing timber volume of 159,261,862 m^3 (Korea Forest Service 2022). These oak species have a long history of use in various applications, including the construction of shrines, fortresses, and palaces, from the 17^{th} to 20^{th} centuries (Lee and Bae 2021). In contrast, modern applications, such as mushroom cultivation, tools handles, firewood, and charcoal production, are primarily low-grade (Han and Chang 2019; Korea Forest Service 2022; Savero *et al*. 2023).

Wood modification by heat treatment is performed between 150 and 260 °C (Hill 2006; Navi and Sandberg 2012). Air heat treatment is the most commonly utilized and established method for modifying wood properties (Hill 2006). This is a simple, economical, and eco-friendly method for improving the smoothness of wood surfaces (Korkut *et al*. 2010; Lee *et al*. 2023), dimensional stability, and hydrophobicity (Hidayat *et al*. 2015, 2016; Suri *et al*. 2023a). Heat treatment can be used to darken wood (Hidayat *et al*. 2017; Prasetia *et al*. 2024) and increase its durability against fungi (Suri *et al*. 2023b). Because no chemical substances are employed, heat-treated wood is an optimal material for interior and exterior applications for human life. Currently, it is commonly used for windows, cladding, playground equipment, sauna interiors, bathrooms, parquet flooring, and decking (Militz and Altgen 2014; Prasetia *et al*. 2024).

Several studies have investigated the effects of air heat treatment on the surface roughness of oak wood. Korkut *et al*. (2010) reported that heat treatment under atmospheric pressure at 120, 150, and 180 °C for 2, 6, and 10 h reduced the surface roughness of sessile oak (*Quercus petraea*) wood grown in northeastern Turkey, with significant improvements at 180 °C for 10 h. Ozcan *et al*. (2012) found similar results for white oak (*Q. petraea*) wood, showing decreased surface roughness at 120, 150, and 180 °C in a laboratory oven, with a notable 15% improvement in R_a values observed at 180 °C for 6 h. Salca and Hiziroglu (2014) reported that *Q. falcata* wood from Oklahoma became smoother with heat treatment at 120 and 190 °C for 3 and 6 h in a laboratory oven, particularly at 190 °C for 6 h. Perçin *et al*. (2016) investigated the effects of heat treatment under atmospheric pressure on *Q. petraea* wood at 150, 170, 210, and 240 °C for 2, 5, and 8 h. They found a gradual decrease in wood surface roughness from 150 to 190 °C across all durations, with a slight increase observed at 210 °C. In contrast, Korkut and Hiziroglu (2014) found that heat treatment under atmospheric pressure at 110 and 200 °C for 8 h did not significantly affect the wood surface of *Q. falcate*, with the R_a value slightly increasing at 110 °C and then decreasing at 200 °C. The decrease in surface roughness in solid wood is very important for some applications, such as finishing and gluing, and for reducing production costs during manufacturing (Kasemsiri *et al.* 2012; Aytin and Korkut 2015).

To date, the shrinkage of oak wood due to air heat treatment has seldom been studied. Uribe and Ayala (2015) reported that the volume shrinkage of oak (*Tabebuia rosea*) wood after air heat treatment at 130, 150, 180, and 210 °C under a pressure of 98 kPa was 3.69, 3.70, 4.55, and 7.03%, respectively. The shrinkage of the wood during heat treatment results in improved dimensional stability, which is desirable for garden furniture, cladding, kitchen, bathroom cabinets, flooring, ceilings, door, window joinery, and other indoor and outdoor applications (Kasemsiri *et al.* 2012).

As aforementioned, the six Korean oak woods are primarily utilized in low-grade applications. To improve their quality and increase their economic value for high-value applications in the Korean wood industry, wood modification methods, such as air heat treatment, are necessary. Recently, the authors investigated the effects of air heat treatment on the color change, weight, and density loss of six Korean oak woods (Prasetia *et al*. 2024). However, there is still limited information available on the fundamental properties of heat-treated wood from the six Korean oak species. Therefore, this study evaluated and compared the effects of air heat treatment at different temperatures on the shrinkage and surface roughness of oak wood to improve its potential for further utilization.

EXPERIMENTAL

Site Description of Sample Collection and Sample Characteristics

Three trees of each oak species were collected from the research forest of Kangwon National University, Chuncheon-si, Gangwon-do, Korea (37° 47' 2.8932" N, 127° 49' 13.368" E). The soil in this region is primarily sandy and gravelly sandy loam (Korea Soil Information System, https://soil.rda.go.kr). The average temperature and precipitation (1966–2023) were as follows: 11.2 °C and 209.0 mm in the spring season, 23.8 °C and 805.3 mm in the summer season, 1.23 °C and 241.0 mm in the fall season, and -2.7 °C and 69.4 mm in the winter season (Korea Meteorological Administration; https://data.kma.go.kr). The diameters of the wood logs at breast height (1.3 m above the ground) ranged from 15.5 cm in *Qal* to 29.7 cm in *Qv*, and the cambial ages ranged from 44 years in *Qal* to 93 years in *Qs*. Fundamental details of the six Korean oak trees are summarized in Table 1.

Wood Board Sample Preparation

After harvesting, the six oak logs were stored in a storage room for one year, cut into flat-sawn lumber with dimensions of 1000 to 1500 mm (longitudinal direction, L) × 200 to 260 mm (tangential direction, T) × 25 to 30 mm (radial direction, R), and air-dried for one month. Twelve defect-free flat-sawn board samples of each oak species with specific dimensions of 300 mm (L) × 90 mm (T) × 25 mm (R) were obtained from the heartwood. The board surface was smoothed using a sanding machine (BSM 6100, 1152 m/min, 1500 W, Topline International, China) equipped with coarse-grit sandpaper (AA80, Dae Sung Abrasive Co. Ltd., Incheon, Korea). The boards were then placed in a controlled environment room at 65 ± 3% relative humidity (RH) and 20 ± 3 °C for two weeks to control moisture content, making them more suitable for subsequent processing and further testing. The air-dried moisture content of six Korean oak wood boards before air heat treatment, measured from ten replications of each species, was approximately 11-12%. Key details of the six Korean oak wood board samples are presented in Table 2.

Air Heat Treatment

Air heat treatment was conducted following Hidayat *et al*. (2015, 2016) using an electric oven with a programmable controller (L-Series, JEIO TECH Ltd., Korea). The treatment started at 20 ± 5 °C and progressed to target temperatures of 160, 180, 200, and 220 °C at a heating rate of 2 °C/min, and then were maintained for 2 h. The oven chamber naturally cooled to 30 ± 5 °C, and the wooden boards were placed in a desiccator filled with silica gel for 1 d. Following this, the boards were stored in a controlled environment room at 65 ± 3% RH and 20 ± 3 °C for 2 weeks before further testing.

Table 1. Fundamental Details about the Six Oak Tree Samples

Scientific name	Tree no.	Breast height diameter (cm)	Cambial age (years)	Location
***Quercus serrata* Murray (*Qs*)**	1	22.2	69	Research forest of Kangwon National University, Chuncheon, Korea (37° 47' 2.8932" N, 127° 49' 13.368" E)
	2	28.3	54	
	3	29.5	93	
***Quercus mongolica* Fisch. ex Ledeb (*Qm*)**	1	21.3	63	
	2	23.7	65	
	3	24.2	64	
***Quercus acutissima* Carruth. (*Qac*)**	1	15.7	48	
	2	23.6	48	
	3	25.8	48	
***Quercus aliena* Blume (*Qal*)**	1	15.5	49	
	2	20.6	44	
	3	25.3	50	
***Quercus dentata* Thunb. (*Qd*)**	1	21.3	82	
	2	21.5	66	
	3	23.7	70	
***Quercus variabilis* Blume (*Qv*)**	1	21.1	63	
	2	23.8	64	
	3	29.7	61	

Table 2. Key Details about the Wood Board Samples from Six Oak Species

Test	Sample dimension (mm)	Species	Air-dry moisture content (%)	Temperature (°C)	*Sample number	Total
Shrinkage and surface roughness	300 (L) × 90 (T) × 25 (R)	*Qs*	11.38 (0.25)	160 180 200 220	$3^{(re)}$ × $6^{(sp)}$ × $4^{(tr)}$	72
		Qm	12.09 (0.22)			
		Qac	11.26 (0.27)			
		Qal	10.88 (0.26)			
		Qd	11.60 (0.30)			
		Qv	11.66 (0.29)			

Numbers within parentheses represent standard deviations. *Sample number = replication $^{(re)}$ × species $^{(sp)}$ × temperature $^{(tr)}$.

Measurement of Shrinkage and Surface Roughness

Radial and tangential shrinkage

To measure the radial and tangential shrinkage of the six Korean oak woods after air heat treatment at different temperatures, the radial (L_r) and tangential (L_t) lengths were measured from six lines (Fig. 1) of each board sample according to KS F 2203 (2009) using an absolute digimatic caliper (CD-45C, 500-500-10, Mitutoyo, Kanagawa, Japan) and calculated using Eq. 1,

$$S_{(r,t)} = \left(\frac{L_1 - L_2}{L_1}\right) \times 100\ (\%) \tag{1}$$

where S (%) represents the shrinkage, and L_1 (mm) and L_2 (mm) denote the lengths in each direction of the air-dried samples before and after air heat treatment, respectively.

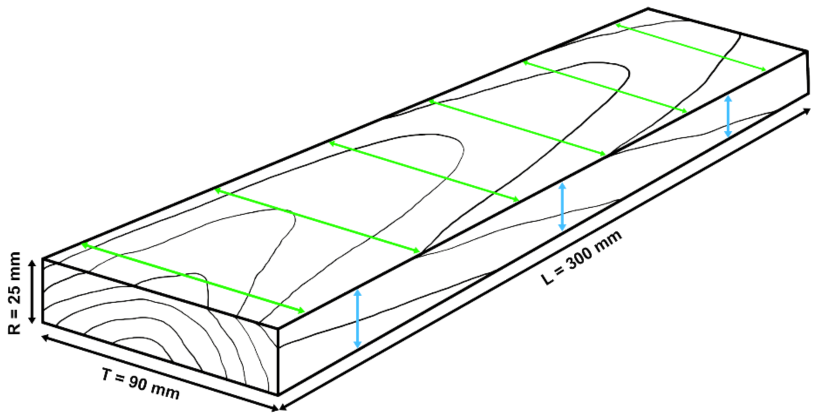

Fig. 1. Schematic of the wood board sample for shrinkage measurement. Six green-lines indicate locations for measuring tangential length, and three blue-lines on one side of the wood board sample indicate locations for measuring radial length.

Surface roughness

To measure the surface roughness, forty-line measurements perpendicular to the fiber direction (Fig. 2) were performed on both sides of the wooden board before and after heat treatment using a portable stylus-type profilometer (Mitutoyo Surftest SJ-210, Kanagawa, Japan). The stylus of the profilometer was calibrated at room temperature before testing. Roughness values were measured with a sensitivity of 0.5 μm using a diamond tip with a radius of 5 μm, scanning line (Lt) length of 15 mm, cut-off of λ = 2.5 mm, and speed of 0.5 mm/s. Three roughness parameters were determined according to ISO 4287 (1997): mean arithmetic deviation of profile (average roughness, R_a), mean peak-to-valley height (R_z), and root mean square roughness (R_q). The changes in surface roughness (R_a, R_z, and R_q) were calculated using Eq. 2,

$$RC_{(a,z,q)} = \left(\frac{R_2 - R_1}{R_1}\right) \times 100\ (\%) \tag{2}$$

where *RC* (%) denotes the surface roughness change and R_1 *and* R_2 the surface roughness of the air-dried samples before and after air heat treatment, respectively.

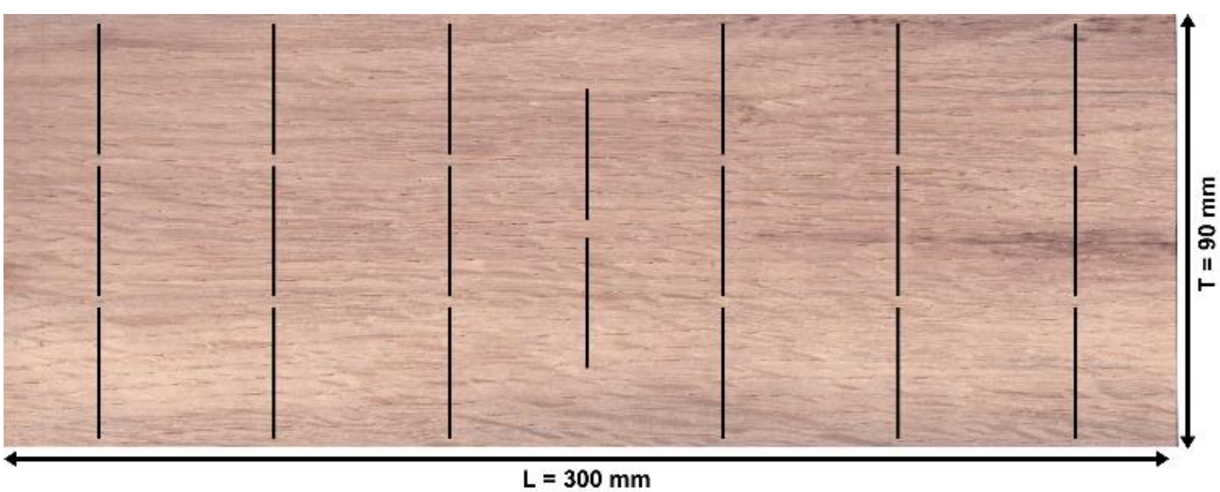

Fig. 2. Twenty black lines on one side of the wood board sample in the tangential surface for measuring surface roughness perpendicular to the fiber direction

Statistical Analysis

The differences in radial and tangential shrinkage and mean surface roughness between temperatures, as well as between species, were statistically analyzed using one-way analysis of variance followed by post hoc Tukey's honest significant difference test (SPSS ver. 24, IBM Corp., NY, USA).

RESULTS AND DISCUSSION

Radial and Tangential Shrinkage

The shrinkage in the radial and tangential directions and the anisotropy coefficient after the air heat treatment are presented in Table 3. Shrinkage increased remarkably with increasing temperature in all six oak wood samples. *Qv* showed the highest shrinkage in both directions at all temperatures among the six oak woods, whereas *Qm* showed the lowest shrinkage.

The radial shrinkage was comparable between *Qv* and *Qac* at 160 and 180 °C. *Qd* and *Qs* showed similar radial shrinkage to *Qm* and *Qal* at 160 and 220 °C, respectively. Additionally, there was no significant difference in the radial shrinkage between *Qm* and *Qal* at all temperatures. Significant differences in radial shrinkage were observed among *Qs*, *Qm*, *Qac*, and *Qv* at 200 °C.

The tangential shrinkage was comparable between *Qv* and *Qd* at 160 °C, and *Qac* showed similar shrinkage to *Qs* and *Qal* at 180 °C. At 200 °C, there were no significant differences between *Qm* and *Qs* or between *Qac* and *Qal*, showing significantly higher tangential shrinkage in *Qac* and *Qal* than *Qm* and *Qs*. At 220 °C, significant differences in tangential shrinkage were observed among the six oak wood samples.

In six oak woods, the anisotropy coefficients decreased from temperature 160 to 200 °C, and then increased at 220 °C. Overall, the highest anisotropy coefficients were observed in *Qal* at 160 and 220 °C and *Qd* at 180 and 200 °C, whereas the smallest anisotropy coefficients were found in *Qac* at 160 °C, *Qs* at 180 and 200 °C, and *Qm* at 220 °C. The reduced dimensions observed during air heat treatment were consistent with those reported in previous studies. Uribe and Ayala (2015) reported that the volume shrinkage of oak wood (*Tabebuia rosea*) was 3.69% at 130 °C, 3.70% at 150 °C, 4.55% at 180 °C, and 7.03% at 210 °C, with significant increases in volume shrinkage observed after 180 °C. Mazzanti *et al*. (2012) mentioned that volume shrinkage showed variation after heat treatment at 180 °C. Hidayat *et al*. (2015) reported that the reduction in the dimension and weight of the wood during heat treatment at temperatures higher than 160 °C was caused by the change in chemical components and wood cell structure. Kasemsiri *et al.* (2012) and Tiryaki e*t al.* (2016) explained that the shrinkage of wood due to heat treatment could enhance dimensional stability and reduce hygroscopicity. The changes in chemical composition, such as the reduction of hydroxyl groups in hemicelluloses, replaced by hydrophobic acetyl groups, lead to crosslinking between wood fibers, thereby making the wood less hygroscopic and more dimensionally stable (Kasemsiri *et al.* 2012; Korkut and Aytin 2015). The magnitude of wood shrinkage is influenced by various factors, including density, wood species, type of wood (juvenile or mature), moisture content, anatomical structure, extractives, chemical composition, and mechanical stress (Tsoumis 1991; Todorova *et al.* 2023).

Table 3. Radial and Tangential Shrinkages and Anisotropy Coefficient of Six Korean Oak Woods Treated at Different Temperatures

Radial (R) and tangential (T) shrinkages (%) and anisotropy coefficient (T/R)																		
Treatment	*Qs*			*Qm*			*Qac*			*Qal*			*Qd*			*Qv*		
	R	T	T/R	R	T	T/R	R	T	T/R	R	T	T/R	R	T	T/R	R	T	T/R
160 °C	2.00^{aBC} (0.07)	2.68^{aB} (0.06)	1.34	1.78^{aA} (0.04)	2.34^{aA} (0.09)	1.32	2.10^{aCD} (0.06)	2.74^{aBC} (0.04)	1.31	1.80^{aA} (0.09)	2.76^{aBC} (0.08)	1.53	1.92^{aAB} (0.08)	2.91^{aCD} (0.09)	1.52	2.24^{aD} (0.05)	3.10^{aD} (0.09)	1.39
180 °C	2.38^{bBC} (0.05)	2.92^{bB} (0.04)	1.23	2.11^{bA} (0.08)	2.77^{bA} (0.04)	1.31	2.42^{bCD} (0.02)	3.03^{bBC} (0.03)	1.25	2.25^{bAB} (0.06)	3.16^{bC} (0.06)	1.40	2.29^{bBC} (0.05)	3.52^{bD} (0.07)	1.54	2.54^{bD} (0.04)	3.73^{bE} (0.06)	1.47
200 °C	2.96^{cC} (0.03)	3.33^{cA} (0.06)	1.13	2.70^{cA} (0.03)	3.17^{cA} (0.04)	1.17	3.24^{cD} (0.07)	3.54^{cB} (0.05)	1.09	2.81^{cAB} (0.03)	3.52^{cB} (0.07)	1.25	2.91^{cBC} (0.02)	4.12^{cC} (0.04)	1.42	3.42^{cE} (0.05)	4.53^{cD} (0.10)	1.32
220 °C	3.64^{dAB} (0.03)	4.85^{dB} (0.07)	1.33	3.49^{dA} (0.02)	4.25^{dA} (0.02)	1.22	3.78^{dB} (0.05)	5.23^{dC} (0.04)	1.38	3.52^{dA} (0.06)	5.50^{dD} (0.04)	1.56	4.14^{dC} (0.05)	5.76^{dE} (0.08)	1.39	4.65^{dD} (0.05)	6.75^{dF} (0.24)	1.45

Numbers within parentheses represent standard deviations. Numbers in the same column with the same superscript lowercase letters indicate nonsignificant outcomes at the 5% significance level for temperature comparisons. The mean values in the same row followed by the same superscript capital letters indicate non-significant outcomes at the 5% significance level for species comparisons.

The smaller and greater shrinkage observed in *Qm* and *Qv* woods, respectively, could be attributed to their density. Schulgasser and Witztum (2015) noted that low-density wood generally shrinks less than denser wood. In our previous study (Prasetia *et al*. 2024), the density of the six Korean oak species, both before and after heat treatment, showed that *Qm* had the lowest density, followed by *Qs*, *Qal*, *Qac*, *Qv*, and *Qd*, which had the highest.

Surface Roughness

The surface roughness, such as R_a, R_q, and R_z values, of six Korean oak woods before and after heat treatment is summarized in Table 4, showing decreased values with increasing temperature.

R_a is the most commonly used parameter for surface-finish measurements (Unsal and Ayrilmis 2005; Korkut *et al*. 2010; Salca and Hiziroglu 2014; Ozcan *et al*. 2012). The R_a values before and after the heat treatment are shown in Fig. 3. R_a value remarkably decreased in *Qs* wood at 160 and 200 °C, in *Qm* and *Qv* woods at 160, 180, and 220 °C, in *Qac* wood at 180 and 220 °C, in *Qal* wood at 200 °C, and in *Qd* wood at 180 °C.

Moreover, the R_a values of the six oak wood samples at different temperatures were mostly comparable. The R_a value of untreated oak wood ranged from 6.457 μm in *Qal* to 8.080 μm in *Qs*. In heat-treated wood, *Qs* exhibited the highest R_a values among the six oak species at all temperatures, measuring 7.549 μm at 160 °C, 7.287 μm at 180 °C, 6.466 μm at 200 °C, and 6.169 μm at 220 °C. In contrast, *Qm* showed the lowest R_a values at 160, 180, and 200 °C, with values of 6.244, 5.701, and 5.478 μm, respectively, while *Qac* had the lowest R_a value at 220 °C, measuring 5.039 μm.

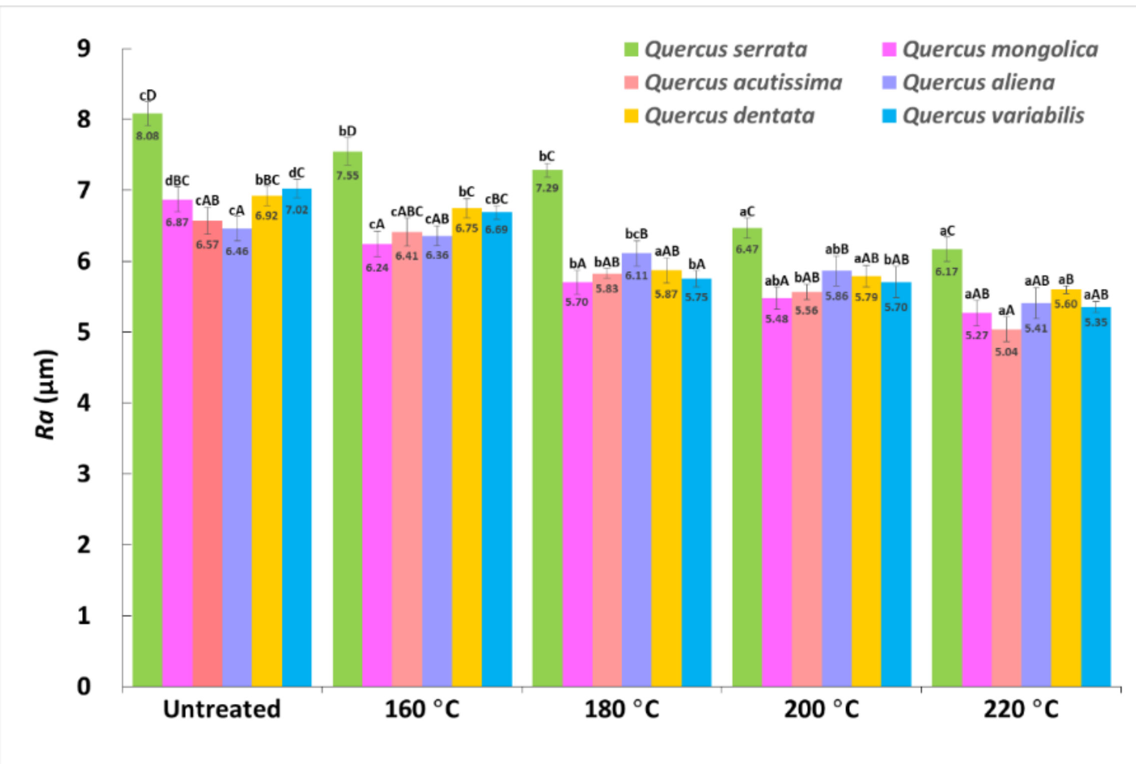

Fig. 3. Effect of air heat treatment on the R_a value of six Korean oak woods. Different lowercase letters and capital letters indicate significant differences at the 5% significance level for comparisons between temperatures and among species, respectively.

The surface roughness changes in the six Korean oak woods after air heat treatment at different temperatures are presented in Table 5, which shows a decrease with increasing temperature. The change in R_a of the six oak woods at 160 °C ranged from -1.5% in *Qal* to -9.1% in *Qm*. The highest decrease in R_a value occurred at 220 °C, ranging from -16.3% in *Qal* to -23.8% in *Qv*. In particular, *Qm* showed the highest decrease at 160 and 200 °C, and *Qv* exhibited the highest decrease at 180 and 220 °C. Conversely, *Qal* consistently decreased the least at all the temperatures

In this study, the surface roughness of the six Korean oak wood samples decreased with increasing temperature. Several studies support these findings on the surface roughness during air heat treatment. Korkut *et al*. (2010) reported that sessile oak treated at 180 °C for 10 h showed an improvement in R_a value of up to 25.7%, which was lower than that of the untreated sample. Salca and Hiziroglu (2014) observed that the *Q. falcate* wood surface became smoother with increasing temperature from 120 to 190 °C and duration for 3 to 6 h, showing a 7.46% improvement in R_a value at 190 °C for 6 h compared to 3 h. Ozcan *et al*. (2012) found that the R_a value of *Q. petraea* decreased with increasing temperature, showing a 15% improvement in the R_a value at 180 °C for 6 h. Perçin *et al*. (2016) reported that the surface roughness values of *Q. petraea* wood decreased at 150, 170, and 190 °C for 2, 5, and 8 h but increased at 210 °C for the same durations. In contrast, Korkut and Hiziroglu (2014) found that heat treatment at both 110 and 200 °C for 8 h did not significantly affect the wood surface of *Q. falcate*, with the R_a value slightly increasing at 110 °C and then decreasing at 200 °C.

The decrease in the surface roughness of the six oak woods after air heat treatment may be attributed to the densification and compactness of the wood surface. According to Korkut *et al*. (2010) and Ozcan *et al*. (2012), heat treatment results in plastification of solid wood surfaces. Furthermore, temperatures above 150 to 160 °C led to the conversion of lignin into a thermoplastic condition, resulting in increased density and compactness of the wood surface layer.

As heat treatment decreases the surface roughness, it could reduce production costs by minimizing the need for extensive sanding and preventing wood thickness reduction during the process. The magnitudes of R_a, R_q, and R_z can be attributed to the anatomical characteristics of the wood, including the porosity, proportions of earlywood and latewood, rays, vessel elements, tracheids, wood fibers, parenchyma cells, and lumber cut style (plain sawn, quarter sawn, or rift sawn). Söğütlü (2005) noted that surface roughness is influenced by various factors, such as parenchyma, tracheids, resin canals, wood species, the proportions of earlywood and latewood, and the direction of the wood cut, whether horizontal, radial, or tangential.

The higher surface roughness observed for *Qs* compared to that of the other oak species may be attributed to its lower proportion of latewood. A previous study by Savero *et al*. (2023) reported that the growth rings of *Qs* measured 1.62 mm and exhibited a significantly smaller percentage of latewood among six Korean oak species. Malkocoğlu (2007) noted that surface roughness tends to be lower in latewood compared to earlywood.

Table 4. Surface Roughness of Six Korean Oak Woods Before and After Air Heat Treatment at Different Temperatures

Treatment	Surface roughness (μm)																	
	Qs			*Qm*			*Qac*			*Qal*			*Qd*			*Qv*		
	R_a	R_q	R_z	R_a	R_q	R_z	R_a	R_q	R_z	R_a	R_q	R_z	R_a	R_q	R_z	R_a	R_q	R_z
Untreated	8.080^{cD} (0.16)	11.056^{fB} (0.15)	61.746^{dB} (1.40)	6.869^{dBC} (0.17)	9.371^{dA} (0.36)	53.487^{cA} (2.42)	6.572^{cAB} (0.19)	9.196^{dA} (0.29)	53.544^{dA} (2.89)	6.457^{cA} (0.17)	9.061^{dA} (0.11)	52.59^{cA} (0.63)	6.919^{bBC} (0.13)	9.297^{cA} (0.19)	52.269^{dA} (1.88)	7.024^{dC} (0.13)	9.528^{cA} (0.31)	54.183^{dA} (2.44)
160 °C	7.549^{bD} (0.20)	10.159^{dD} (0.19)	54.340^{cC} (0.97)	6.244^{cA} (0.18)	8.636^{cAB} (0.27)	51.254^{cBC} (0.26)	6.413^{cABC} (0.20)	8.453^{cA} (0.07)	46.943^{cA} (0.50)	6.359^{cAB} (0.14)	8.574^{cA} (0.20)	48.819^{bAB} (1.13)	6.745^{bC} (0.14)	9.121^{cBC} (0.33)	50.432^{cdB} (2.52)	6.687^{cBC} (0.09)	9.168^{cC} (0.07)	50.733^{cdB} (1.22)
180 °C	7.287^{bC} (0.10)	9.525^{cB} (0.21)	51.415^{cC} (2.77)	5.701^{bA} (0.17)	7.793^{bA} (0.38)	45.257^{bAB} (1.93)	5.830^{bAB} (0.08)	7.811^{bA} (0.20)	43.772^{bcA} (1.59)	6.111^{bcB} (0.18)	8.282^{cA} (0.21)	47.306^{bABC} (1.40)	5.869^{aAB} (0.18)	8.115^{bA} (0.21)	47.324^{cABC} (1.69)	5.748^{bA} (0.12)	8.061^{bA} (0.28)	48.104^{cBC} (1.36)
200 °C	6.466^{aC} (0.14)	8.318^{bB} (0.27)	45.225^{bB} (1.68)	5.478^{abA} (0.15)	7.704^{bA} (0.20)	43.749^{bB} (1.16)	5.563^{bAB} (0.11)	7.553^{bA} (0.20)	40.091^{abA} (1.75)	5.863^{abB} (0.21)	7.488^{bA} (0.10)	37.914^{aA} (0.92)	5.788^{aAB} (0.15)	7.808^{bA} (0.19)	43.021^{bB} (0.84)	5.704^{bAB} (0.22)	7.773^{bA} (0.07)	43.451^{bB} (1.55)
220 °C	6.169^{aC} (0.17)	7.783^{aC} (0.13)	40.970^{aB} (1.35)	5.270^{aAB} (0.18)	6.954^{aAB} (0.28)	37.636^{aAB} (2.96)	5.039^{aA} (0.18)	6.609^{aA} (0.25)	35.796^{aA} (1.66)	5.407^{aAB} (0.22)	6.787^{aAB} (0.23)	36.130^{aA} (0.96)	5.599^{aB} (0.05)	7.118^{aB} (0.09)	38.974^{aAB} (0.50)	5.353^{aAB} (0.08)	7.011^{aAB} (0.13)	38.009^{aAB} (0.98)

Numbers within parentheses represent standard deviations. Numbers in the same column with the same superscript lowercase letters indicate nonsignificant outcomes at the 5% significance level for temperature comparisons. The mean values in the same row followed by the same superscript capital letters indicate non-significant outcomes at the 5% significance level for species comparisons.

Table 5. Surface Roughness Change of Six Korean Oak Woods Treated at Different Temperatures

Treatment	Surface roughness change (%)																	
	Qs			*Qm*			*Qac*			*Qal*			*Qd*			*Qv*		
	R_a	R_q	R_z	R_a	R_q	R_z	R_a	R_q	R_z	R_a	R_q	R_z	R_a	R_q	R_z	R_a	R_q	R_z
160 °C	-6.6	-8.1	-12.0	-9.1	-7.8	-4.2	-2.4	-8.1	-12.3	-1.5	-5.4	-7.2	-2.5	-1.9	-3.5	-4.8	-3.8	-6.4
180 °C	-9.8	-13.8	-16.7	-17.0	-16.8	-15.4	-11.3	-15.1	-18.2	-5.4	-8.6	-10.1	-15.2	-12.7	-9.5	-18.2	-15.4	-11.2
200 °C	-20.0	-24.8	-26.8	-20.3	-17.8	-18.2	-15.4	-17.9	-25.1	-9.2	-17.4	-27.9	-16.4	-16.0	-17.7	-18.8	-18.4	-19.8
220 °C	-23.7	-29.6	-33.6	-23.3	-25.8	-29.6	-23.3	-28.1	-33.1	-16.3	-25.1	-31.3	-19.1	-23.4	-25.4	-23.8	-26.4	-29.9

CONCLUSIONS

1. Shrinkage in the radial and tangential directions increased with increasing temperature. *Quercus mongolica (Qm)* exhibited the smallest shrinkage in both directions, whereas *Quercus variabilis (Qv)* exhibited the highest shrinkage at all temperatures.
2. The anisotropy coefficients of the six Korean oak woods decreased from 160 to 200 °C and increased at 220 °C. *Quercus aliena* (*Qal*) and *Quercus dentata* (*Qd*) had the highest anisotropy coefficients at 160 and 220 °C, and 180 and 200 °C, respectively. *Quercus acutissima* (*Qac*), *Quercus serrata* (*Qs*), and *Qm* exhibited the smallest anisotropy coefficients at 160 and 180 °C, and 200 and 220 °C, respectively.
3. The surface roughness of six Korean oak wood samples decreased with increasing temperature. Among the untreated and heat-treated samples, *Qs* exhibited the highest R_a value. The smallest R_a values were observed in untreated *Qal*, in *Qm* at 160–200 °C, and in *Qac* at 220 °C.
4. The change in surface roughness decreased with increasing temperature for all wood samples. *Qm* showed the highest change in the R_a value at 160 and 200 °C, while *Qv* had the highest change at 180 and 220 °C. *Qal* consistently exhibited the smallest change in R_a at all temperatures.

Air heat treatment significantly smoothed the surfaces of the six Korean oak wood samples. Although noticeable differences were observed in the radial and tangential shrinkage among the species, the surface roughness of the six oak woods after air heat treatment was mostly comparable. These findings provide valuable insights into the effects of air heat treatment on the wood properties of six oak species grown in Korea, thus improving their potential for further utilization.

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