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RELATIONSHIP BETWEEN WOOD ANATOMICAL FEATURES AND SURFACE ROUGHNESS CHARACTERISTICS

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ABSTRACT

This study aimed to investigate the relationship between surface roughness and anatomical features of wood in 15 different species of boards. Surface roughness was measured parallel and perpendicular to the wood grain using a surface profilometer, and anatomical features such as pore size and distribution were analyzed using microscopic techniques. The results showed that surface roughness perpendicular to the grain direction was consistently higher than that parallel to the grain direction for all wood samples. This difference in roughness was correlated with pore size and density. It shows that the larger pores and lower density lead to higher roughness perpendicular to the grain. The study also found that traditional hand planning methods (push and pull) produced a smooth surface finish, with no statistical differences in roughness.

KEYWORDS: Wood surface roughness, anatomical features, hand planning, wood board density, wood grain direction.

INTRODUCTION

The surface roughness of wood is an important quality parameter as it influences the tactile and visual perception of the wood surface (Bertheaux et al. 2020, Todaro et al. 2015, Todde et al. 2018, Zhong et al. 2013). The surface roughness of wood is influenced by various factors such as constituent cells, cell wall density, moisture content, and processing methods (Brémaud et al. 2011, Korkut and Donertas 2007, Lemaster and Beal 1993, Ling and Xie 2022, Wengert 1994). The surface roughness of wood affects aesthetic appearance and feeling of touch and affects subsequent processing processes such as bonding, painting, or grinding (Thoma et al. 2015). However, measuring wood surface roughness is challenging due to its complex nature, which includes multiple forms of roughness such as form, waviness, and roughness (Myshkin et al. 2003).

The statistical processing is carried out, such as the average amplitudes corresponding to the roughness height or the average of roughness intervals. Although surface roughness is commonly stated as average surface roughness at the center line (R_a), R_{max}; maximum roughness, and R_z; mean peak-to-valley height (Hiziroglu 1996). Kilic et al. (2006) observed that wood surface roughness influences aesthetics from macroscopic and microscopic levels. A person can effectively recognize the magnified microscopic surface texture by looking at it. However, this is a labor-intensive and time-consuming procedure. Therefore, Razaei et al. (2020) used the laser approach to measure wood's surface roughness and waviness and compared it to the touch method. They found that the laser approach had 31% greater surface roughness and 35% higher average waviness than the touch method.

Various techniques are employed in the wood processing industry to measure the surface roughness of wood. These methods range from subjective evaluations using visual and tactile senses to objective measurements using surface-measuring equipment. The initial algorithms used to assess wood surface roughness rely on physical characteristics such as pressure and touch rubbing. These methods are often more precise and economical compared to techniques that utilize surface-measuring equipment (Fujiwara et al. 2005). Besides, surface roughness detection methods can be classified as touch and non-contact, as well as line and area methods (Chang and Ravathur 2005). A contact method is a stylus profilometer (Lee and Cho, 2012). This method employs a stylus pin to draw a straight line directly on the sample surface, with the estimated location substantially influencing the surface roughness value. Non-contact technologies are commonly used in the industrial area for the simplicity of accessibility and process automation (Lee and Kim 1999, Park and Jeong 1992). The irregularity of processed wood surfaces, resulting from the complex cellular structure of wood and various machining processes, makes it challenging to establish standards for measuring wood surfaces, rendering their use unreliable (Funck et al. 1993, Thoma et al. 2015). A recent article described sawing oak wood's theoretical machined surface roughness profile along the grain with a circular saw (Đukić et al. 2023).

Karlinsari et al. (2018) and Piao et al. (2010) reported that the higher the surface roughness, the higher the surface hydrophilicity or the lower the contact angle. In addition, contact angle values that are decreasing, stagnating, or rising are correlated with surface roughness (Papp and Csiha 2017). A lower contact angle is due to associated with increased adhesion (Csiha and Gurau 2011). On the other hand, wood specimens densified with a high compression ratio (40%) could provide better results (lower roughness and higher contact angle) (Pelit and Arısüt 2023). Besides, Piao et al. (2010) and Margos (2008) reported that the cellular structure affects wood surface roughness. Moreover, the internal structure of wood is characterized by anatomical cavities such as vessels and cell lumens, which are unique to this material (Luo et al. 2020).

However, a hand planer can finish the wood surface but has the same surface roughness as a machined surface. Hand planning is a typical method of finishing wood surfaces, and there are pushing and pulling processes. Before the 15th century, the push method was used in Japan. Nowadays, the pulling approach is popular in Japan. However, the push and pull methods are applied in Korea, even though the pulling approach is more popular.

In this study, we estimated the surface roughness of 11 species of hardwoods and 4 conifers using the SJ-310 surface roughness tester. This tester was chosen because it yields precise results and accommodates various measuring orientations. The 2D contact measurement of wood surface roughness could be improved by a three-dimensional (3D) non-contact measurement technique like an optical profilometer. Wood materials are not suitable for modern 3D optical profilometers because of their large surface areas, which result in more uneven surfaces than metals (Li et al. 2014). Moreover, we observed each species' anatomical characteristics and correlated the findings with the surface roughness of 15 species of wood. Also, we investigated the effect of wood surface roughness when surfaced by the pushing and pulling method. Surfacing was performed by pushing one side and pulling the other side, ignoring the wood component, and measuring the difference by planning technique.

MATERIAL AND METHODS

Samples preparation

Fifteen species of boards with a dimension of 17 mm (tangential) x 100 mm (radial) and a length of 150 mm (longitudinal) from 11 hardwoods such as *Ulmus davidiana, Prunus sargentii, Carster Aralia, Zelkova serrata, Cornus controversa, Phellodendron amurense, Castanea crenata, Paulownia tomentosa, Betula schmidtii, Cedrela sinensis, and Populus canadensis*, and 4 softwoods including *Metasequoia glptostroeboides, Larix kaemferi, Pinus densiflora, and Ginkgo biloba* were used. The moisture content and specific gravity of the specimens range from 6.0 to 9.3% and 0.26 to 0.95 $g{\cdot}cm^{-3}$, respectively.

For this investigation, specimens were sliced by pulling the type plane, and the other by pushing the type plane, as shown in Fig. 1. A skilled craftsman operated a push-pull type planer at a consistent speed and rhythm. The operation was assumed to be regularly repeated. As a result, apart from the direction of the plane, i.e., pulling or pushing, the sample specimen conditions on all sides were considered the same.

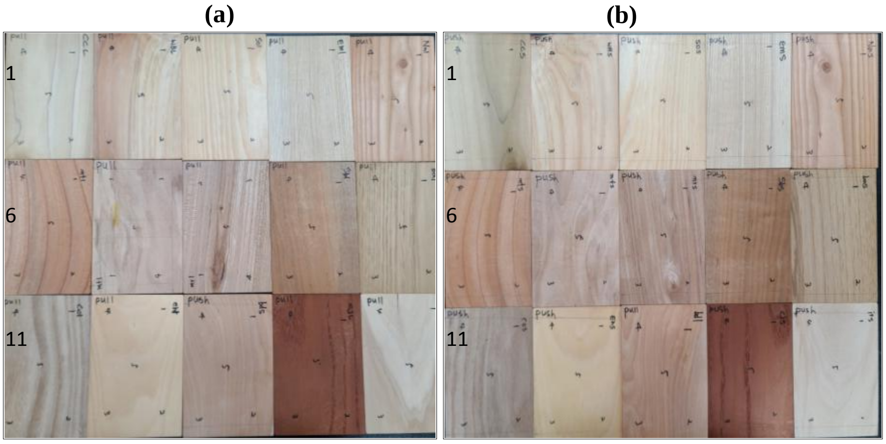

Fig. 1: Sample specimens for measuring wood surface roughness (a) pull-type planed surfaces and (b) push-type planed surfaces (1. Cornus controversa, 2. Phellodendron amurense, 3. Pinus densiflora, 4. Carster Aralia, 5. Larix kaemferi, 6. Zelkova serrata, 7. Metasequoia glptostroeboides, 8. Ulmus davidiana, 9. Prunus sargentii, 10. Castanea crenata, 11. Paulownia tomentosa, 12. Ginkgo biloba, 13. Betula schmidtii, 14. Cedrela sinensis, 15. Populus canadensis).

Wood surface roughness estimation

A Mitutoyo SJ-310 to observe the surface of the push and pull-type planed surfaces of the 15 species boards was used, as shown in Fig. 2. The Mitutoyo SJ-310 can estimate surface roughness by line tracing with a piezoelectric sensor. Wood surface roughness was estimated in five numbered places, including the top left, bottom left, bottom right, and central region, both parallel and perpendicular to the grain.

From the roughness estimations at these five places, we evaluated the surface roughness characteristics, such as average roughness (Ra), mean peak-to-valley (Rz), and maximum roughness (Rmax), of the specimens. The sampling length and evaluation length were 0.8 mm and 4 mm, respectively.

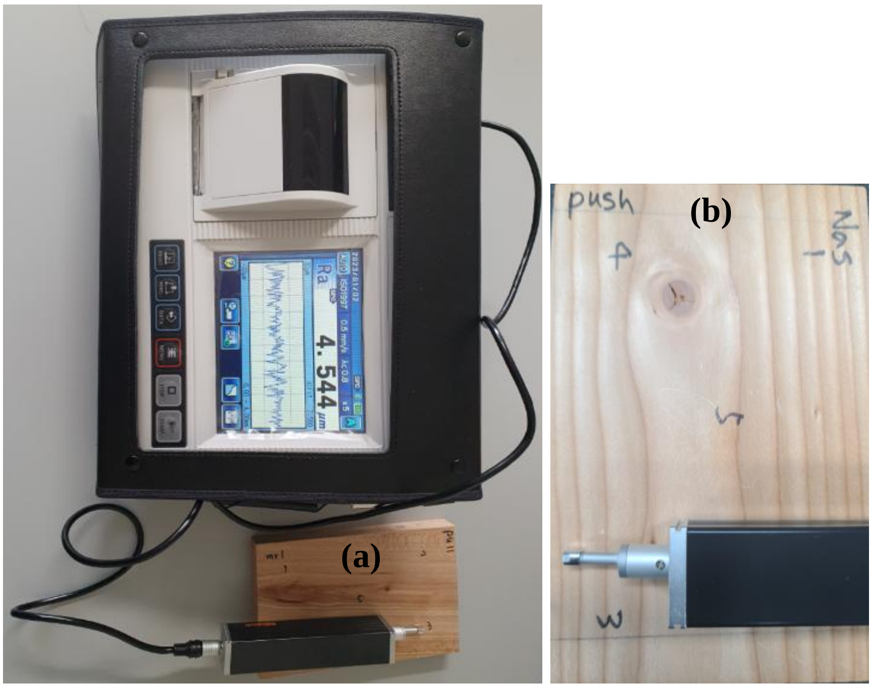

Fig. 2: Wood surface roughness estimation using SJ-310 at the 5 places of parallel and perpendicular to the grain of pull and push planner surface (a) parallel, (b) perpendicular measurement pictures.

SEM observation and pore diameter estimation

A Genesis-1000 SEM from Emcrafts (Korea) to analyze the cross-sectional surface of wood specimens was used. The sample specimens had dimensions of 6 mm x 6 mm x 5 mm (tangential x radial x longitudinal). To evaluate the relationship between surface roughness in the inline direction and pore diameter, we measured the diameters of vessel elements in 11 species of hardwoods and the diameters of tracheids in 4 species of softwoods. The diameters of vessel elements of early-wood and tracheids of early wood, which are expected to have a significant effect on surface roughness were measured. ImageJ software (version 1.44p, Bethesda, USA) was used to measure the diameters of 10 spots in cross-sectional electron micrographs of each species. For example, Fig. 3 shows SEM images of four different species at a magnification of 100x.

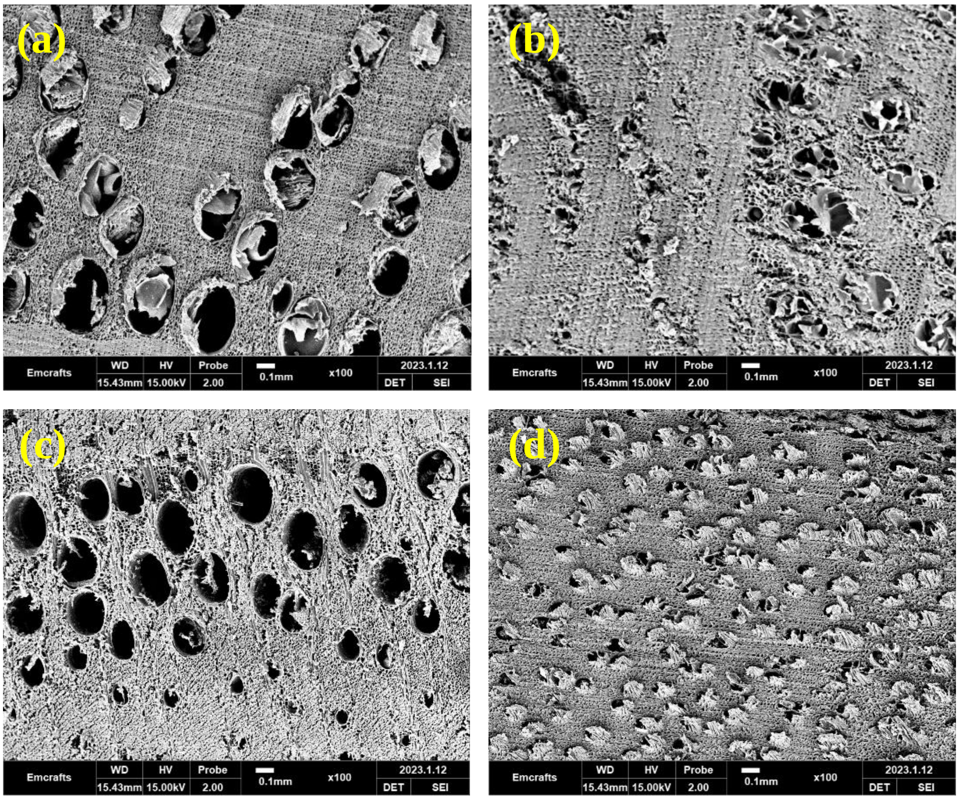

Fig. 3: SEM micrographs of (a) Castanea crenata, (b) Paulownia tomentosa, (d) Cedrela sinensis, and (e) Populus canadensis.

RESULTS AND DISCUSSION

The surface roughness estimation results for 15 wood species are presented in Tab. 1. The values shown in the table represent the mean values and standard deviations of surface roughness parameters, which were measured for 15 wood specimens that underwent both push and pull hand planing. The measurements were taken from five different regions of the board surface, and the average values were calculated accordingly.

Surface roughness is a complex shape comprising mountains and valleys of different heights, depths, and intervals. Among them, the periodicity is relatively short, and it refers to a surface condition with undulations at narrow intervals. This graph is called the total profile, which contains roughness and waviness profiles. The roughness profile contains only high-frequency constituents from the traced profile. Fig. 4 illustrates the roughness profiles of pinus densiflora board samples. The average peak height of the 15 wood species boards, Ra, was obtained from the roughness profile and shown in Tab. 1.

Tab. 1: Mean surface roughness values of 15 wood species boards after hand planning using push and pull methods.

Sample name	**Density ($g\ cm^{-3}$)**	**Ra push (µm)**	**Ra pull (µm)**
Cornus controversa	0.55	4.68 ± 2.09	4.93 ± 2.10
Phellodendron amurense RUPR	0.34	5.24 ± 1.52	4.96 ± 2.83
Pinus densiflora	0.48	4.28 ± 1.15	4.44 ± 1.19
Carster Aralia	0.62	6.57 ± 3.36	6.30 ± 2.49

Larix kaemferi	0.55	3.49 ± 1.13	4.19 ± 1.97
Zelkova serrata	0.74	4.20 ± 2.28	5.75 ± 3.07
Metasequoia glptostroeboides	0.79	4.49 ± 2.02	4.38 ± 2.67
Ulmus davidiana var. japonica	0.65	6.83 ± 3.50	5.64 ± 3.80
Prunus sargentii Rehder	0.70	3.64 ± 1.96	3.40 ± 1.54
Castanea crenata S.et Z.	0.50	7.54 ± 7.12	6.05 ± 4.12
Paulownia tomentosa	0.26	6.59 ± 2.81	8.80 ± 4.70
Ginkgo biloba	0.46	4.78 ± 0.99	4.92 ± 1.10
Betula schmidtii	0.95	2.36 ± 1.04	3.13 ± 1.63
Cedrela sinensis	0.60	9.08 ± 7.54	6.93 ± 8.34
Populus canadensis	0.35	7.62 ± 3.30	7.59 ± 2.21

The cutting conditions and anatomical characteristics of wood significantly impact its surface roughness. If the cutting conditions are the same, the surface roughness of wood is affected by anatomical structural variables such as wood cell wall ratio, thickness, lumen diameter, annual ring formation, earlywood and latewood transition, and latewood ratio.

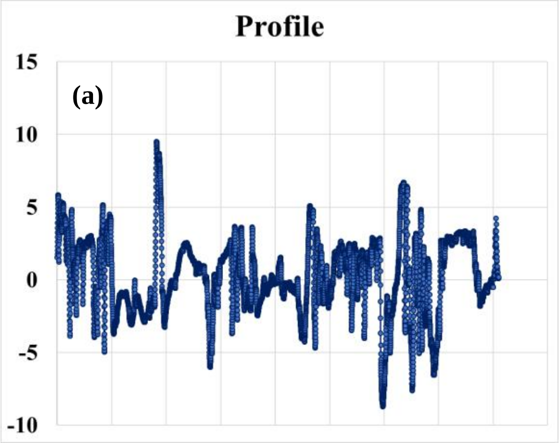

Fig. 4: Typical roughness profiles of Pinus densiflora board (unit: μm).

These factors work together in a complex way to produce surface roughness, which can be observed roughly by wood density. From the roughness profile, surface roughness in line was calculated. The highest Ra of parallel to the grain direction (PAGD) was 5.37 ± 3.13 μm, while the Ra value of PEGD was observed at 10.01 ± 2.85 μm in *Paulownia tomentosa* with a density of 0.26 g cm^{-3}. However, on the *Betula schmidtii* board, the smallest Ra of PAGD was found at 1.92 ± 0.83 μm, and for perpendicular to the grain direction (PEGD) was 3.57 ± 1.47 μm with a density of 0.96 g cm^{-3}. Wood is a heterogeneous anisotropic porous material, composed of the wood cell wall, the frame, and the tracheid cell wall lumen or vessel element lumen. The surface roughness becomes rough when the specific gravity decreases due to high porosity or large diameter pores. Fig. 5a shows the relationship between the specific gravity and average surface roughness of the 15 samples. From the figure, it can be observed that surface roughness tends to increase inversely proportional to the specific gravity.

To investigate the relationship between pore size and roughness, the relationship between the largest pore diameter and average roughness in cross-sectional electron micrographs of 15 wood species is shown in Fig. 5b. In the graph, pore size is the average of the diameters of ten large pores, like vessel elements in hardwoods and earlywood tracheids in softwoods in cross-section from the scanning electron micrographs of the cross-sectional surface of the wood. Therefore, the structure analysis can predict the roughness of the wood surface. The surface roughness values of *Paulownia tomentosa* and *Populus canadensis* were found to be higher than those of *Larix kaemferi* and *Betula schmidtii* boards. The higher surface roughness values in *Paulownia tomentosa* can be attributed to the big diameter pore of the vessel of early wood, which influences the surface roughness. Similarly, the sudden change in diameter between earlywood and latewood and the thin cell wall ratio and high porosity during the high density and low porosity and slow diameter change between earlywood and latewood in Betula schmidtii are responsible for the higher surface roughness values.

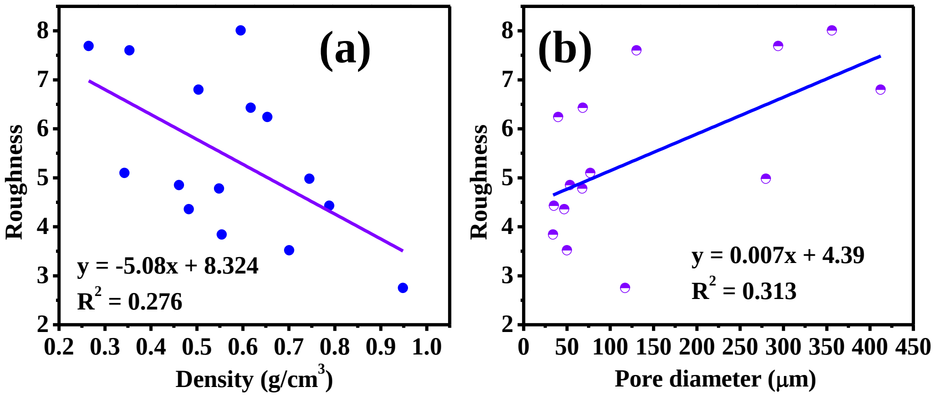

Fig. 5: Relationship between surface roughness with (a) wood density and (b) pore diameter of 15 species of board.

According to Thoma et al. (2015), wood texture and uniformity play a significant role in determining the roughness of wood surfaces. Wood species with a delicate texture, like beech or white fir, have smoother surface roughness than those with a coarse texture, like oak and Aleppo pine. The uniformity of texture or the size and distribution of pores, particularly in the early wood zone, can also contribute to an uneven wood texture (Daoud et al. 2005). Diffuse-porous woods with tiny pores are usually more evenly textured than wood species with larger and more open pores, such as oak (Thoma et al. 2015).

It can be challenging to accurately estimate surface roughness values using line estimation, as the values show a big difference in the estimated position. In this study, surface roughness values were estimated at ten places on both pulled and pushed surfaces. Each surface contains five places parallel to the grain and perpendicular to the grain, resulting in an arithmetic mean value of 20 estimations. The surface roughness in line estimation perpendicular to the grain direction was found to be higher than that parallel to the grain direction, as fluctuations in the direction perpendicular to the voids are more significant than in the direction parallel to the longitudinal voids.

When comparing planning directions, there were almost no differences observed between pulling and pushing planning in the case of the 15 species used in this study.

CONCLUSIONS

The study found that surface roughness perpendicular to the grain direction was higher than that parallel to the grain direction for 15 wood species. The higher-density boards yielded a smoother surface finish, and the surface roughness increased with the diameter of the pores in the wood. Moreover, results show no significant difference in surface roughness between the pushing and pulling hand planning methods. This information can be helpful for professionals in the woodworking industry.

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