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ORIGINAL ARTICLE

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Assessment of wood surface roughness: comparison of tactile roughness and three-dimensional parameters derived using a robust Gaussian regression filter

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Abstract Japanese oak and Japanese beech were sanded by hand with abrasive papers of varying grit number. Two three-dimensional parameters selected to characterize their surface roughness – one parameter for the distribution of roughness-profile peaks and the other for the relative area of the roughness-profile peaks above the threshold height – were compared against tactile roughness. The parameters were obtained from roughness profiles as determined by a robust Gaussian regression filter (RGRF) using seven cutoffs. The RGRF filtering process was adjusted specifically for the evaluation of wood surface roughness. Except for a cutoff wavelength of 0.25 mm, the RGRF lent itself well to the determination of roughness profiles. No distortion of roughness profiles occurred around deep valleys, and there was a good correlation between the parameters and tactile roughness.

Key words Wood surface roughness · Tactile roughness · Three-dimensional parameter · Robust Gaussian regression filter

Introduction

Surface roughness is an important criterion when assessing wood product quality. It is usually evaluated by surface texture parameters defined in standards such as ISO 4287-1997 and JIS B 0601-2001. However, these parameters, which are based on a single roughness profile, cannot always adequately characterize the surface roughness of wood because the surface of machined wood shows irregularities caused by heterogeneities in both machining tools and the cellular structure of wood. There is no established parameter for characterizing the roughness of wood surfaces despite numerous reports[1–7] published on the subject since the 1950s.

Such a parameter would have to correspond to tactile roughness because the surface of wood products is often assessed by tactile contact. Only a few reports have examined the relation between the surface roughness of wood and tactile roughness. Fujii et al.[8] found that there was no relation between certain parameters described in JIS B 0601-1994 and tactile roughness. Fujiwara et al.[9–11] tried to link three-dimensional parameters, which are also what the present study is based on, to tactile roughness. Their attempt failed because the primary profile had local deep valleys due to vessel features in the wood. This was mainly due to the filtering process of ISO 11562-1996, in which roughness profiles are pushed up at the edges of vessels above original primary profiles, and artificial peaks appear around the edges. These artificial peaks, which have little effect on tactile roughness, strongly distort the roughness profiles on which the parameters are based. To eliminate such effects, Brinkmann et al.[12] applied the robust Gaussian regression filter[13] (RGRF) to the evaluation of a metal surface processed by plateau honing and showed that it is applicable to surfaces with local deep valleys. With this filtering scheme, the tolerance to end the filtering process should be preset according to the material and the purpose of the evaluation.

In the current study, the surfaces of two species of hardwood were sanded with abrasive papers of several grit numbers. Two three-dimensional parameters describing these surfaces, one for the distribution of roughness-profile peaks, the other for the relative area of roughness-profile peaks above the threshold height, were compared with their tactile roughness. The parameters were obtained from roughness profiles determined by the RGRF using seven cutoffs. The tolerance for the RGRF filtering process was also examined in a preliminary experiment.

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Materials and method

Specimens

Specimens (35 × 65 × 15 mm) of air-dried flat and edge grain boards of Japanese oak (*Quercus mongolica* var. *grosseserrata*) and Japanese beech (*Fagus crenata*) were sanded manually with the grain using varying grit numbers of abrasive papers: P80, P120, P150, P180, and P240. The fiber direction was parallel to the 35-mm side of the specimens. The average annual ring widths and specific gravities were 0.64–2.00 mm and 0.59–0.69, respectively, for specimens of Japanese oak and 1.2–3.1 mm and 0.63–0.69, respectively, for Japanese beech.

Surface roughness measurement

Primary profiles were obtained of 15 × 10 mm areas using a stylus instrument (Surfcom1400A-3DF-12, Tokyo Seimitsu) with a 5 μm tip radius and 90° tip angle. The stylus was moved perpendicular to the fiber direction with a speed of 0.6 mm/s over a distance of 15 mm. This was repeated at 10 μm intervals parallel to the fiber direction so that 1001 primary profiles were obtained for each specimen. The output signal from the stylus was recorded at a sampling interval of 10 μm. Roughness profiles were obtained from the primary profiles using the RGRF with cutoffs of 0.25, 0.8, 2.5, 8.0, 16.0, and 32.0 mm.

Two three-dimensional parameters (i.e., the distribution of roughness-profile peaks and the relative area of roughness-profile peaks above the threshold height) were used in this study. Figure 1 shows an example of the distribution of roughness-profile peaks and the definition of the roughness-profile peak. The roughness-profile peaks were defined as the outwardly directed portion of the roughness profile connecting two adjacent points of the intersection of the profile with the raised reference line, which was set at a threshold height of D from the original reference line. The distance between the original and the raised reference line was defined as the threshold height. In the figure illustrating the distribution of the roughness-profile peaks, the roughness-profile peaks are shown in black, and the others in white. The other parameter, the relative area of roughness-profile peaks above the threshold height, was denoted by A_{rp} in the present study. The parameter A_{rp} was the area of black regions in a distribution of roughness-profile peaks. It was defined as the proportion of the number of data points above the threshold to all data points contained in the 1001 profiles.

Tolerance to stop the filtering process of the RGRF

The RGRF filtering process was described in detail by Bodschwinna[13] and Brinkmann et al.,[12] among others. Thus, we need only provide a brief outline of the RGRF and the determination of the threshold for stopping the filtering process used in this study. The RGRF is applicable to the evaluation of surface irregularities of materials with local deep valleys, such as the vessels found on hardwood surfaces. It is characterized by the iteration of the filtering process using a Gaussian regression filter (GRF), which works in the same way as the Gaussian filter defined by JIS B 0632-2001 and ISO 11562-1996, with the difference that in the case of the RGRF process there is no data loss at either end of the profile, and there is additional vertical weighting. The end of the iteration is determined using the equation

$$|m_i - m_{i-1}| < T \tag{1}$$

where i is the number of iteration steps; m_i is the median of the difference between the primary and i-th waviness profile, which are the low-frequency components obtained from the i-th iteration of the filtering process; and T is a user-specified tolerance. Brinkmann et al.[12] reported that the median value for a metal surface processed by plateau honing converges after two to five iterations. In the present study, the tolerance is determined by the following experiment.

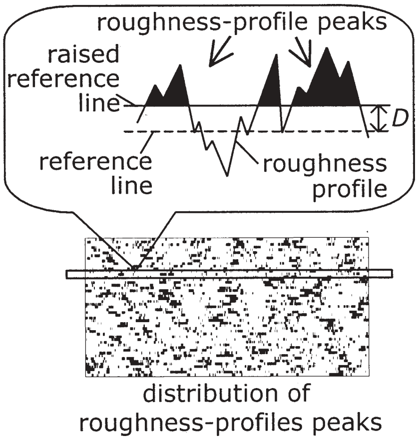


Fig. 1. Definition of roughness-profile peaks (**top**) and an example of distribution of roughness-profile peaks (**bottom**). D, threshold height

Specimens (35 × 65 × 10 mm) obtained from air-dried flat or edge grain boards of Japanese oak, Japanese beech, and Japanese cypress (*Chamaecyparis obtusa*) were finished by a fixed-knife planner with a feed speed of 1 m/s. The bias angles of the knife were 15°–20° for Japanese oak and Japanese beech and 40°–45° for Japanese cypress. The fiber direction was parallel to the long side of the specimens. The species were specially selected to cover a range pore structures. Five primary profiles were obtained from the surface of each specimen using the stylus instrument mentioned above. The stylus was moved perpendicular to the fiber direction over a distance of 30 mm, and the output signal from the stylus was recorded at a sampling interval of 5 μm. Roughness profiles were obtained from the primary profiles using the RGRF with cutoffs of 0.8, 2.5, and 8.0 mm. The filtering process was completed after the 10th iteration, and the values of the medians m_i (i = 0, 1, 2, . . . , 10) for each iteration step were recorded. At each iteration step, the absolute value of the difference between m_i and m_{i-1} was averaged based on the five profiles for each specimen. This average is denoted by δ in this study. Waviness profiles were obtained for the 0th, 1st, 2nd, 5th, and 10th iteration steps.

Sensory evaluation

A paired comparison test was used to evaluate tactile roughness. Each of 15 male and 15 female subjects was asked to wear an eye mask obstructing his or her vision while he or she rubbed an index finger on the surface of a pair of specimens and identified the rougher of the two. The pairs of specimens were chosen randomly from among 10 specimens, and the subject judged the roughness of each possible pair from 45 pairs. The tactile perception of roughness was estimated statistically from the results of the sensory evaluation. The score for each specimen was determined according to the number of judgments of "rougher surface" using the equation

$$x = \frac{R_+ + 0.5N}{nN} \tag{2}$$

where x is the score for each specimen, R_+ is the number of judgments of "rougher surface," N is the number of subjects, and n is the number of specimens. The score standardized using the standard deviation σ as shown in Eq. (3) is the tactile roughness Z of a specimen.

$$Z = \frac{x - 0.5}{\sigma} \tag{3}$$

where σ is defined as

$$\sigma = \sqrt{\frac{\sum (x - 0.5)^2}{n}}. \tag{4}$$

Results and discussion

Tolerance to end the filtering process of RGRF

Figure 2 shows waviness profiles determined following the 0th, 1st, 2nd, 5th, and 10th iteration at a cutoff wavelength of 2.5 mm for Japanese oak, Japanese beech, and Japanese cypress superimposed on primary profiles. It is clear from Fig. 2 that the waviness profiles converge as the number of iterations is increased. For Japanese oak, the waviness profiles for the last two iteration steps had almost the same shape. There was only a slight difference between the waviness profiles of Japanese beech and Japanese cypress except for the 0th iteration step. The first few iteration steps could not remove the effects of deep valleys from the waviness profiles of Japanese oak, and the last few iteration steps were too much for Japanese beech and Japanese cypress. Figure 3 shows the variation of $|m_i - m_{i-1}|$, δ, with the number of iteration steps for a cut-off wavelength of 2.5 mm. The values of δ for all three species decreased exponentially with each iteration step, and those for Japanese oak were the largest at each step. This suggests that the value of δ, which is sufficiently low to remove the effects of deep valleys of Japanese oak, is enough for the convergence of the waviness profiles of Japanese beech and Japanese cypress. Based on these findings, the tolerance was selected to be 0.1 μm in this study. Figure 4 shows primary, waviness, and roughness profiles for Japanese oak determined by GRF and RGRF using a tolerance of 0.1 μm. The waviness profile determined by GRF was distorted

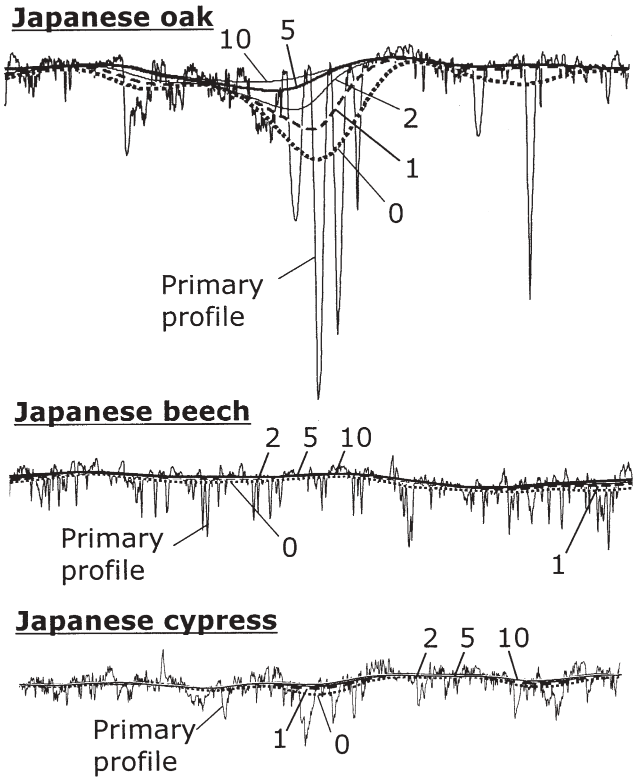


Fig. 2. Variation of waviness profiles (determined by a robust Gaussian regression filter) with iteration steps for primary profiles of three species at a cutoff wavelength of 2.5 mm. The numerals 0–10 represent iteration steps in the filtering process

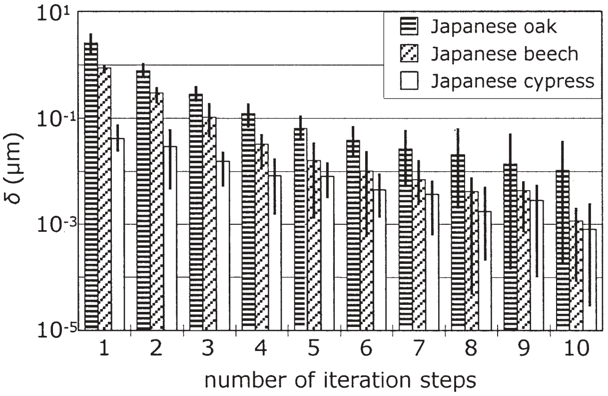


Fig. 3. Variation of $|m_i - m_{i-1}|$, δ, with the number of iteration steps for a cutoff wavelength of 2.5 mm. i, number of iteration steps; m_i, median of the distance between primary and waviness profiles. *Vertical bars* represent the range of observed values

Fig. 4. Primary, waviness, and roughness profiles determined by the Gaussian regression filter (*GRF*) and the robust Gaussian regression filter (*RGRF*) at a cutoff wavelength of 8.0 mm for Japanese oak. *p.p.*, *w.p.*, and *r.p.*, primary, waviness, and roughness profiles, respectively; *m.l.* and *r.l.*, mean and reference lines, respectively

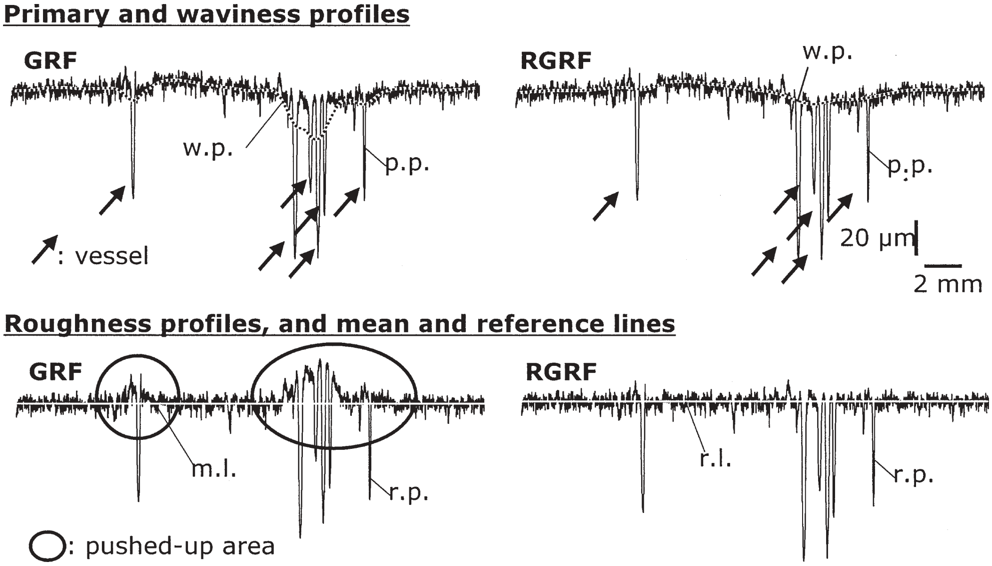
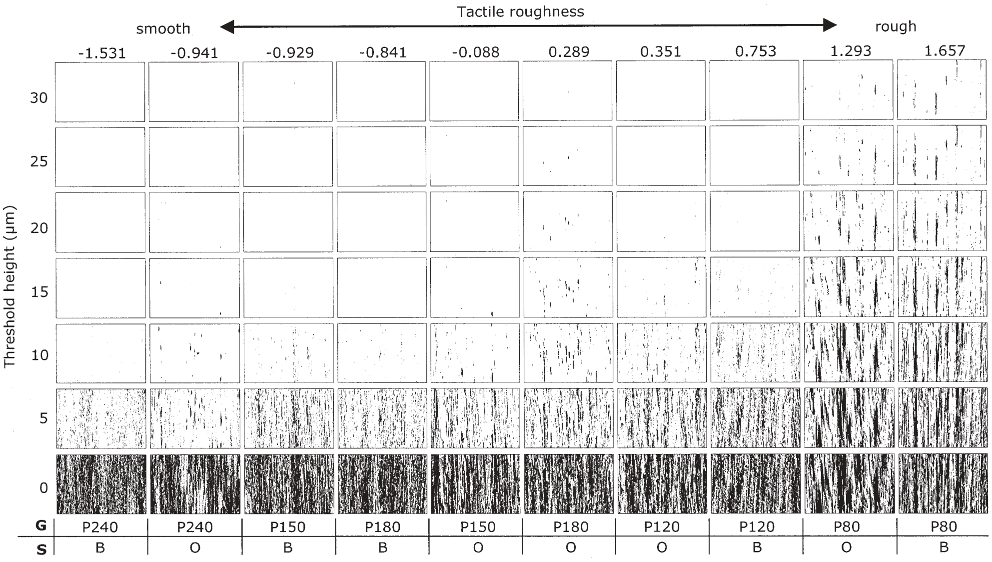


Fig. 5. Relation between tactile roughness and distribution of roughness-profile peaks at a cutoff wavelength of 8.0 mm for Japanese oak (*O*) and Japanese beech (*B*). *Black regions* denote roughness-profile peaks. *G* and *S*, grit number of abrasive papers and species, respectively



downward around vessels, and the edges of vessels in a roughness profile were pushed up to produce higher peaks above the mean line compared to the primary profile. The waviness profile determined by RGRF eliminated these vessel-induced effects.

Relation between three-dimensional parameters and tactile roughness

Distribution of roughness-profile peaks

Figure 5 shows the relation between the tactile roughness and the distribution of roughness-profile peaks at seven threshold heights for a cutoff wavelength of 8.0 mm. The area of the roughness-profile peaks increased with tactile roughness for all threshold heights except for 0 μm. Similar results were obtained for cutoffs of 0.8 to 32.0 mm. The tactile roughness showed that the surfaces of both Japanese oak and Japanese beech sanded with P180 abrasive paper were rougher than those sanded with P150. Figure 6 shows the same distribution for Japanese oak as is seen in Figure 5 but at a cutoff wavelength of 0.25 mm and a threshold height of 10 μm. For all surfaces except for P80, the roughness-profile peaks appeared at the edge of vessels. These peaks are a kind of artifact caused by the filtering and cannot affect the tactile feeling. This suggests that too low a cutoff wavelength is not suitable for evaluating the surface roughness of wood, especially if there are deep valleys on its surface.

Relative area of roughness-profile peaks

Figure 7 shows the relation between the tactile roughness and A_{rp} at five threshold heights for a cutoff wavelength of

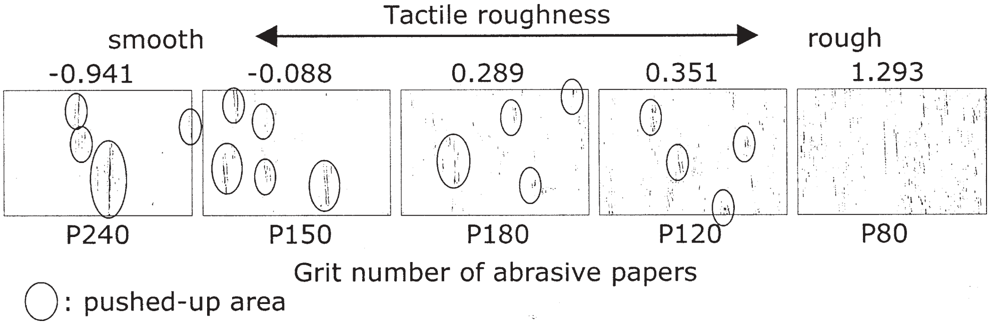


Fig. 6. Relation between tactile roughness and distribution of roughness-profile peaks determined at a cutoff wavelength of 0.25 mm and a threshold level of 10 μm for Japanese oak. *Black regions* denote roughness-profile peaks

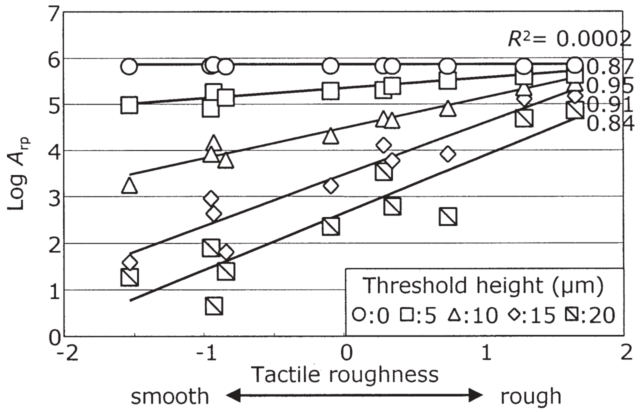


Fig. 7. Relation between tactile roughness and A_{rp} at five threshold heights for a cutoff wavelength of 8.0 mm

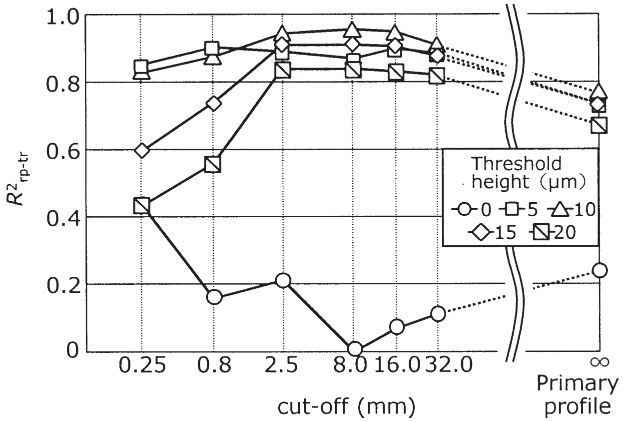


Fig. 8. Variation of coefficient of determination between relative area of roughness-profile peaks and tactile roughness, $R^2_{\mathrm{rp-tr}}$, with cutoff wavelengths for five threshold heights

8.0 mm. As defined earlier, A_{rp} is the relative area of roughness-profile peaks above the threshold height. The logarithm of A_{rp} increased monotonically with tactile roughness for each threshold. The coefficient of determination (R^2) between A_{rp} and the tactile roughness depended on the threshold height and showed a maximum at a threshold height of 10 μm.

Figure 8 shows the variation of the coefficient of determination between A_{rp} and the tactile roughness with cutoffs for five threshold heights. Because the primary profiles can be considered the roughness profiles at a cutoff wavelength of infinity, the coefficients of determination for the primary profile were also plotted in Fig. 8. The coefficients of determination showed maxima at cutoffs of 0.8–8.0 for all threshold heights except 0 μm.

Conclusions

The roughness parameters for evaluating a wood surface should correspond to tactile roughness because the roughness of the wood surface is often evaluated by touch. It is better to use three-dimensional parameters to characterize the roughness of a wood surface given the material's heterogeneity. Two three-dimensional parameters were found to correlate well with tactile roughness. It was also found while estimating the parameters that the RGRF, in which a tolerance specifically selected for the characterization of a wood surface was employed, greatly reduced the effects of deep valleys from roughness profiles. Further study is necessary to confirm the applicability of the present method to other machining processes and wood species.

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