Correlation of Near Infrared Spectroscopy Measurements with the Surface Roughness of Wood

Maomao Zhang, Yana Liu, and Zhong Yang*

The surface roughness of Chinese fir and *Eucalyptus* wood samples were measured using the stylus profile method in order to investigate the correlation between near infrared (NIR) spectroscopy and surface roughness. The results showed that the NIR spectra absorption showed differences among samples from different surface roughnesses, and the absorption decreased with the increase of the surface roughness. A strong relationship was found between the surface roughness parameters, *i.e.*, the arithmetical mean deviation of the profile (R_a), the ten-point height of irregularities (R_z), and the maximum height of profile (R_y). Based on the NIR spectra of the Chinese fir wood samples and the mixed wood samples of the two wood species, and the correlation coefficients of these two types of wood samples in a calibration set were 0.77 to 0.83 and 0.67 to 0.74, respectively. A relatively poor correlation was found in the model based on the *Eucalyptus* samples; however, it was still significant. These results suggested that there was relative information about the surface roughness from the NIR spectra, which further illustrated that the surface roughness may influence the effect of models for wood properties built by NIR data.

Keywords: Wood; Surface roughness; Near infrared spectroscopy; Correlation

*Contact information: Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing 100091, China; *Corresponding author: zyang@caf.ac.cn*

INTRODUCTION

Surface roughness characterizes the microcosmic geometry features composed of irregularities determined by small spacing, peaks, and valleys on a machined surface (Magoss 2008). Wood is a porous natural material; its surface roughness can be mainly attributed to the machining conditions and the anatomical structural properties of the wood. There are significant differences in cellular structure between hardwood and softwood, and the surface roughness exhibits great differences depending on the variety and if other conditions are the same. Even for one species, the surface roughness changes with the diameter of the vessels (Magoss 2008). Thus, the surface roughness is sensitive to changes in certain influencing factors (Fujiwara *et al.* 2003).

Though wood surface roughness is difficult to control, it is still an important index for wood product quality. In addition, it directly affects the bonding performance, machining properties (Ozdemira and Hiziroglub 2007), and surface quality (Richter *et al.* 1995) of wood products during production. Finally, it is also a waste of wood resources.

Near-infrared (NIR) spectroscopy, as a nondestructive evaluation technique, has been successfully used to rapidly and accurately estimate the physical properties of wood, such as wood density (Inagaki *et al.* 2012), moisture content (Adedipe *et al.* 2008), the microfibril angle (Hein *et al.* 2010), wood color (Yang *et al.* 2012), chemical composition (Kelley *et al.* 2004; Üner *et al.* 2011), and surface properties (Tsuchikawa *et al.* 2001; Defo *et al.* 2007). In addition, the relationship between the NIR spectra and the surface roughness has been studied for *Pinus taeda* (Schimleck *et al*. 2005). The cited study reported that surface roughness contributed to weaker statistics and that the surface roughness of *Pinus taeda* has a weak influence on the effect of models built by the NIR data. However, very few studies have investigated the use of Chinese fir and *Eucalyptus* wood surface roughness using the NIR spectra.

This paper focuses on the use of NIR spectroscopy in combination with the partial least squares (PLS) analysis to investigate the relationship between wood surface roughness and the NIR spectra. This study aimed at revealing information pertaining to the surface roughness and its influence in the effect of models for Chinese fir and *Eucalyptus* wood properties built by NIR data because of their high correlation relationship.

EXPERIMENTAL

As two of the most important plantation wood species in China, Chinese fir (*Cunninghamia lanceolata*) and Eucalyptus (*Eucalyptus pellita*), collected from Anhui and Guangdong provinces, respectively, were chosen as representative typical wood species of softwood and hardwood, respectively. Five trees were collected from each species, and disks of 10 cm in length were cut from each tree at the height of 1.3 m. After the disks were air-dried, the disks were cut into small samples with different surface roughnesses and a size of 15 mm × 15 mm ×15 mm. Each species include 60 samples and a total of 120 samples were prepared.

The Handysurf (E-35A) surface profileometer (Tokyo Seimitsu, Tokyo, Japan) with the stylus contour method was used to measure the surface roughness of samples, with a sampling length of 0.8 mm, an evaluation length of 4 mm, a profile resolution of 0.02 μm, and a measuring speed of 1 mm/s. The surface roughness was measured five times for each sample, and the arithmetical mean deviation of the profile (R_a), (R_y), and (R_z) were obtained to analysis the surface roughness.

The NIR reflectance spectra, expressed in the form of log (1/*R*), were obtained from the cross, radial, and tangential sections of wood samples by an ASD Field Spec® spectrometer (Analytical Spectral Devices, Boulder, CO, USA) from 350 to 2500 nm at a 1 nm interval. A fiber optic probe with an 8 mm spot diameter was oriented perpendicular to the surface of wood sample. A piece of commercial PTFE (polytetrafluoroethylene) panel was used as the white reference material. Thirty scans were collected and averaged to obtain a single spectrum. All measurements were made in a controlled humidity chamber (< 60%) and at 20 ± 2 °C.

Unscrambler® software (CAMO Software Inc., Woodbridge, NJ, USA) was used for the multivariate data analysis. The partial least squares (PLS) analysis, which provides a model for the relationship between a set of predictor variables *X* and a set of response variables *Y*, was used to develop calibration models of surface roughness. Two thirds of the samples were assigned to a calibration set, and one third of the samples were assigned to a prediction set. The performance of the models was assessed using several common statistical measures: coefficient of determination (R^2), the root mean square error of calibration (RMSEC), and the root mean square error of prediction (RMSEP). A 780 to 2500 nm area was selected to be analyzed for the relationship between the NIR spectra and the surface roughness of wood.

RESULTS AND DISCUSSION

Results of Wood Surface Roughness Determination

Three height parameters were measured in this study, and the surface roughness was expressed by the following parameters: the arithmetical mean deviation of the profile (R_a), which refers to the mean value of the absolute distance measured from each point of the profile to the mean lines in one sampling length; ten-point height of irregularities (R_z), which refers to the sum of the average value of five largest peak heights and five largest valley depths in one sampling length; and the maximum height of profile (R_y), which measures the distance between the top line and the bottom line of the outline in one sampling length. The R_a was generally analyzed because it could fully reflect the profile of the sample surface.

Table 1. Statistical Summary of Surface Roughness of Chinese Fir and Eucalyptus

Samples		R_a				R_z				R_y			
		Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD
Chinese fir (n=60)	C	3.1	22.7	10.9	5.2	20.8	114.0	58.0	23.1	31.4	168.2	81.4	31.1
	R	2.0	12.3	4.5	1.8	11.3	64.4	24.6	10.5	16.6	104.2	36.8	18.8
	T	1.8	8.6	3.8	1.5	10.2	47.7	21.3	8.0	11.8	73.4	30.9	13.7
Eucalyptus (n=60)	C	1.4	11.9	5.0	2.0	10.8	63.6	30.6	11.2	16.6	133.9	49.4	21.0
	R	1.7	8.8	4.2	1.8	9.1	55.5	24.4	10.9	12.5	87.5	39.5	19.8
	T	1.4	8.3	3.8	1.7	7.9	47.2	21.2	8.8	10.2	78.2	34.0	16.6

C: cross section; R: radial section; and T: tangential section

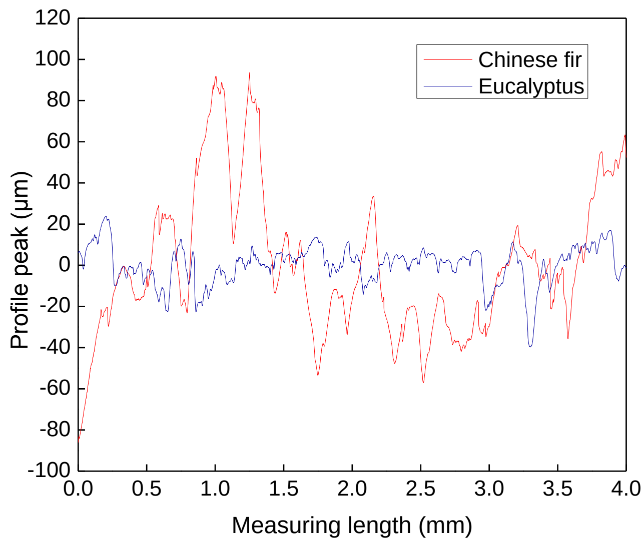

Fig. 1. Profile curve of the cross section of wood

The statistical results of the surface roughness of samples from two species are shown in Table 1. The roughness parameters (R_a, R_z, and R_y) and standard deviations obtained from the cross section were much larger than that from the radial and tangential sections, especially for the samples of Chinese fir. It could be explained that this wood was a more porous material, and the wood cells were arranged in parallel to the longitudinal axis of the wood. In addition, the cutting direction was perpendicular to the fiber direction in the cross section, which made it easy to produce surface irregularities because of the transverse fracture of the wood tissue on the cutting surface. The experiment also revealed that the samples of Chinese fir were rougher than the samples of *Eucalyptus*. This result could also be shown by the roughness profile of Chinese fir and *Eucalyptus* in the cross section in Fig. 1. The profiles were obtained from 5 sampling lengths and consisted of 6677 points. According to Fig. 1, the profile peak of Chinese fir was higher than that of *Eucalyptus*, and the R_a values of Chinese fir and *Eucalyptus* were 13.20 μm and 5.50 μm, respectively. To more accurately understand the differences in surface roughness of the three sections between the two species, ANOVA was performed at the 5% significance level. The surface roughness in the cross section between the two species was found to be significantly different (F=45.03, $P < 0.05$), while only a few significant differences ($p > 0.05$) were observed in the radial and tangential sections between the two species.

NIR Spectroscopy of Samples with Different Surface Roughness

Figures 2 and 3 show the NIR absorption of Chinese fir and *Eucalyptus* with three different surface roughness samples (a, b, and c) at wavelengths of 780 to 2500 nm.

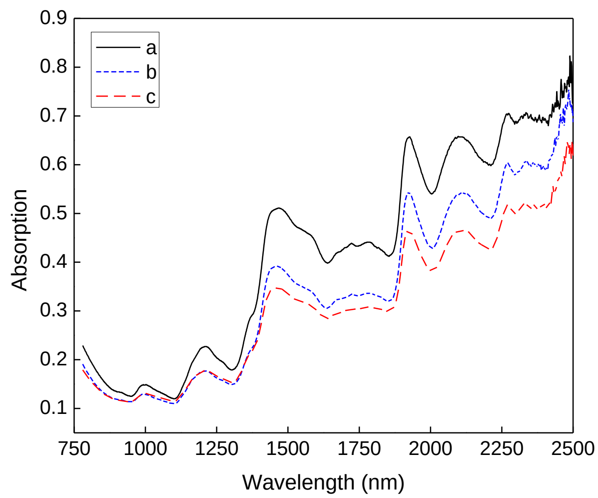

Fig. 2. The NIR spectrum of Chinese fir; a: Ra=5.10, Rz=32.40, Ry=49.60; b: Ra=9.60, Rz=49.30, Ry=64.20; c: Ra=18.80, Rz=96.00, Ry=132.60

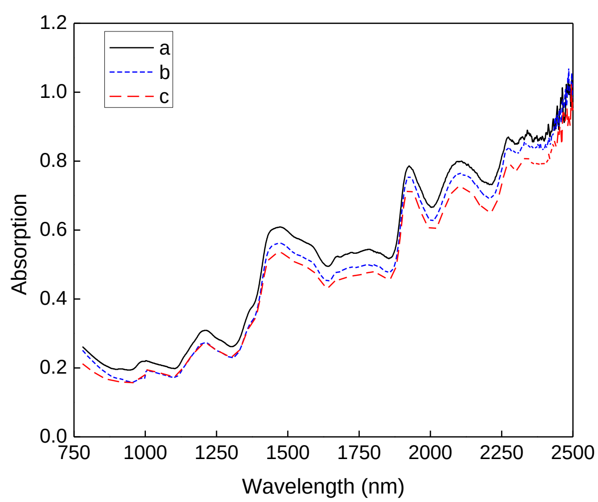

Fig. 3. The NIR spectrum of Eucalyptus; a: Ra=1.40, Rz=10.80, Ry=16.60; b: Ra=6.10, Rz=37.30, Ry=50.60; c: Ra=11.90, Rz=63.60,Ry=76.80

According to the figures, the spectral absorptions in the NIR region were different among the samples with different surface roughness, and the absorption decreased with the increase in the roughness parameters values (R_a, R_z, and R_y), independent of the species. This may be mainly because the relatively stronger diffuse reflection was associated with an increase in surface roughness (Huang *et al.* 2007; Hauptmann *et al.* 2013). When the surface roughness was relatively large, the NIR reflectance was affected, which led to the decrease in absorption. On the contrary, when the surface was smooth, the reflectance would be denser and the absorption increased.

1

Correlation between Wood Surface Roughness and NIR Spectra

Wood surface roughness affected the sample absorption, reflectance, and refraction of NIR, and samples with different surface roughnesses exhibited a different NIR absorption. Therefore, the feasibility of NIR to predict wood surface roughness as a non-contact measurement was investigated in this study. The raw spectroscopic data of samples in the cross section was used to build calibration models.

Table 2. Regression Statistics for Calibration and Prediction of PLS Models

Model types	Parameters	No. of PCs	R_C^2	RMSEC (%)	R_P^2	RMSEP (%)	RPD
Model 1 (n=60)	Ra	6	0.77	2.36	0.62	3.91	1.61
	Rz	6	0.83	9.38	0.66	15.74	1.71
	Ry	6	0.79	13.75	0.69	18.04	1.76
Model 2 (n=60)	Ra	5	0.55	1.27	0.56	1.54	1.44
	Rz	5	0.59	6.28	0.55	9.29	1.42
	Ry	5	0.46	10.67	0.46	24.09	1.23
Model 3 (n=120)	Ra	6	0.71	2.70	0.66	2.80	1.60
	Rz	6	0.74	11.58	0.64	13.84	1.62
	Ry	6	0.67	18.19	0.56	20.07	1.46

PCs: principal components; R_C^2 : coefficient of determination of the calibration model; RMSEC: root mean standard error of calibration; R_P^2: coefficient of determination of the prediction by prediction set RPD: ratio of performance to derivation

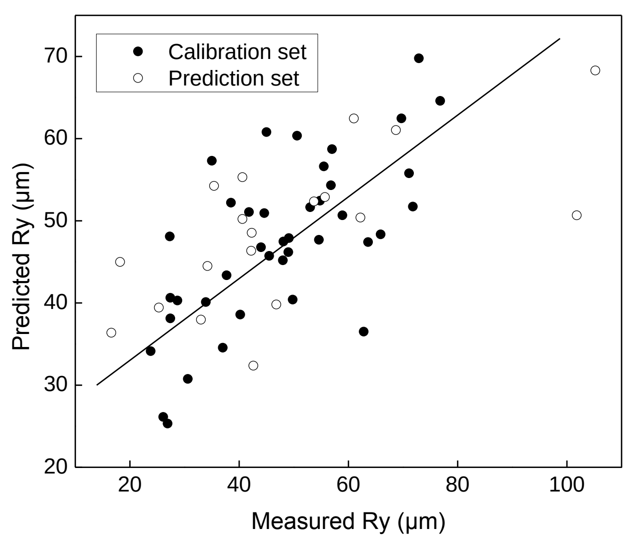

Fig. 4. Relationship between measured and predicted Ry of the samples from model 2. Calibration set (n=40); Prediction set (n=20)

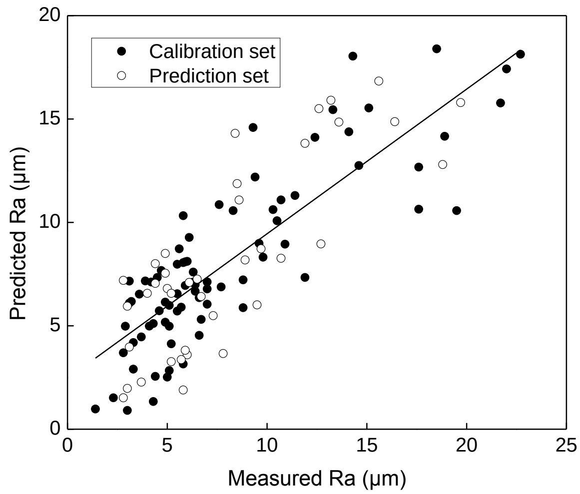

Fig. 5. Relationship between measured and predicted Ra's of the samples from model 3. Calibration set (n=80); Prediction set (n=40)

Table 2 shows the summary statistics of the PLS models developed for the roughness parameters (R_a, R_z, and R_y) using NIR spectra in the wavelength range of 780 to 2500 nm. Model 1 was based on Chinese fir samples, model 2 was based on *Eucalyptus* samples, and model 3 was based on a mix of these two species samples. All of the principal components that were based on NIR spectra explained more than 95% of the variance in the spectral data. For model 1, the calibration for R_z provided the strongest correlation, with an R_C^2 of 0.83, RMSEC of 9.38%, R_P^2 of 0.66, RMSEP of 15.74%, and RPD of 1.71. Similar results were also observed in models 2 and 3. In almost all cases, the values for the coefficient of determination were lower for the prediction set than the calibration set. It has been shown that an RPD value of approximately 1.5 is sufficient for the initial screening (Schimleck *et al*. 2003). The RPD value for R_a, R_z, and R_y of *Eucalyptus* samples were 1.44, 1.4, and 1.23, respectively; it seemed that the performance of models built with *Eucalyptus* samples was relatively poor. The correlations between the roughness parameters of *Eucalyptus* samples and the NIR spectra were not as good as those from the other samples. This may have been because the *Eucalyptus* samples had less surface roughness, which provided a minimal effect on the absorption of the NIR spectra, and *Eucalyptus* wood had a more complex composition. When the samples from the model-building set were used, a better prediction of performance was exhibited, which might be because there were more data points and a larger surface roughness range. There was a relatively poor relationship between the measured and predicted R_y values of the samples from model 2, as shown in Fig. 4. Figure 5 shows the relationship between the measured and predicted R_a values of the samples from model 3. From the above analysis, the correlation between surface roughness and the NIR spectra was not very high but overall, was still significant. This was contradictory to other research that found the surface roughness contributed to a weaker correlation statistic (Schimleck *et al*. 2005).

CONCLUSIONS

1. The results clearly showed that there were great differences among samples of different surface roughness, and the absorption decreased with the increase in surface roughness.

2. Strong correlations were obtained between the measured and predicted values based on the Chinese fir samples and the mix of these two species samples. A relatively poor correlation was found in the models based on *Eucalyptus* samples; however, it was still significant.
3. It can be concluded that the NIR spectra provides some information about surface roughness in the samples. However, because of the high relationship between NIR and the surface roughness, the surface roughness may influence the effect of models intended to predict other attributes of Chinese fir and *Eucalyptus* wood properties built using the NIR data.
4. In general, the surface roughness models did not achieve the most optimal accuracy because of the limitation in the number and surface roughness of the samples. In future research, it would be helpful to choose a larger number of samples from more species and to include different surface roughness levels.

ACKNOWLEDGMENTS

The authors are grateful for the support of the China National Natural Science Fund (Grant No. 31370711), and the support of the Ministry of Science and Technology of the People's Republic of China (Grant No. 2012104006).

REFERENCES CITED

Adedipe, O. E., and Dawson-Andoh, B. (2008). "Predicting moisture content of yellow-poplar (*Liriodendron tulipifera* L.) veneer using near infrared spectroscopy," *Forest Products Journal* 58(4), 28-33.

Defo, M., Taylor, A. M., and Bond, B. (2007). "Determination of moisture and density of fresh sawn red oak lumber by near infrared spectroscopy," *Forest Products Journal* 57(7), 68-72.

Fujiwara, Y., Fujii, Y., and Okumura, S. (2003). "Effect of removal of deep valleys on the evalution of machined surfaces of wood," *Forest Products Journal* 53(2), 58-62.

Hauptmann, M., Müller, U., Obersriebnig, M., Gindl-Altmutter, W., Beck, A., and Hansmann, C. (2013). "The optical appearance of wood related to nanoscale surface roughness," *BioResources* 8(3), 4038-4045. DOI: 10.15376/biores.8.3.4038-4045

Hein, P. R., Clair, B., Brancheriau, L., and Chaix, G. (2010). "Predicting microfibril angle in *Eucalyptus* wood from different wood faces and surface qualities using near infrared spectra," *Journal of Near Infrared Spectroscopy* 18(6), 455-464. DOI: 10.1255/jnirs.905

Huang, A. M., Fei, B. H., Jiang, Z. H., and Hse, C. H. (2007). "Influence of sample surface roughness on mathematical model of NIR quantitative analysis of wood density," *Spectroscopy and Spectral Analysis* 27(9), 1700-1702.

Inagaki, T., Schwanninger, M., Kato, R., Kurata, Y., Thanapase, W., Puthson, P., and Tsuchikawa, S. (2012). "*Eucalyptus camaldulensis* density and fiber length estimated by near-infrared spectroscopy," *Wood Science and Technology* 46(1-3), 143-155. DOI: 10.1007/s00226-010-0379-6

Kelley, S. S., Rials, T. G., Snell, R., Groom, L. H., and Sluiter, A. (2004). "Use of near infrared spectroscopy to measure the chemical and mechanical properties of solid wood," *Wood Science and Technology* 38(4), 257-276. DOI: 10.1007/s00226-003-0213-5

Magoss, E. (2008). "General regularities of wood surface roughness," *Acta Silvatica & Lingaria Hungarica* 4, 81-93.

Ozdemira, T., and Hiziroglub, S. (2007). "Evaluation of surface quality and adhesion strength of treated solid wood," *Journal of Materials Processing Technology* 186(1-3), 311-314. DOI: 10.1016/j.jmatprotec.2006.12.049

Richter, K., Feist, W. C., and Knaebe, M. T. (1995). "The effect of surface roughness on the performance of finishes," *Forest Products Journal* 45(7-8), 91-97.

Schimleck, L. R., Doran, J. C., and Rimbawanto, A. (2003). "Near infrared spectroscopy for cost-effective screening of foliar oil characteristics in a *Melaleuca cajuputi* breeding population," *Journal of Agricultural and Food Chemistry* 51(9), 2433-2437. DOI: 10.1021/jf020981u

Schimleck, L. R., Stürzenbecher, R., Mora, C., Jones, P. D., and Daniels, R. F. (2005). "Comparison of *Pinus taeda* L. wood property calibrations based on NIR spectra from the radial-longitudinal and radial-transverse faces of wooden strips," *Holzforschung* 59(2), 214-218. DOI: 10.1515/HF.2005.034

Tsuchikawa, S., Torii, M., and Tsutsumi, S. (2001). "Directional characteristics of near infrared light reflected from wood," *Holzforschung* 55(5), 534-540. DOI: 10.1515/HF.2001.086

Üner, B., Karaman, İ., Tanrıverdi, H., and Özdemir, D. (2011). "Determination of lignin and extractive content of Turkish Pine (*Pinus brutia* Ten.) trees using near infrared spectroscopy and multivariate calibration," *Wood Science and Technology* 45(1), 121-134. DOI: 10.1007/s00226-010-0312-z

Yang, Z., Lv, B., and Fu, Y. J. (2012). "The relationship between near infrared spectroscopy and surface color of eight rosewoods," *Advanced Materials Research* 479-481, 1772-1776. DOI: 10.4028/www.scientific.net/AMR.479-481.1772

Article submitted: May 20, 2015; Peer review completed: July 10, 2015; Revised version received and accepted: August 10, 2015; Published: August 31, 2015.
DOI: 10.15376/biores.10.4.6953-6960