THE POTENTIAL OF VIS- AND NIR-SPECTROSCOPY FOR THE NONDESTRUCTIVE EVALUATION OF GRAIN-ANGLE IN WOOD

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ABSTRACT

Grain angle is of major importance for load-bearing applications of wood because it exerts a strong influence on strength and elasticity. This study proposes PLS (partial least squares) analysis of Vis and NIR reflectance spectra as a possible means for a rapid and nondestructive determination of grain angle. With a root mean square error of 6°, and a coefficient of determination of 0.77 (Vis) and 0.80 (NIR), both spectral ranges proved suitable for the measurement of grain angles up to 40°.

Keywords: Grain angle, near infrared light, partial least squares regression, spectroscopy, visible light.

INTRODUCTION

The orientation of grain in lumber, i.e., the axial direction of wood fibers with reference to the longitudinal axis of a board, is seldom parallel to the plane of cutting because of the particular growth characteristics of trees. The bole is tapered instead of cylindrical, fibers deviate from the vertical axis in the vicinity of branches, and fibers grow spirally around the pith (Harris 1989). As wood is a highly anisotropic composite, grain angle exerts a strong influence on its material properties (Bodig and Jayne 1982). At a grain angle of 45°, Young's modulus and axial strength are reduced to 10–25% of the value at 0° (Kollmann 1968), whereas longitudinal shrinkage increases considerably. Therefore, grain angle is a factor that has to be considered when lumber is graded for use in load bearing structures.

Slope of grain due to stem taper is easily perceived visually in softwood and ring-porous hardwood, where growth rings are distinct. Slope of grain due to spiral grain is more difficult to assess visually. Drying cracks are of some help, but not always present. Scribing of the surface is a possible means to visualize spiral grain, but it leaves permanent marks on the surface and is tedious.

McLauchlan et al. (1973) proposed a slope of grain indicator using a rotating capacitance-type transducer sensor. This method is based on the principle that the dielectric constant parallel to the grain is about 1.5 times greater than the dielectric constant across the grain. Several studies have been dedicated to applications of this method (Samson 1984, 1988; McDonald and Bendtsen 1986; Samson et al. 1993).

The so-called "tracheid effect" is a further nondestructive principle (Matthews and Beech 1976; Fischer and Wendland 1999). The reflection of an incident laser beam with circular cross section is stretched to an ellipsis on the wood surface, because a certain amount of the

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incident light is diverted inside fiber cavities. The degree of stretching of the ellipsis, recorded with a CCD-camera and computed by digital image analysis, is an indicator of grain angle.

X-ray computed tomography was successfully applied to detect spiral grain distribution in whole logs (Sepulveda 2001), and, finally, thermal anisotropy was shown to provide information on the orientation of grain in wood (Naito et al. 2000).

At the transition of two phases with different optical properties, various optical phenomena such as transmittance, absorbance, reflection, and others occur. For the near infrared (NIR) range, Tsuchikawa et al. (1998) clearly demonstrated that the direction under which a wood surface is investigated bears a measurable influence on the quantity and spectral characteristics of reflected light. Thus, an effect of grain orientation on reflected light spectra is expected. Therefore this study aims to assess the suitability of reflected light spectroscopy in the visible light and NIR range, in combination with multivariate analysis, for the nondestructive evaluation of grain angle in lumber.

MATERIAL AND METHODS

Material

Larch blocks (*Larix decidua* Mill.) with a length of 80 mm, a tangential width of 50 mm and radial widths between 10 and 20 mm were sawn from the juvenile and mature parts of a total of 12 trees and stored in a climate chamber kept at 20°C and 65% ambient moisture content. The material was selected specifically to represent an optimum variability of grain angle. After reaching an equilibrium moisture content of about 12%, the blocks were sanded with 180 grit paper. By splitting the blocks along the radial plane using a steel wedge, 195 specimens as depicted in Fig. 1, showing different grain angle, were obtained.

Methods

The grain angle, i.e., the angle between the sanded plane and the plane split along the wood rays and the axial fiber direction as given in Fig. 1, of the specimens was measured to the nearest 0.5° by means of a goniometer.

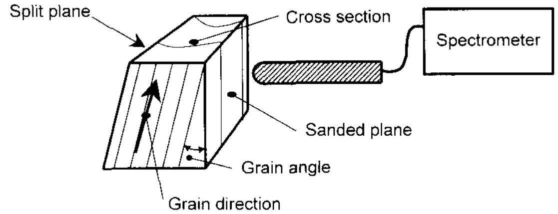

FIG. 1. Experimental setup for the measurement of Vis and NIR spectra from wood surfaces with different grain angles.

Reflectance spectra from the freshly sanded plane were measured using two different spectrometers. A Phyma Codec 400 Vis spectrometer operating in the visible light (Vis) range, wavelength 400–700 nm, and a Bruker Equinox FT-IR spectrometer with a fiber optics probe operating in the near infrared (NIR) range, wavelength 1,000–1,960 nm. The direction of illumination was perpendicular to the sample surface. The scanning stepwidth was 10 nm in the Vis and approximately 1.6 nm in the NIR.

Multivariate analysis of the spectra was performed using Unscrambler 7.6 software. For this purpose, the sample set was split into a calibration set of 130 specimens and a test set of 65 specimens. Applying partial least squares regression analysis (PLS), models describing the variability of grain angle by reflectance spectra were calculated for the Vis and NIR range, respectively. Thereafter, the grain angle of unknown samples (test set) was predicted using the calibration model. The quality of the prediction was evaluated by comparing the predicted values with the actual values measured using the goniometer. Correlation coefficient (r), coefficient of determination (R^2), and root mean square error of calibration (RMSEC) and prediction (RMSEP), respectively, served as statistical measures. RMSEC (RMSEP) yields a measure for the average deviation between the predicted and the true value.

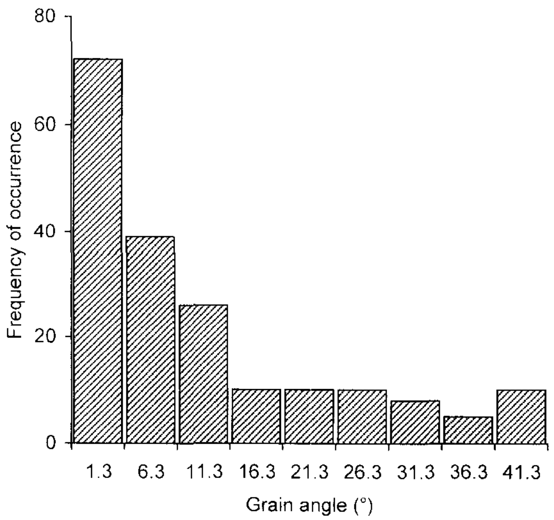

FIG. 2. Distribution of grain angle in the investigated larch samples.

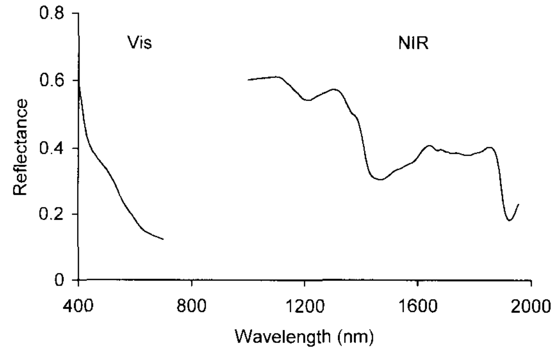

FIG. 3. Typical reflectance spectra of wood surfaces in the Vis and NIR range.

RESULTS

Grain angle of the investigated samples ranged from 0° to 40°. Angles between 0° and 5° were clearly most numerous as seen in Fig. 2. The Vis reflection spectra of the larch samples did not show distinct bands (Fig. 3). Differences between the spectra of individual specimens were hardly discernible by visual inspection of plotted spectra. A few distinct bands were present in the NIR region (Fig. 3), although, the same as with Vis spectra, differences between individual samples were not conspicuous. When the average reflectance over all wavelengths was computed, significant correlations with grain angle could be obtained. In the Vis range, average reflectance increased with increasing grain angle ($r = 0.42$, $P < 0.01$), whereas it decreased in the NIR range ($r = -0.77$, $P < 0.01$). Since this simple correlation analysis did not take into account that reflectance may react differently to changing grain angle, depending on the wavelength, multivariate analysis was performed.

Partial least squares regression analysis revealed the presence of significant differences between the spectra of individual specimens, suitable for modeling grain angle. The PLS regression coefficients plotted in Fig. 4 show that the relationship between grain angle and reflectance was highly variable over the investigated range of wavelength, changing repeatedly from positive to negative. Table 1 gives the results of the PLS analysis. Models with rank 4 (4 components included) gave the lowest error in prediction. In the calibration process as well as in prediction, 2 cases were omitted as outliers with Vis spectra, and 1 case was omitted with NIR. Correlation coefficients were similar in calibration and prediction and the RMSEP of the Vis and the NIR test set was virtually identical. Figures 5 and 6 show scatter plots of grain angles predicted by spectroscopy, compared to the respective true values. It can be seen that the Vis model is more accurate with larger grain angles, whereas the NIR model is equally precise with all inves-

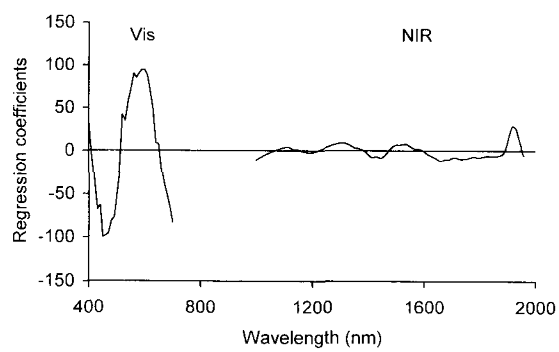

FIG. 4. Regression coefficients obtained with PLS regression analysis.

TABLE 1. *Statistics of the partial least squares regression analysis.*

	Rank	Calibration			Prediction		
		n	*r*	RMSEC	n	*r*	RMSEP
Vis	4	128	0.89	4.95	63	0.87	5.67
NIR	4	129	0.89	4.45	64	0.89	5.75
Vis + NIR	4	127	0.89	5.06	63	0.89	5.80

tigated angles. Combining Vis and NIR data did not lead to a further improvement of the model (Table 1).

DISCUSSION

Multivariate analysis of near infrared reflected light spectra has been successfully applied to reveal chemical composition (Schimleck et al. 1997), density (Thygesen 1994; Schimleck et al. 1999), and water content of wood (Tsuchikawa et al. 1996; Thygesen and Lundqvist 2000). NIR spectroscopy has also shown considerable potential for the nondestructive evaluation of mechanical properties of small clear wood specimens (Hoffmeyer and Pedersen 1995; Gindl et al. 2001). Also in the visible light range, wood characteristics such as compression wood were successfully evaluated by multivariate analysis of spectra (Hagman 1997).

The strong relationship between grain angle and reflected light spectra obtained in the present study clearly demonstrates the usefulness of reflected light spectroscopy combined with PLS regression analysis for the nondestructive evaluation of grain angle in wood. Both investigated ranges of wavelength proved equally useful in prediction individually, but combining Vis and NIR data to a single model did not improve the ability to determine grain angle. This fact points to a common cause of the observed correlation in both ranges of wavelength. This physical cause is the dependence of diffuse reflection on the angle between incident light and wood surface as demonstrated by Tsuchikawa et al. (1998) for the NIR, and by Hon and Minemura (2001) for the Vis range.

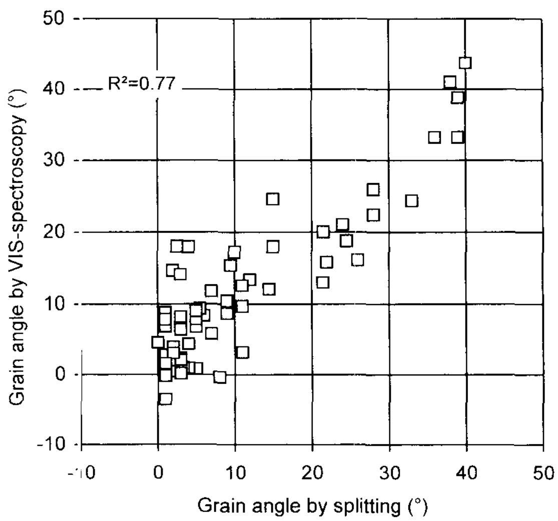

FIG. 5. Comparison of grain angle predicted by the PLS model in the Vis range with grain angle determined by splitting (test set validation).

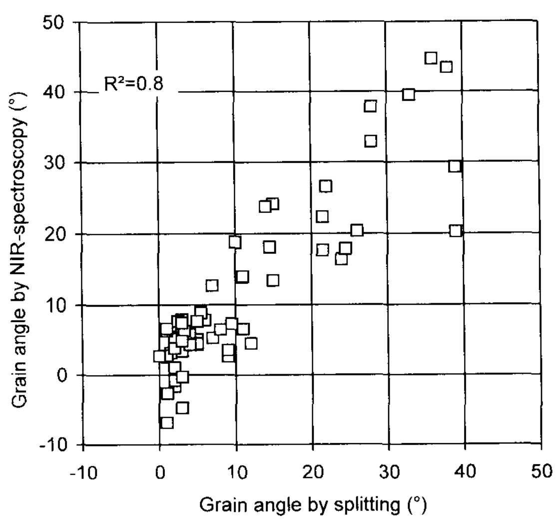

FIG. 6. Comparison of grain angle predicted by the PLS model in the NIR range with grain angle determined by splitting (test set validation).

The accuracy of 6° achieved in predicting grain angle (Table 1) is rather modest at first view. It has to be considered, however, that small changes of grain angle (0°–5°) hardly affect strength properties (Kollmann 1968; Courtney 2000). Changes of 10° and more, as they are required to induce significant change, were reliably detected.

In comparison to other nondestructive techniques, the explained percentage of variability of grain angle is average. Coefficients of determination of 0.77 (Vis) and 0.80 (NIR) are clearly inferior to the 0.96 obtained with the slope of grain indicator (Samson et al. 1993), but superior to the value of 0.73 yielded by X-ray computed tomography (Sepulveda 2001), and also superior to values between 0.75 and 0.50 achieved by thermographic measurement of different wood species (Naito et al. 2000).

While the study presented clearly proves that a relationship between grain angle and reflected light spectra in the Vis and NIR range exists, a few limitations have to be considered with regard to potential future applications. The orientation of grain was measured only in the radial plane. In practice, grain deviation in tangential and radial direction occurs. Therefore, a three-dimensional grain orientation has to be measured (Bindzi and Samson 1995). This could be done by measuring on the wide and the narrow side of a board. As with capacitance measurements (Samson et al. 1993), moisture content may bear an influence on the spectra. Finally, surface roughness has to be kept constant to enable spectroscopic measurement of grain angle.

With the increasing importance of nondestructive evaluation in the wood industry, reliable and rapid techniques are required. The spectroscopic method to determine grain angle introduced through this study may serve this purpose.

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