ORIGINAL

Simultaneous measurement of lathe check depth and the grain angle of birch (*Betula pendula* Roth) veneers using laser trans-illumination imaging

Toni Antikainen[1] · **Joona Eskelinen**[2] ·
Anti Rohumaa[1] · **Teemu Vainio**[1] · **Mark Hughes**[1]

Abstract Lathe check depth (LCD) and the grain angle (GA) of veneer are important factors because they have an impact on the strength properties of plywood. Several methods to measure the LCD of veneer and the GA of wood or veneer have been developed over the years. In this study, a method to simultaneously measure LCD and GA from veneer is presented using silver birch (*Betula pendula* Roth) veneer of 3.5 mm nominal thickness as an example. The measurement is based on laser trans-illumination imaging through the veneer. From these images, the projected area of the crack mouth of slightly opened lathe checks was calculated using image analysis techniques. Reference LCD values were measured manually by dyeing the veneer and imaging with an optical microscope. The relationship between the area of lathe checks in the images and the reference LCD values was modelled with regression analysis, and R^2 was found to be 0.86 and the root-mean-square error was 9.9 %. GA was determined by recognizing an elliptical illuminated area projected through the veneer from which GA was obtained by measuring the angle of the major axis of the ellipse. The range in the GA of the veneer samples studied was from 1° to 11°. Furthermore, the uncertainty in the reference LCD measurements taken by four operators was estimated with a reproducibility and repeatability test. The reference LCD measurements were found to be dependent on the operator.

✉ Toni Antikainen
toni.antikainen@aalto.fi

[1] Wood Material Technology, Department of Forest Products Technology, Aalto University School of Chemical Technology, P.O. Box 16400, 00076 Aalto, Finland

[2] Electronics Research Laboratory, Department of Physics, University of Helsinki, Helsinki, Finland

Introduction

In general, the mechanical properties of veneer may be characterized by the tensile strength perpendicular to and along the grain. During the production of rotary-peeled veneer, the conversion of an essentially cylindrical form into a flat plate produces tensile stresses in the veneer that lead to the formation of cracks known as lathe checks, the depth and frequency of which are dependent upon many factors including the veneer thickness and production parameters. Tensile strength perpendicular to the grain and lathe check depth (LCD) strongly correlates with one another (Antikainen 2001). High tensile strength perpendicular to the grain indicates shallow peeling checks (Corder and Atherton 1963; Antikainen 2001). Furthermore, there is a relationship between LCD and lathe check frequency (LCF); deep checks tend to be less frequent than shallow checks (Koch 1965; Korpijaakko 1999; Dupleix et al. 2013). LCD is an important factor because it affects the properties of plywood and, in general, a lower LCD indicates higher strength and better quality plywood (Chow 1974; Neese et al. 2004; DeVallance et al. 2006, 2007; Sinn et al. 2009; Rohumaa et al. 2013).

Similarly, the grain angle (GA) of wood or veneer affects the tensile strength along the grain. In general a lower GA leads to higher tensile strength (Corder and Atherton 1963). Hirvonen and Karonen (1984) presented a study in which the strength of wood was estimated by the grain deviation on the wood surface. In addition, GA has also been found to affect the erosion rate of wood (Williams et al. 2001). According to Söyrilä and Koponen (2000), when using veneers with low GA in plywood production, the boards are straighter.

In the industrial plywood manufacturing process, LCD is not monitored at all or at least not in real time. From a peeling quality control point of view, it would obviously be beneficial to measure the depth of peeling checks online and to control the peeling process with that measurement. Feedback about LCD to the lathe operator could result in higher peeling quality (Tomppo et al. 2009). Nowadays, the peeling process is controlled by the lathe operators who have different opinions about veneer peeling quality and how to adjust the lathe during operation to achieve the veneer quality desired.

Studies on the measurement of LCD have, to date, mainly focused on either destructive techniques or contact methods. Both these approaches have drawbacks that make it difficult to envision them as a part of an online, real-time monitoring system in an industrial environment. The SMOF (Systeme de Mesure d'Ouverture des Fissures) device described by Pałubicki et al. (2007, 2010) is a partly automated system designed to measure lathe checks in veneer strips from 15 to 40 mm wide. In the device, the checks in the veneer are 'opened' slightly as it passes over a pulley and images are taken of the edge of the veneer. From these images, LCD is estimated with an algorithm developed for this purpose. It is suspected that opening the veneer may affect the results, since when opening the checks more they may deepen and, if unopened, they may not be visible. The system, however, remains essentially offline, making it difficult to use for real-time process monitoring.

Tomppo et al. (2009) measured the LCD of dry and moistened birch veneers using ultrasound with a contact measurement set-up and used a non-contact, air-coupled through-transmission and reflection mode for green veneer. With the contact method for measuring dry and moistened veneer, the best correlation coefficients between LCD and the measured ultrasound parameters were 0.63 and −0.85, respectively. With the air-coupled through-transmission and reflection mode measurements, the best correlation coefficients between LCD and the ultrasound parameters were 0.6 and 0.77, respectively. The advantage of using ultrasound is that it can be both non-destructive and non-contact.

Denaud et al. (2007) measured lathe check frequency (LCF) by recording sound and cutting forces during laboratory scale peeling. Signal peaks occurred when there was a lathe check in the veneer and LCF was estimated from both signals by detecting the signal peaks using the root mean square (RMS) and calculating its local average. As a reference, LCF was estimated by simultaneously measuring the profile of the checked veneer surface with a laser. Later, Denaud et al. (2012) compared different signal processing methods to estimate LCF from the sound recorded during laboratory scale peeling; however, in these studies, LCD was not measured.

Wang et al. (2001) measured LCD and total lathe check number (LCN) of a sample using acousto-ultrasonic and stress wave methods. When modelling the relationship between the acousto-ultrasonic parameters and LCD by multiple regression analysis, the best coefficient of determination, R^2, of the model was 0.52. The best R^2 of the model for LCD and stress wave parameters was 0.63. These measurement methods were not sensitive to LCN, and both methods require contact with the veneer.

When developing a non-destructive and non-contact measurement method, a laser-based measurement method could be an option. Wahl et al. (2001), for example, measured microcracking in wood caused by drying by detecting the intensity variations of a speckle pattern induced by a focused laser beam scattered from the surface. Nieminen et al. (2013) measured defects and GA from timber using laser trans-illumination imaging.

The GA of wood or veneer has been measured in different ways. Steele et al. (1991), for example, used a rotating capacitance head (capacitance method) that is based on measuring the dielectric constant of wood. Tsuchikawa and Tsutsumi (1997) measured the GA and surface roughness of solid wood by NIR spectroscopy and by a multiple linear regression analysis. Gindl and Teischinger (2002) proposed the partial least square analysis of Vis and NIR reflectance spectra as a possible means of determining GA. Silvennoinen et al. (2000), Simonaho et al. (2004), Hu et al. (2004) and Huang et al. (2008) all measured wood GA using a laser light source. These methods utilized the reflected laser beam. Using this approach, GA is determined by obtaining the orientation of an elliptical area illuminated by the laser. Tolonen et al. (2001) developed a method based on laser light reflected from the wood surface to measure the diving angle of wood grain. Wood veneer has also been studied to determine GA deviation by examining the scattering pattern of transmitted light on the un-illuminated side of the veneer (Söyrilä and Koponen 2000). Using this method, the elliptical illumination pattern is recognized by image

analysis and the orientation of the major axis of the ellipse is determined. According to Söyrilä and Koponen (2000), GA may be determined with good accuracy using this method.

In general, the measurement of GA in wood and veneer is well known. However, it would be beneficial to combine the measurement of GA with LCD measurement so that both quantities could be measured simultaneously. Some of the methods described above are more suitable than others for the further development of an online peeling check depth measurement system. This paper reports a study in which the LCD and GA of birch veneer were measured simultaneously by laser. Laser light can penetrate wood veneer, and from the penetrating signal, the depth of the peeling checks can be estimated. Furthermore, from the elliptical light pattern formed by the laser, GA can be estimated. This method is non-destructive and could, feasibly, be used industrially in real-time measurements.

Materials and methods

Veneer peeling and conditioning

Three fresh birch (*Betula pendula* Roth) logs were soaked in water at 20, 40 and 70 °C for 48 h and peeled with a rotary lathe (Model 3HV66; Raute Oyj, Lahti, Finland) to produce veneers with a nominal thickness of 3.5 mm. Soaking temperature is known to affect LCD (Rohumaa et al. 2013), so by using different soaking temperatures different LCDs were obtained. In all, 26 veneer specimens having dimensions of 60×50 mm^2 (60 mm along the grain) were cut from the veneer produced and were conditioned at a relative humidity (RH) of 65 % and temperature of 20 °C until equilibrium was reached. The samples were knot-free and were cut from the veneer sheets far from any knots. The moisture content (MC) and density of the veneers were obtained gravimetrically. The thickness of the veneers was measured to two decimal places with a digital micrometer (Mitutoyo ID-C112 PB, Japan) combined with an instrument which ensure that the veneer was flat when measured. The MC, density and thickness on the veneers are shown in Table 1.

LCD reference measurements

The measurement of LCD for use as a reference was performed in a similar manner to that described by Pałubicki et al. (2010), after the measurement of LCD using the

Table 1 Average and standard deviation of MC, dry density and thickness of conditioned veneers. Standard deviations are in parenthesis ($n = 5$/group)

| Soaking temperature (°C)	MC (%)	Density (kg/m^3)	Thickness (mm)
20	14.9 (0.1)	554 (9)	3.48 (0.03)
40	13.8 (0.2)	604 (14)	3.50 (0.03)
70	15.3 (0.1)	608 (7)	3.39 (0.05)

laser set-up presented in Fig. 1 had been carried out. Briefly, following LCD measurement with the laser, the loose side of each veneer sample was coloured using a black textile dye (Dylon, Spotless Group, Paris, France). After applying the dye, the samples were again conditioned at RH 65 %, 20 °C until equilibrium was reached. The samples were then sawn across the grain into two pieces, and the LCD measured optically from the sample cross section using an optical stereo microscope (Wild MZ8, Leica, Wetzlar, Germany) and image processing using National Instruments, Vision Assistant 7.1 software. In all, four operators measured the reference values from the images three times. Each lathe check in every sample was measured.

LCD laser measurement system and measurements

The laser measurement set-up used is shown schematically in Fig. 1. It consisted of a laser light source, polarizers, optics and camera.

The laser used was a 785-nm (TEM00) GaAlAs diode laser (Toptica Photonics XTRA) projected through a single-mode polarization maintaining fibre (Toptica Photonics, MDF = 4.5 μm, numerical aperture NA = 0.11, 3 m in length). The maximum power of the laser was 500 mW. The radiation was collimated using an aspheric lens ($f = 11.0$ mm) at the fibre output, which produced a beam with a diameter of 2.2 mm. The polarization and laser power were controlled by two zero-order half-wave plates and an anti-reflection-coated Glan–Taylor calcite polarizer. The diameter of the sample holder was 122 mm. The veneer holder was designed such that the veneer sample would be bent a little so that the lathe checks would be opened slightly to make them more visible. On the side of the holder was a mechanism that supported the sample and kept it in place. The sample was always positioned so that the loose side containing the checks faced the camera. During measurement, the sample was manually moved downwards along the surface of the sample holder and 200 frames of video were taken with a monochromatic camera (Pixelink PL-B741F; Ottawa, Ontario, Canada). From these videos, estimates of LCD and GA were obtained.
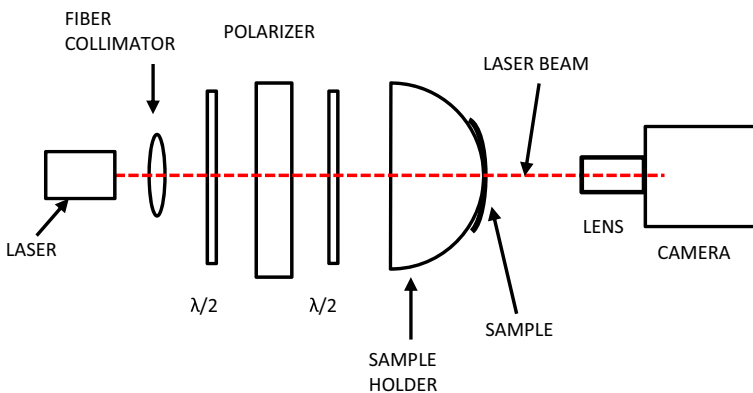
Fig. 1 Principle of the LCD and GA measurement set-up

Analysis of reference LCD data

Generally, the reliability of data is an important matter and measurement should not be dependent upon the operator (person performing the measurement), and so for this reason, a repeatability and reproducibility (R & R) study was conducted to determine whether the reference LCD measurement procedure was adequate (Burdick et al. 2003). An analysis of variance approach to this test was used for this purpose. In general, if the measurement variation is small relative to the actual process variation, the measurement procedure is adequate. If it is not, the measurement procedure must be improved before it can be used satisfactorily. In this test, repeatability represents the variability arising from the measurement procedure when used to measure the same unit (with the same operator or set-up in the same time period). Reproducibility reflects the variability arising from different operators, set-ups or time periods (Burdick et al. 2005). For the R & R study, a data set of 15 samples was used. Measurement of these 15 samples resulted in a total of 3817 individual LCD values. As noted previously, the average over the 15 samples was calculated and since four operators each measured LCD three times, a total of 180 average values were used in the R & R study.

The analysis of variance model (Burdick et al. 2003) used in the R & R study is shown in Eq. 1.

$$Y_{ijk} = \mu + S_i + O_j + (SO)_{ij} + E_{ijk}$$
$$i = 1, \ldots, s; j = 1, \ldots, o; k = 1, \ldots, r; \tag{1}$$

where μ is a constant, and S_i, O_j $(SO)_{ij}$, E_{ijk} are jointly independent normal random variables with means of zero and variances of σ_S^2, σ_O^2, σ_{SO}^2 and σ_E^2, respectively. These variances are often referred to as variance components. S represents samples (parts), O represents the operators (appraisers), and E represents the random error. In terms of this model, repeatability is σ_E^2, reproducibility is $\sigma_O^2 + \sigma_{SO}^2$, and the total variability associated with the measurement procedure is $\sigma_O^2 + \sigma_{SO}^2 + \sigma_E^2$, which may be called the R & R value. The process (sample-to-sample) variability is represented by σ_S^2. A ratio, δ, that compares process variability to measurement variability is given by Eq. 2 (Burdick et al. 2003).

$$\delta = \frac{\sigma_s^2}{\sigma_O^2 + \sigma_{OS}^2 + \sigma_E^2} \tag{2}$$

Several indices have been devised to summarize the results of such an R & R study. For example, the number of distinct product categories that can be reliably distinguished by the measurement procedure is given by Eq. 3 (Burdick et al. 2003).

$$\text{Distinct categories} = \sqrt{\frac{2\sigma_S^2}{\sigma_O^2 + \sigma_{OS}^2 + \sigma_E^2}} \tag{3}$$

In Table 3, some of the key R & R study results are shown. The column headed '5.15 Std dev' in Table 3 is the square root of the variance associated with each term

multiplied by the sigma multiplier (5.15). The sigma multiplier defines the percentage of the normal distribution that is compared to the process variability and establishes the magnitude of the range of the measurement variable. The most common value used is 5.15, because the mean plus or minus (5.15)/2 sigma contains 99.0 % of the area under the normal distribution curve (Barrentine 2003). Hence, by comparing these values, the relative impact of each source of variation can be seen.

In Table 3, the column headed '% Total variation' is 100 times the ratio of this term's standard deviation to the total variation's standard deviation. One of the key statistics to look at is whether the R & R value in this column is small enough. If the R & R value is <10 %, the measurement procedure is deemed excellent, and when it is <20 %, it is deemed adequate. When it is <30 %, it is marginal. When the R & R value is >30 %, it should not be used for process monitoring (Barrentine 2003). The last column headed '% Total variance' is 100 times the ratio of this term's variance to the total variation's variance.

Analysis of camera data

Before analysis, half of data were set randomly as a 'training' set and the other half as a 'test' set. The training set was used when modelling the relationship between the reference LCD and camera data. The test set was used when estimating the RMSE of the estimated model.

The videos were analysed frame by frame using MATLAB 2013b software. Of the 200 frames captured, the first 10 frames and the last 50 frames were omitted from the analysis to ensure that only the sample was in the image. (Although the manual movement of the samples was as steady as possible, at the beginning and the end of the videos, the sample was not in the images.) The frames were analysed differently according to whether LCD or GA values were being obtained. In the case of LCD, the target was to recognize lathe check depth from the elliptical illuminated area of the image. Prewitt filtering was used since it emphasizes horizontal structures (Gonzalez and Woods 2001). After filtering, the image was thresholded using Otsu's method (Otsu 1979), which chooses the threshold in such a way as to minimize the intraclass variance of the black and white pixels. This enabled the lathe checks to be recognized, and their area calculated objectively. To ensure differentiation between the lathe checks and wood grain, only the object with a maximum area recognized by the system was chosen for further analysis. The average of these maximum lathe check areas obtained from the 140 frames/sample was subsequently calculated. Then, the relationship between the average lathe check areas of the samples and the reference LCDs was statistically modelled using regression analysis. The training data set was used when the regression parameters were trained, and the RMSE of the estimated model was obtained using the test data set.

As described by Söyrilä and Koponen (2000), GA can be measured by examining the scattering pattern of transmitted light on the un-illuminated side of the veneer. When determining GA, the threshold value was manually chosen so that an elliptical illuminated area was recognized. The threshold value was then kept constant during image analysis. The orientation of the ellipse was subsequently

obtained by fitting an ellipse to the recognized object (illuminated elliptical area) and obtaining the angle of the major axis of the ellipse.

Results and discussion

Reliability analysis of reference LCD data

The average reference LCD over all operators and repeated measurements and in different veneer groups soaked at different temperatures is presented in Table 2.

Table 2 shows that soaking temperature has an impact on LCD; the higher the soaking temperature the smaller the LCD. In addition, the number of lathe checks is higher when the LCD is lower, which supports earlier findings of Koch (1965), Korpijaakko (1999) and Dupleix et al. (2013). Visually, this can be seen in Fig. 2 where there are images of veneer below the chart showing the characteristics of the samples at each soaking temperature. In the veneer produced from logs soaked at 20 °C, the lathe checks are infrequent and the LCD is high. In contrast, in the 70 °C group, the lathe checks are more frequent and the LCD is low. The 40 °C group is intermediate.

Figure 2 also shows the average LCDs for each of the four operators over three repeated measurements in each material group. As may be seen, each operator's average measurements differ. However, in the 20 and 40 °C groups, the first two operators have measured almost identical LCDs, but in the 70 °C group, their results differ from each other. This might be explained by the fact that the first two operators had former experience in measuring LCD using this method. The other two operators were taught the measurement system in a similar manner, but they had no prior experience.

Generally, the greatest difference is in the 70 °C group and also the error bars, i.e. standard deviations are highest. This might be because in this group there were samples that had a lot of checks near to each other and the LCD was low. Sometimes, it is difficult to determine whether there is a small check or not or whether there are two checks near to each other or only one check. Every operator seems to determine these situations differently. In Fig. 2, for example (shown with an arrow), in the 70 °C group in the right corner, there are two checks very near to each other. The R & R study was performed on these reference LCD data. The Distinct Categories Index (Eq. 3) was 5.5. AIAG (2002) recommends that the
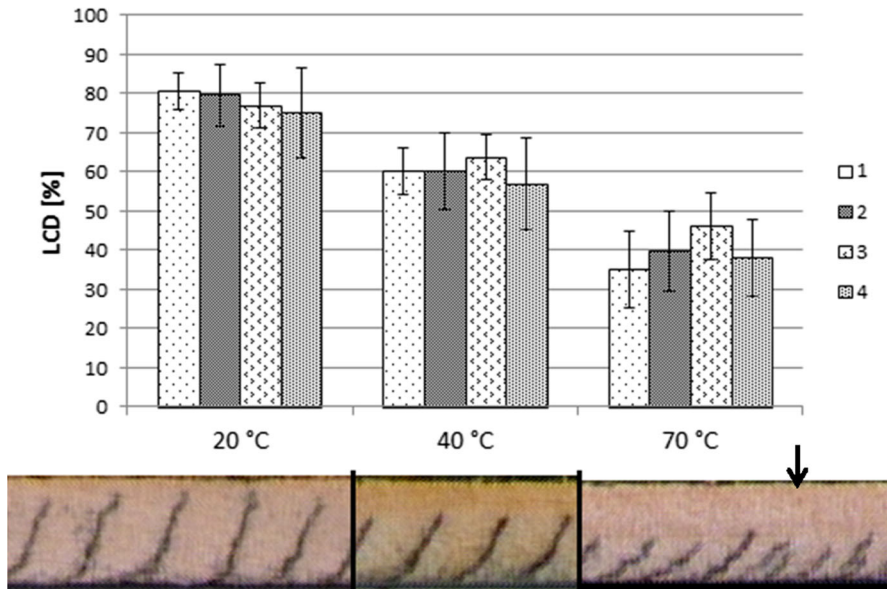
Table 2 Average and standard deviation of reference LCDs

Soaking temperature (°C)	Number of lathe checks/measurement*	LCD (%)
20	90	78.0 (8.2)
40	98	60.2 (9.1)
70	146	39.7 (10.5)

Standard deviations are in parentheses ($n = 5$/group)

* For each operator

Fig. 2 Average LCDs in each veneer group soaked at different temperatures and for each operator. The *error bars* are ± standard deviation. *Under the bars* of each veneer group is a representative image of the corresponding veneer

Table 3 Some of the key results of the R & R study

Term	Variance	Standard deviation	5.15 Std dev	% Total variation	% Total variance
Sample	268.8	16.4	84.4	96.8	93.8
Operator	4.6	2.2	11.1	12.7	1.6
Interaction	9.6	3.1	15.9	18.3	3.3
Reproducibility	14.2	3.8	19.4	22.3	5.0
Repeatability	3.6	1.9	9.7	11.1	1.2
R & R	17.8	4.2	21.7	24.9	6.2
Total variation	286.5	16.9	87.2	100.0	100.0

Distinct Categories Index should be 5 or above in order for the measurement system to be adequate. So, based on this Distinct Categories Index, this measurement system is adequate.

In Table 3, some key results of the R & R study are shown. Most of the variation comes from the samples since the range of reference LCDs was from 25.7 to 84.2 % (See 'variance' column in Table 3).

In Table 3, the R & R value in the '% Total variation' column is one of the key statistics. In this study, the measurement procedure is deemed marginal based on the value of this criterion. The value for reproducibility in the '% Total variation' column is approximately twice as high as that of the repeatability term, so most of the measurement variation arises from the operators. On the other hand, the

repeatability of the operator seems to be quite good meaning that operators may have a different perception of the measurement but they can repeat it quite well. The last column '% Total variance' indicates the same as the preceding statement because reproducibility is 5.0 % of total variance and repeatability only 1.2 %.

Furthermore, it can be concluded that this R & R test procedure does not take into account the uncertainty coming from staining the samples. From experience, the dye is sometimes difficult to get into the bottom of checks when the LCD is high, so there always remains the question of whether the checks are properly dyed or not. It is possible that the staining of the veneer is an even larger source of error than the operator.

LCD

Figure 3 shows images taken from samples in the 20 and 70 °C groups. First in Fig. 3a, e, the raw images are seen. In the filtered greyscale images shown in Fig. 3b, f, the lathe checks may be clearly observed. They are seen as brighter horizontal lines inside the illuminated area. In the 20 °C group, the lathe checks are longer and wider. In the 70 °C group, the lathe checks are quite small and they are not so clearly visible. Lathe checks follow the same pattern as seen in Fig. 2: in the
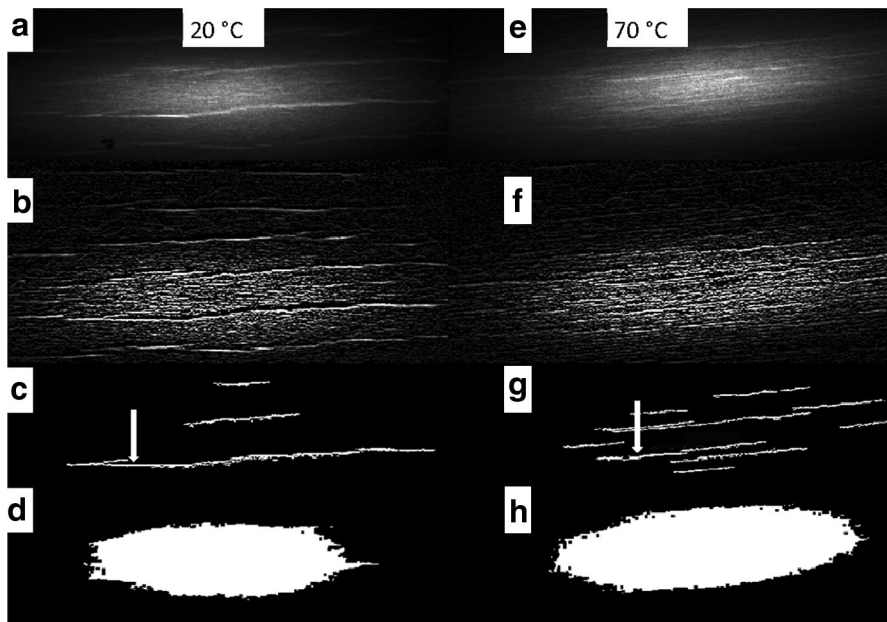
Fig. 3 **a** Example from the 20 °C group of a greyscale video frame before filtering, **b** example from the 20 °C group of a greyscale video frame after filtering, **c** corresponding binary image differentiating the lathe checks, **d** corresponding binary image identifying the elliptical illuminated area; **e** example from the 70 °C group of a greyscale video frame before filtering, **f** example from the 70 °C group of a greyscale frame after filtering, **g** corresponding binary image differentiating the lathe checks, **h** corresponding binary image identifying the elliptical illuminated area

20 °C group, the lathe checks are farther apart from each other, and in the 70 °C group, the distance is smaller.

Figure 3c, g shows the corresponding binary images where the lathe checks can be clearly identified. In the 20 °C group (Fig. 3c), the area of the largest check is markedly larger than in the 70 °C group (Fig. 3g) where a greater number of smaller checks can be observed. The area of the largest check in Fig. 3c is 1902 pixels and in Fig. 3g 458 pixels. Checks are marked on the images with white arrows.

In Fig. 4, the reference LCD values as a function of the average sample lathe check area in the training set can be seen. The average area (in pixels) of lathe checks has been scaled by dividing it by 10 to obtain a scale nearer to the reference LCD scale.

Figure 4 shows that the dependency between the area of the lathe checks and the reference LCD appears to be linear. The area of lathe checks increases as the reference LCD increases. Greater deviation can be seen when the reference LCD is higher (above 70 %). One source of this variation could be the aforementioned incomplete penetration of the dye colour in the veneer samples when the LCD is high.
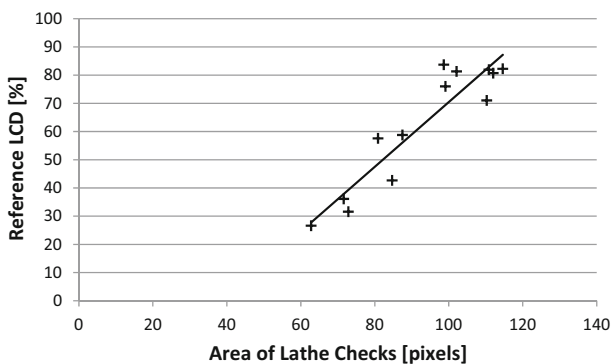
The relationship between the area of the lathe checks and the reference LCD was modelled by linear regression. The data follow the form (Eq. 4)

$$LCD = 1.15ALC - 44.34 \tag{4}$$

where ALC is the area of lathe checks.

The R^2 of the estimated regression model is 0.86. Previously, Tomppo et al. (2009) measured LCD from 1.5-mm-thick dry birch veneer using contact ultrasound. When modelling the relationship between LCD and the ultrasonic parameters, the best R^2 for the model was 0.47. One explanation for the lower R^2 could be that the LCD from the 1.5-mm veneer is more difficult to measure.

Wang et al. (2001) also measured LCD as well as lathe check number (LCN) from 2.5-mm-thick Douglas-fir veneer (MC 7 %) with acousto-ultrasonic and stress wave methods. When modelling the relationship between acousto-ultrasonic parameters and LCD, the best R^2 of the model was found to be 0.52 and the best R^2 of the model for the relationship between LCD and stress wave parameters was 0.63.

Fig. 4 Reference LCD as a function of sample average area of recognized lathe checks (training set, $n = 13$)

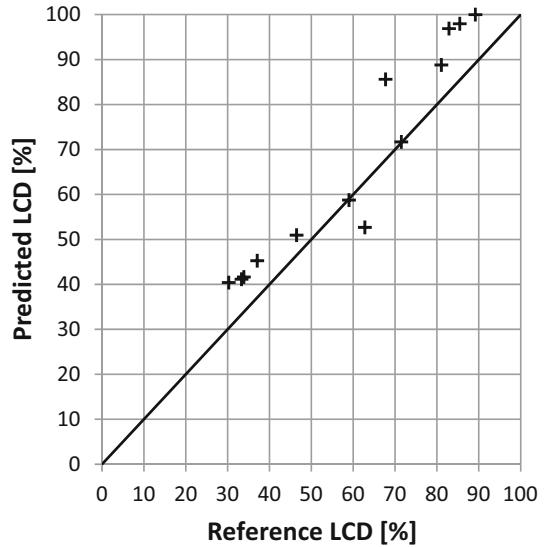**Fig. 5** Reference LCD versus
predicted LCD

Figure 5 shows the relationship between the reference LCD and the LCD predicted using Eq. 4 with the test data set. Ideally, the points should lie on the line where the reference LCD and the predicted LCD would be the same.

Figure 5 shows that with Eq. 4, the LCD of the samples not used in the training model could be predicted relatively accurately. As might be expected, the greatest error is when the LCD is the highest and the predicted LCDs are higher than the reference LCDs. The RMSE of the model presented was 9.9 % for the test set.

Previously, Pałubicki et al. (2007, 2010) described the SMOF device for LCD measurement, in which a green veneer strip is bent to open up the lathe checks using a 70-mm-diameter pulley for veneer >3.0 mm in thickness. In this present study, the diameter of the pulley used to open up the veneer to improve the contrast was 122 mm; the larger the pulley diameter, the lower the risk of damage to the samples. However, these methods could not be directly compared since wet veneer may be twisted more than the dry veneer used in this study. Another advantage of the method presented is that it is independent of the sample cutting quality since the images are not obtained from the cross section. In addition, with the method presented, the GA could be obtained simultaneously which makes the estimation of other veneer properties possible.

GA

The GA of the samples was measured simultaneously with LCD from same frames but with different image analysis techniques. Figure 3d, h illustrates the elliptical illuminated area identified by image analysis in the 20 and 70 °C veneer groups. In Fig. 3h, the GA is higher most probably because of the manual sawing technique used to produce the samples; some of the veneers have been more tilted than others when sawing. If the orientations of the lathe checks are compared with the ellipses
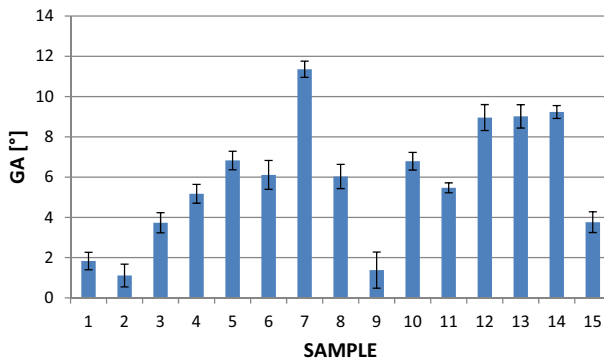
Fig. 6 Average GA of the samples. *Error bars* are ±standard deviation of each sample

seen in Fig. 3d, h, it can be noted that the lathe checks follow approximately the grain direction, which is to be expected.

Söyrilä and Koponen (2000) mentioned that the average absolute error using this method to determine GA was 1.1°. According to Söyrilä and Koponen (2000), the ratio between the major and minor axes of the illuminated ellipse is greater using this method than methods which rely upon reflected scattered light. This helps in image analysis to determine the orientation of the major axis of the identified ellipse. Another advantage of this method is that it describes the GA throughout the whole thickness of veneer.

Figure 6 shows the average GAs of the training set samples. As mentioned previously, the GAs differ from each other due to the sawing process. The standard deviation is quite low because GA does not change too much over the 5-cm path in the sample. In principle then, the GA over an entire veneer sheet could be 'mapped' using this approach.

Light propagation and scattering in wood have been studied (Kienle et al. 2008). Heterogeneous materials scatter and absorb light in a random fashion. However, the fibres in wood have a certain orientation and this ordered arrangement affects light propagation in the material. In knots and in their vicinity, the orientation of the fibres deviates from the main direction of the wood fibre. In a radial or tangential plane, the scattering pattern of incident light takes the shape of the aforementioned ellipse. According to Simonaho et al. (2004), the reason for this is the fact that the cell walls and cell cavities act as optical waveguides, which stretch the scattering pattern observed on the surface of the sample in the grain direction. Thus, the orientation of the scattering pattern on the surface of wood is related to the orientation of the wood GA.

Conclusion

In this study, it has been shown that LCD and GA can be measured simultaneously using laser trans-illumination imaging. The contrast in the method was improved by slightly opening the lathe checks, by bending the veneer. It was found that the average lathe check area given by image analysis was strongly correlated with the

reference LCD data obtained manually using a microscopic method. A strong correlation between area of lathe checks and reference LCD was found, and the method presented in this study seems to be promising. On the basis of the results reported herein, the accuracy of the method presented would appear to be similar, or better than, other methods reported in the literature. The RMSE of the method presented was 9.9 %. The GA of the samples was also measured simultaneously using image analysis. In time, it may be possible to develop an online measurement method for an industrial peeling line based on this approach, though further research and validation are, of course, required.

In addition, the uncertainty of the reference (manual) LCD measurement method was tested with an R & R test because the operator may have an impact on the measurement results when manually measuring LCD under a microscope. The test revealed that this measurement method is questionable and needs an experienced operator or the measurement from images should be automated with image analysis for more reliable results. This implies that the difficulty of obtaining reliable reference LCD data makes the development of a non-destructive LCD measurement method more challenging.

References

AIAG (2002) Measurement system analysis, 3rd edn. Automotive Industry Action Group, Detroit

Antikainen T (2001) Effect of peeling parameters on the quality of spruce veneers (In Finnish), Master thesis. Helsinki University of Technology, Department of Forest Products Technology, Espoo

Barrentine LB (2003) Concepts for R & R studies, 2nd edn. ASQ Quality Press, USA

Burdick RK, Borror CM, Montgomery DC (2003) A review of methods for measurement systems capability analysis. J Qual Technol 35:4

Burdick RK, You-Jin, Montgomery DC, Borror CM (2005) Confidence intervals for misclassification rates in a gauge R & R study. J Qual Technol 37:4

Chow S (1974) Lathe-check influence on plywood shear strength. Information report VP-X-122. Canadian Forest Service, Vancouver, BC, Canada

Corder SE, Atherton GH (1963) Effect of peeling temperatures on Doughlas fir veneer. Oregon State University, Forest Products Laboratory

Denaud LE, Bléron L, Ratlec A, Marchal R (2007) Online control of wood peeling process: acoustical and vibratory measurements of lathe checks frequency. Ann For Sci 64(2007):569–575

Denaud LE, Bléron L, Eyma F, Marchal R (2012) Wood peeling process monitoring: a comparison of signal processing methods to estimate veneer average lathe check frequency. Eur J Wood Prod 70:253–261

DeVallance DB, Funck JW, Reeb JE (2006) Influence of several preparation conditions on Douglas-fir plywood gluebond quality test results. For Prod J 56:47–50

DeVallance DB, Funck JW, Reeb JE (2007) Douglas-fir plywood gluebond quality as influenced by veneer roughness, lathe checks, and annual ring characteristics. For Prod J 57:21–28

Dupleix A, Denaud L, Bléron L, Marchal R, Hughes M (2013) The effect of log heating temperature on the peeling process and veneer quality: beech, birch and spruce case studies. Eur J Wood Prod 71(2):163–171

Gindl W, Teischinger A (2002) The potential of Vis- and NIR-spectroscopy for the nondestructive evaluation of grain-angle in wood. Wood Fiber Sci 34:651–656

Gonzalez RC, Woods RE (2001) Digital Image Processing, 2nd edn. Prentice Hall, USA

Hirvonen K, Karonen A (1984) Method for identifying timber surface properties US Patent Specification 4,482,250

Hu C, Tanaka C, Ohtani T (2004) On-line determination of the grain angle using ellipse analysis of the laser light scattering pattern image. J wood Sci 50(4):321–326

Huang C-L, Floyd SL, Stanish MA, Bogue DN (2008) Methods for using light reflection patterns to determine location of pith and curvature of the annual ring US Patent Application Publication US 2008/0078473 A1

Kienle A, D'Andrea C, Foschum F, Taroni P, Pifferi A (2008) Light propagation in dry and wet softwood. Opt Express 16:9895–9906

Koch P (1965) Effects of seven variables on properties of southern pine plywood. Part II, maximizing wet shear strength. For Prod J 15:463–465

Korpijaakko S (1999) Factors affecting strength properties of birch veneer, in particular relative to plywood manufacturing of heavy transport industry floors (In Finnish). Master's thesis. Helsinki University of Technology, Department of Forest Products Technology Espoo

Neese JL, Reeb JE, Funck JW (2004) Relating traditional surface roughness measures to gluebond quality in plywood. For Prod J 54:67–73

Nieminen S, Heikkinen J, Räty J (2013) Laser transillumination imaging for determining wood defects and grain angle. Meas Sci Technol 24:125401. doi:10.1088/0957-0233/24/12/125401

Otsu N (1979) A threshold selection method from gray-level histograms. IEEE Trans Syst Man Cybern 9(1):62–66

Pałubicki B, Butaud J-C, Bléron L, Collet R, Marchal R (2007) Development of veneer quality measuring device—SMOF. 3rd International Symposium on Veneer Processing and Products, October 23–26 2007, Shanghai, China, pp 161–169

Pałubicki B, Marchal R, Butaud J-C, Denaud L-E, Bléron L, Collet R, Kowaluk G (2010) A method of lathe checks measurement; SMOF device and its software. Eur J Wood Prod 68:151–159

Rohumaa A, Hunt CG, Hughes M, Frihart CR, Logren J (2013) The influence of lathe check depth and orientation on the bond quality of phenol-formaldehyde bonded birch plywood. Holzforschung 67:779–786

Silvennoinen R, Koponen S, Huovinen A, Kanerva P, Räsänen J (2000) Method and device for determining wood grain angle using laser-optical sensor (In Finnish). Finnish patent and registration office, Suomi-Finland 20001736

Simonaho S-P, Jari Palviainen, Tolonen Y, Silvennoinen R (2004) Determination of wood grain direction from laser light scattering pattern. Opt Lasers Eng 41:95–103

Sinn G, Sandak J, Ramananantoandro T (2009) Properties of wood surfaces—characterisation and measurement. A review. Holzforschung 63:196–203

Söyrilä P, Koponen T (2000) Method for measurement of veneer grain angle using laser (In Finnish), Finnish patent and registration office Suomi-Finland 20002047

Steele PH, Neal SC, McDonald SM (1991) The slope-of-grain indicator for defect detection in unplanned hardwood lumber. For Prod J 41(1):15–20

Tolonen Y, Simonaho SP, Silvennoinen R (2001) The use of laser light and holographic interferometry in research of timber and its deformations 1st International Conference of the European Society for Wood Mechanics, Swiss Federal Institute of Technology(EPFL, Switzerland, 19–21 April 2001) pp 591–601

Tomppo L, Tiitta M, Lappalainen R (2009) Ultrasound evaluation of lathe check depth in birch veneer. Eur J Wood Prod 67:27–35

Tsuchikawa S, Tsutsumi S (1997) Application of near infrared spectrophotometry to wood. 5. Calibration equations for physical conditions of wood. Mokuzai Gakkaishi 43:149–158

Wahl P, Hanhijärvi A, Silvennoinen R (2001) Investigation of microcracks in wood with laser speckle intensity. Opt Eng 40(5):788–792

Wang J, Biernacki JM, Lam F (2001) Nondestructive evaluation of veneer quality using acoustic wave measurements. Wood Sci Technol 34:505–516

Williams RS, Knaebe MT, Sotos PG, Feist WC (2001) Erosion rates of wood during natural weathering: part I, effect of grain angle and surface texture. Wood Fiber Sci 33(1):33–42