Hypothesis on the role of cell wall structure in differential transverse shrinkage of wood

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Cell wall thickness under dry and wet conditions and the cellulose fibril arrangement on transverse-fracture surfaces of the S2 layer of the tangential and radial walls of Scots pine tracheids were examined using SEM images and ESEM images, respectively. A hypothesis for explaining the anisotropic transverse shrinkage of wood was proposed based on the test results and statistical analysis. A simplified model of a tracheid's cross-section was drawn for calculating the differential transverse shrinkage. Results of this study indicate that the radial cell wall of Scots pine latewood is about 25 percent thicker than the tangential wall. Earlywood does not show such a difference. Furthermore, there is a significant tendency of a preferential orientation (i.e. packing density) of the fibrils on the tangential and radial walls in the overall tangential direction. Despite some phenomena of the cell wall structure not yet clearly understood, this might explain the anisotropic transverse shrinkage of wood to a major extent.

Hypothese zur Bedeutung der Zellwandstruktur für die anisotrope Schwindung von Holz quer zur Faser

Es wurden die Zellwanddicken unter feuchten und trockenen Bedingungen und die Anordnung der Cellulosefibrillen der S2-Schicht auf Querbruchflächen der radialen und tangentialen Zellwände von Kiefernspiltholz mit FE-SEM- und FE-ESEM-Mikroskopen untersucht. Auf der Basis der Messresultate und ihrer statistischen Auswertung wird eine Hypothese zur Erklärung der anisotropen Schwindung quer zur Faser aufgestellt. Dazu wird ein vereinfachtes Modell des Tracheidenquerschnitts entwickelt, mit dem die unterschiedliche radiale und tangential Schwindung abgeschätzt wird. Entsprechend den Messresultaten sind die radialen Zellwände von Kiefernspiltholz durchschnittlich rd. 25% dicker als die tangentialen, während Frühholzzellen diesen Unterschied nicht zeigen. Tendenziell sind die Fibrillen der S2-Schicht auf radialen und tangentialen Querflächen von Früh- und Spätholz in einer tangentialen Vorzugsrichtung agglomeriert bzw. ist ihre Packungsdichte tangential grösser als radial. Zwar sind einige Phänomene der Zellwandstruktur noch ungeklärt, doch kann diese Fibrillenanordnung der S2-Schicht

die Schwindungsanisotropie quer zur Faser zu einem Grossteil erklären.

1

Introduction

Due to the anisotropy of its structure, wood changes its longitudinal, radial, and tangential dimensions (L, R, T) with hygroscopic changes in the wood moisture content to quite a different extent. The average ratio of this hygroexpansion L/R/T for all wood species is about 1/10/20. It is widely agreed that the hydroexpansion is mainly caused by the cellulosic fibrils and their arrangement and orientation within the wood cell wall whereas the lignin matrix is assumed to be dimensionally rather stable. Furthermore, there is an agreement that hygroexpansion normally occurs at right angles to the fibril axis (Skaar 1988). The fibril axis of the thickest and, therefore, the expansion dominating S2 layer of the cell wall of normal wood is directed at small angles to the cell (fiber) axis. This explains why the dimensional changes of wood are much greater perpendicular than parallel to the grain. It does not explain, however, the fact that the tangential hygroexpansion is about twice the radial expansion.

Possible reasons for anisotropic shrinking/swelling of wood in the two transverse-fiber directions have been the subject of numerous studies, often with controversial results and hypotheses. According to Pentoney (1952) and Skaar (1988), four theories have been developed. Two of them are based on the gross wood structure: the ray restraint theory in which the wood ray tissue limits the radial movement of the other cells, and the earlywood/latewood interaction theory according to which the thick-walled latewood governs the movement and forces the less dense earlywood to shrink to a greater extent than it would do by its own. The third theory proposes that the differential tangential and radial hygroexpansion is caused by differences in the swelling characteristics of the various cell wall layers. According to this, particularly different arrangements and thicknesses of the compound middle lamella are the main reasons for this phenomenon. The fourth proposal deals with different angles of the longitudinal fibril orientation of the S2 layer: since the angle is reported to be greater in radial than in tangential walls, it leads to more hygroexpansion of the radial walls or in the tangential direction, respectively.

Skaar (1988) believes that both the ray-restraint and dominant latewood hypotheses are most probable in explaining the different dimensional changes. However, in

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our opinion there are good reasons to assume that the fine structure of the cell wall is also important in this context. After all, it is the cell wall that undergoes moisture related dimensional changes. Therefore, the arrangement of the cellulose fibrils might be of major importance, especially within the thick S2 layer. This is not only true for the longitudinal structure of the walls but also for the fibril arrangement perpendicular to the cell axis or on cross-sections of the wall, respectively. This fine structure of the wooden cell wall has been intensely studied by numerous researchers, particularly since electron microscopy became widely available in the 1950's. Côté (1968) described a model of the cell wall which consists of the well known 'concentric' layers of the secondary walls of adjacent cells (S1, S2, S3) which are connected by the compound middle lamella (CML). According to Côté's model, the thick S2 layer itself is built up by numerous concentric lamellae with slightly different fibril angles to the cell axis.

Similar or identical models have been proposed by several authors before and after the article of Côté (1968). There are, however, some reports on a cross-section structure of the S2 layer consisting of fibril arrangements more or less perpendicular to the CML or radial to the cell axis, respectively; the respective literature has been summarised by Zimmermann and Sell (1997). The discussion on fibril arrangements of the S2 layer perpendicular (or inclined) to CML has been resumed recently when high-resolution SEM studies on transverse-fracture surfaces of tension-loaded softwoods and hardwoods revealed non-concentric 'agglomerations' of fibrils of the S2 layer (Sell, Zimmermann 1993; 1998). These perpendicular structures are meanwhile confirmed by means of other microscopical and detection techniques (Larsen et al. 1995; Schwarze, Engels 1998; Sell 1994a; Singh et al. 1998) and are assumed to improve the mechanical performance of the wooden cell wall (Booker, Sell 1998; Sell 1994b). The formation of fibril agglomerations of the S2 layer perpendicular to CML is explained by a higher packing density of the fibrils in this direction and, therefore, by thicker parts of the lignin matrix between these agglomerations (Sell, Zimmermann 1993; 1998). This leads to the consideration that the higher packing density of the cellulose fibrils in a preferential direction more or less perpendicular to CML might be an additional reason for the different radial and tangential hygroexpansion.

The present study is trying to propose a hypothesis for partially explaining the anisotropic shrinking/swelling of cross sections of wood based on the following elements of the cell wall structure: radial and tangential cell wall thickness and fibril arrangement on cross-sections of the S2 layer.

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Materials and methods

2.1

Cell wall thickness

To measure the average cell wall thickness in the radial and tangential direction, three $6 \times 6 \times 6 \text{ mm}^3$ cubes were cut from a green Scots pine sapwood (*Pinus sylvestris*) rod which was freshly cut and stored in water until prepara-

tion. Two cubes with the flattest ring orientation were chosen for the SEM examination. The cross sections of these 2 cubes were smoothed with a razor blade and then put into a vacuum dryer with the temperature set at 40°C . After drying for 12 hours, the samples were removed, mounted on SEM sample holders, and sputtered with platinum. The cross-sections were then examined in the field emission scanning electron microscope (FE-SEM) JEOL-6300-F for measuring the thickness of the radial and tangential cell walls under the dried condition.

In addition, one $6 \times 6 \times 6 \text{ mm}^3$ cube with a smoothed cross-section was examined under the Philips XL30-FEG Environmental Scanning Electronic Microscope with field emission cathode (FE-ESEM). This sample was totally wet since it had been soaked in water for several days after being cut from the fresh pine board without any drying or vacuuming process before the observation. This ESEM equipment allows the observation in a normal environment, i.e. in a humid atmosphere with normal air pressure. So, the cell wall thickness of the radial and tangential walls could be measured under 'original' wet condition (swollen state) to compare with the dry wall thickness of the 2 samples from the same rod.

Five images each with a magnification of $400\times$ were taken from earlywood and latewood parts by the ESEM from the smoothed cross-section of Scots pine under wet condition (Figs. 1, 2). Another 10 images, 5 from earlywood and 5 from latewood, were taken by the SEM under dry condition (Figs. 3, 4). Then 10 cells were randomly selected from each of the images for measuring the radial and tangential wall thickness by an image analysis software (ImageAccess). 50 measurements each of the tangential and radial wall thickness for both wet latewood and earlywood tracheids were obtained. Then under the dry condition, the same data collecting procedures were performed on the SEM images of the dried samples. Table 1

Fig. 1. Smoothed cross-section of wet (swollen) Scots pine latewood. FE-ESEM micrograph for the measurement of cell wall thickness

Bild 1. Geglätteter Querschnitt von feuchtem (gequollenem) Kiefern-Spätholz. FE-ESEM-Aufnahme zum Messen der Zellwanddicke

Fig. 2. Cross-section of swollen Scots pine earlywood, same conditions as with Fig. 1
Bild 2. Querschnitt von gequollenem Kiefern-Frühholz. Bedingungen wie bei Bild 1

summarises the total number of images taken and thickness data measured.

2.2

Fibril arrangement on traverse-fracture surfaces of the S2 layer

In order to observe the fine cell wall structure under the FE-SEM, transverse-fracture surfaces were prepared by tension-loading. Three Scots pine (*Pinus sylvestris*) rods, $20 \times 20 \times 360 \text{ mm}^3$, were chosen for the bending test, based on the most parallel ring orientation. These pine strips had been conditioned at 20°C , 65% RH until an equilibrium wood MC of 12%. These 3 rods were loaded by

Fig. 3. Smoothed cross-section of dried (shrunk) Scots pine latewood (from the same wood sample source used for Figs. 1 and 2). FE-SEM microphotograph for the measurement of cell wall thickness
Bild 3. Geglätteter Querschnitt von getrocknetem (geschwundenem) Kiefernspätholz. FE-ESEM-Aufnahme zum Messen der Zellwanddicke (gleiches Material wie in Bild 1 und 2)

Fig. 4. Cross-section of shrunk Scots pine earlywood, same conditions as with Fig. 3
Bild 4. Querschnitt von getrocknetem Kiefern-Frühholz, Bedingungen wie bei Bild 3

a Zwick testing machine for bending failure: short-time bending mode, 3-point loading, loading speed of 2 N/s, whole bending test within 90 s. After the test, some samples of the fracture surface were carefully taken from the tension zone of each of the pine rods (Fig. 5), and glued on the SEM-holders. The mounted samples were stored in a cabinet for about 12 hours to cure the adhesive and were then sputtered with platinum. After sputtering, the samples were inserted into the high-resolution FE-SEM for examining the fine cell wall structure of Scots pine. The SEM examination was performed with an accelerating voltage of 5 kV and a working distance between 18 and 22 mm.

65 latewood cells (with magnification at least 1000 $\times$) were chosen for measuring the angle of the preferential fibril orientations of the S2 layer (with respect to the CML) on cross-surfaces of the tangential and radial walls by means of the ImageAccess software. Usually, 4 angle measurements were obtained from each of the 2 tangential walls of every single latewood tracheid observed. The average of the 8 measurements was defined as the mean orientation angle of the fibril agglomeration on the tangential wall for that single cell. The same data-collecting procedure was used for obtaining the fibril orientation on radial walls. Examples of the measurement method are shown in Fig. 6 for latewood. Since the radial wall is usually shorter compared to the length of the tangential wall and often additionally reduced by bordered pits, it was not possible to select as many measurable areas on radial walls as on tangential walls. Thus, only 47 latewood tracheid cells (from 65) were chosen for the measurement on radial walls.

The same measuring procedure was carried out for earlywood tracheids. Since the earlywood tracheids have much thinner cell walls than the latewood tracheids, it was more difficult to select earlywood cells with clearly distinguishable fibril orientations. Thus, the orientation angles of the S2 fibrils from only 28 earlywood cells were

Table 1. Number of SEM and ESEM photographs and the number of measurements of the cell wall thickness on these photograph
Tabelle 1. Anzahl der SEM- und ESEM-Aufnahmen und Anzahl der Messungen der Zellwanddicke an diesen Bildern

	Images		Wall thickness			
	Latewood	Earlywood	Latewood		Earlywood	
			Tangential	Radial	Tangential	Radial
wet condition	5	5	50	50	50	50
dry condition	5	5	50	50	50	50

measured. 4 to 8 measurements were taken from the tangential walls for each of the 28 earlywood tracheids and 2 to 8 measurements from the radial walls of only 19 earlywood tracheids (for the same reason mentioned above). Some data measured by the ImageAccess software are shown in Fig. 7 for earlywood. The statistical evaluation of the measurements were carried out using the ANOVA software.

3 Results and discussion

3.1 Cell wall thickness of radial and tangential walls

The mean thicknesses of the tangential (T) and radial (R) walls of earlywood and latewood in both green and dry conditions are shown in Table 2, including the R/T ratios of the thicknesses.

GLM (General Linear Model) of the SAS Software (v6.0) was used for the analysis of variance of the cell wall thicknesses. For latewood tracheids, the results show that the tangential wall thickness is significantly smaller (about 25 percent) than the radial wall thickness. Both wall thicknesses show statistically significant differences between wet and dry conditions (Table 3) as to be expected. The R/T ratio of the wall thickness for latewood under wet condition is 1.24, which probably contributes to a certain extent to the differential transverse hygroexpansion of wood, but not enough to explain the overall ratio of 2:1 of the tangential-over-radial shrinkage.

For earlywood tracheids, statistical analysis shows that there is no significant difference between the tangential and the radial wall thickness. Therefore, the reason for the differential transverse shrinkage found for earlywood (even higher than with latewood) can in no way be explained by the difference of the cell wall thickness. Additionally, if the hypothesis is correct that latewood forces the weaker earlywood to shrink to a greater extent than it would by itself, the R/T ratio of the latewood wall thicknesses (1.24) mentioned above might explain the differ-

Fig. 5. Fracture surface of a Scots pine rod obtained from the bending test. The rough part of the surface on the right-hand side of the sample represents the tension zone from which the samples for the FE-SEM have been prepared

Bild 5. Bruchfläche von geschwundenem Kiefern-Frühholz nach Biegetest. Der raue Teil der Probe (rechts) entspricht der Zugzone, woraus die Proben für die FE-REM-Aufnahmen entnommen wurden

Fig. 6. Transverse-fracture surface (tension zone) of a cell wall of Scots pine latewood. The numbers on the radial (right-hand side) and tangential (top) wall indicate the angles of the orientation of fibril agglomerations of the S2 layer with respect to the CML. FE-SEM microphotograph

Bild 6. Querbruchfläche (Zugzone) einer Kiefern-Spätholz zelle. Die Zahlen auf der Radialseite (rechts) und Tangentialseite (oben) bezeichnen die Winkel der Fibrillenbündel der S2 in Bezug zur Mittelschicht. FE-REM-Aufnahme

Fig. 7. Transverse-fracture surface (tension zone) of parts of a cell wall of Scots pine earlywood, same conditions as with Fig. 6
Bild 7. Querbruchfläche (Zugzone) einer Kiefern-Frühholzzelle (Ausschnitt). Bedingungen wie in Bild 6

ence of the earlywood hygroexpansion to a small extent only.

For both earlywood and latewood tracheids, substantially more shrinkage of the tangential wall than the radial wall was found (Table 2). This result corresponds with findings of Watanabe et al. (1998), who used a powerful method of image analysis (spectrum and replica analysis) to measure the change of the lumen size and wall thickness for 4 Japanese softwoods, due to shrinkage. One would assume that more shrinkage in the tangential wall means more shrinkage in the radial than in the tangential direction when looking at single cells. This is, however, contrary to the anisotropic shrinkage on the macroscale level. The results presented below may explain this phenomenon to a certain extent.

3.2

Fibril arrangement on fracture surfaces

The tension-zone fracture surfaces of the Scots pine samples exhibited the characteristic fibril orientations of the S2 layer already described by Sell and Zimmermann (1993). The fibrils are agglomerated perpendicular (i.e. with an angle of 90°) or more or less inclined to CML,

respectively. Very seldom, however, with a part of the wall, the agglomerations are concentrically oriented (i.e. with an angle of 0° to CML). The angle of the fibril agglomerations of the S2 layer vary substantially from cell to cell and also within one single cell wall. Table 4 contains the statistically evaluated angles formed by the fibril agglomerations of the S2 layer – with respect to the CML – for the radial and tangential walls of pine latewood and earlywood. The data show that the mean inclination of the S2 fibril agglomerations to CML is quite different for radial and tangential walls both of latewood and earlywood. On radial walls the fibril agglomerations are relatively steeply inclined to CML (latewood 68°, earlywood 64°), whereas on tangential walls the angles to CML are flatter (latewood 46°, earlywood 40°). The respective data of latewood and earlywood cells show rather small differences which are, however, statistically significant.

Since the fibril agglomerations on cross-sections of the S2 layer, according to former results mentioned above, are characterised by a higher packing density of the cellulose fibrils, the results evaluated indicate the following:

Related to the main transverse directions of wood, the preferential direction of the S2 fibril agglomeration and therefore, of the cell wall zones of the highest packing density of the fibrils is tangential rather than radial. The strongly simplified scheme of the cell wall layer S2 in Fig. 8 illustrates these findings. Our hypothesis is that the differential hygroexpansion of wood in the tangential and radial direction can partially be explained by this arrangement of the S2 fibrils.

Based on the inclination angles of the fibril agglomerations measured, a simplified model for the latewood tracheid cross-section can be drawn as Fig. 9a. The different shrinkage in the tangential and radial direction can be calculated as follows:

Assuming along the fibril agglomerations the shrinkage value is 1, then for latewood tracheids the total shrinkage T in the tangential direction can be calculated as

$$\sin 68.4 + \cos 46.1 = 1.623$$

(radial wall component) (tangential wall component)

and the total shrinkage R in the radial direction is:

Table 2. Radial and tangential cell wall thickness of earlywood and latewood tracheids under wet and dry condition
Tabelle 2. Radiale und tangentiale Zellwanddicke in Früh- und Spätholztracheiden in feuchtem und trockenem Zustand

		Latewood tracheids		Earlywood tracheids	
		Tangential wall (µm)	radial wall (µm)	tangential wall (µm)	radial wall (µm)
Wet condition	mean	6.22	7.73	2.85	2.66
	std.dev.	0.84	1.03	0.38	0.36
	R/T ratio		1.24		0.93
at 40 °C vacuum-dried	mean	5.45	7.24	2.05	2.15
	std.dev.	0.55	1.21	0.39	0.3
	R/T ratio		1.33		1.05
	percent shrinkage	14.13	6.77	39.02	23.72

$$\cos 68.4 + \sin 46.1 = 1.089$$

(radial wall (tangential wall
component) component)

Thus, the ratio T/R for the latewood transverse differential shrinkage is 1.49.

If we are considering the different wall thicknesses measured for the radial and tangential wall of latewood with a R/T thickness ratio of 1.24, total shrinkage in the tangential direction can be modified as

$$1.24 \times \sin 68.4 + \cos 46.1 = 1.846$$

(radial wall (tangential wall
component) component)

and in the radial direction as

$$1.24 \times \cos 68.4 + \sin 46.1 = 1.177$$

(radial wall (tangential wall
component) component)

The ratio of the latewood transverse differential shrinkage T/R is now 1.57. This calculated ratio is close to the T/R ratio data of 1.4 reported by Skaar (1988) after Vintila (1939) from his measurements of free shrinkage of isolated pine latewood (probably Scots pine) in tangential and radial direction.

The same calculation carried out from our measurement results (Figure 9b) for the earlywood tracheids leads to a total shrinkage of 1.660 in the tangential and 1.087 in the radial direction. Thus, the different shrinkage ratio T/R calculated for earlywood is 1.53. This is much lower than

Table 3. Statistical significance of the cell wall thicknesses under wet and dry conditions (5% level of significance)

Tabelle 3. Signifikanz der Zellwanddicken in feuchtem und trockenem Zustand (5% Signifikanzniveau)

	Latewood	Earlywood
Tangential wall vs. radial wall	significantly different	not significantly different
Wet vs. dry condition	significantly different	significantly different

Table 4. Results of the measurement of the orientation angles of the cellulose fibril agglomerations of the S2 layer on transverse fracture surfaces of latewood and earlywood cells of Scots pine sapwood

Tabelle 4. Messergebnisse der Winkel von Fibrillenbündeln in der S2 in quergebrosenen Früh- und Spätholzzellen von Kiefern-splintholz

	Latewood tracheids		Earlywood tracheids	
	tangential wall (degree)	radial wall (degree)	tangential wall (degree)	radial wall (degree)
Mean	46.1	68.4	40.4	64
Std.dev.	7.06	7.98	6.37	8.79
Min	35.3	51.8	32.1	47.3
Max	65.7	85.1	56.6	78.4
No. of cells Measured	65	47	28	16

Fig. 8. Schematic illustration of a cross section of a cell wall. The black lines within the S2 layer indicate the orientations of fibril agglomerations (or directions of their highest packing density, respectively) which can be observed even within a single cell wall. The preferential direction of the S2 fibril agglomerations, however, is tangential

Bild 8. Schema eines Zellwand-Querschnitts. Die schwarzen Linien in der S2 bezeichnen die Orientierung der Fibrillenbündel (bzw. die Richtungen der höchsten Packungsdichte), welche auch in einer einzelnen Zellwand beobachtet werden können. Die Vorzugsrichtung der Fibrillenbündel der S2 ist jedoch tangential

the respective value of 2.8 measured by Vintila according to Skaar (1998).

Nevertheless, generally the results of our calculation of the relative amount of the radial and tangential shrinkage (with an assumed shrinkage of 1 in the direction of the fibril agglomerations on S2 cross-sections) and the R/T ratios derived from these results are in the same order of the anisotropy of wood on the macroscopic level, especially with latewood.

On the other hand, divergent from the macroscopic anisotropy are the results of our measurements of the shrinkage of single cell walls. In accordance with findings of Watanabe et al. (1998) a greater shrinkage was measured of the tangential than of the radial walls. This seems to be just the opposite one would expect from the macroscopic anisotropy and from the R/T ratio that was calculated by means of our model of the fibril arrangements of the S2. This apparent contradiction is still not explained and needs, therefore, further studies.

Fig. 9a, b. Mean angles of the fibril agglomerations of the S2 layer measured on radial and tangential walls of Scots pine latewood and earlywood
Bild 9a, b. Mittlere Winkel der Fibrillenbündel in der S2, gemessen an radialen und tangentialen Wänden im Spät- und Frühholz von *Pinus sylvestris*

4

Conclusion

The ca. 25 percent higher thickness found for radial cell walls compared with tangential walls of latewood of Scots pine may contribute to the anisotropic transverse shrinkage of wood to a certain extent. This contribution, however, is obviously of minor importance. As compared with this possible influence, the role of the rather tangentially than radially oriented fibril agglomerations (i.e. zones of higher packing density of the fibrils) on cross sections of the S2 layer in the anisotropy of wood transverse shrinkage might be of major importance (if the above model of the S2 structure and its influence on 'hygroexpansion' is correct).

The R/T ratios here derived from this model differ from results of Vintila's (1939) measurements on latewood and earlywood strips, cited by Skaar (1988). This is especially true for earlywood. We assume that the difference is caused by the different methods used for the measurement of the wood shrinkage. Probably of particular importance is the fact that the shrinkage of single cell walls on SEM microphotographs, the shrinkage of separated earlywood and latewood strips, and the calculation of the mean relative shrinkage by a model of the fibril arrangement on cross sections of the S2 layer do not (or only partially) reflect the 'real' macroscopic conditions. Particularly the mutual hindering or increasing of the hygroexpansion of latewood and earlywood are not – or to a limited degree – represented by these measurement methods. Moreover, these interactions are different in the radial and tangential directions. In other words: with respect to hygroexpansion or shrinkage, a superposition of influences of the wood structure on the macroscopic, microscopic, and on the nanometer level takes place which is quantitatively hard to evaluate. However, we are convinced that the fibril arrangement (i.e. their packing density) on cross sections of the cell walls, especially of the thick S2 layer, contributes considerably to the different hygroexpansion/shrinkage of

wood in the radial and tangential direction. Additional work is necessary to confirm this hypothesis.

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