Weathering of Radial and Tangential Wood Surfaces of Pine and Spruce

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Summary

The development of cracks and changes in appearance have been investigated on radial and tangential surfaces of pine (*Pinus silvestris* L) and spruce (*Picea abies* Karst) which have been exposed outdoors for 33 months. The degradation of the surfaces has also been studied at the micro-level.

Untreated samples, samples impregnated with a CCA-agent and samples surface treated with linseed oil have been tested.

The annual ring orientation is the most important factor for crack development on weathering. The type of wood, impregnation treatment and surface treatment with linseed oil have only a marginal effect on the crack development. No relation has been found between the density of the samples and the crack development.

After 33 months of outdoor exposure, tangential surfaces of pine have 13 times more total crack length per unit area than the corresponding radial surfaces. In spruce, the total crack length on the tangential surfaces is 6 times greater than on the radial surfaces. Tangential surfaces of both pine and spruce have a greater number of cracks per unit area and wider cracks than the corresponding radial surfaces.

Tangential and radial surfaces show the same colour change in the surface as a result of weathering.

On the micro-level, tangential surfaces have more and deeper cracks than radial surfaces. The cracks on the tangential surfaces occur frequently in both earlywood and latewood. On radial surfaces, cracks occur primarily at the annual ring borders, but to a certain extent also in the earlywood.

The radial cell wall of the earlywood has a large number of pits which are degraded at an early stage. Decomposition of the cell wall takes place on both radial and tangential surfaces. Cracks arise which follow the S2 fibril orientation in the cell-wall. Delamination in the middle lamella is especially noticeable in the latewood on tangential surfaces. No differences have been observed regarding linseed oil treatment, impregnation or type of wood.

Keywords

Weathering

Pinus silvestris L.

Picea abies Karst.

Cracking

Star-sawing

UV laser ablation

Introduction

The sensitivity of the wood to degradation is one of its greatest weaknesses in outdoor usage. Like all biological materials, wood decomposes under the influence of the surrounding environment. When wood is exposed outdoors above ground, a complex decomposition process continues in the material as a consequence of chemical, biological, mechanical and light energy related factors. A common name for this process is "weathering" (Feist 1982).

The factors which are generally considered to cause changes in wood surfaces on weathering are sunlight (UV, visible and infrared radiation), moisture (dew, rain, snow), temperature and oxygen (Hon 1983).

Because of the limited ability of light to penetrate into wood (Browne and Simonson 1957), the effect of the weathering is limited to a 2.5 mm thick surface layer and the erosion is slow, 5-12 mm per 100 years (Feist and Mraz 1978). Investigations of the effect of weathering on wood, carried out by different researchers, have dealt with several aspects, e.g. colour change (Fengel and Wegener 1984, Sandermann and Schlumbom 1962, Sell and Leukens 1971), erosion (Arnold et al 1992, Feist and Mraz 1978, Feist and Hon 1984), free radicals (Hon et al 1980; Hon and Feist 1981; Hon and Shiraishi 1991), surface wetting characteristics (Kalnins and Knaebe 1992; Kalnins and Feist 1993), anatomical changes (Miniutti 1967, Borgin 1970, 1971, Borgin et al 1975, Derbyshire and Miller 1981), and strength (Derbyshire et al 1995, Raczkowski 1980). Of the whole electromagnetic spectrum, it is only the shortwave and energy-rich region which has a measurable influence on wood and which is thus of technical interest. As a consequence, a large number of studies have been carried out within this field and summaries of earlier results have been published by e.g. Kenaga and Cowling (1959), Desai (1968), Kringstad (1969), Hon and Glasser (1979) and Hon and Shiraishi (1991).

On a macroscopic level, the colour change of an untreated wood surface is one of the first and perhaps the clearest sign of the degradation of the wood during outdoor exposure. Visible light and UV-radiation alter the colour of the wood to a darker or lighter shade, depending on the type of wood (Sandermann and Schlumbom 1962; Fengel and Wegener 1984). After a long period of outdoor use, all types of wood develop a greyish appearance (FRN 1966; Sell and Leukens 1971) due to the fact that water-soluble decomposition products are removed and the more or less delignified fibres are exposed. If, on the other hand, the wood surface is protected against rain, it develops a dark red-brown surface (Browne 1959).

The photochemical degradation is a very slow process which during a decade degrades only a few millimetres of the wood surface and leaves the underlying wood practically unaffected (Hon and Ifju 1978). The combined effect of water and sunlight degrades the main components of the wood and transforms the wood surface into a network of weakly connected cellulose fibrils which are strongly contaminated by spores from microorganisms (Sell and Wälchli 1969). Visible cracks arise in the wood surface during outdoor exposure because of the

growth of microcracks formed during the drying of the wood, photochemical reactions or moisture-induced stress fields (Coupe and Watson 1967). Stamm (1965a) considers that wood for outdoor use should have vertical annual rings. This minimizes the risk of cracks as a consequence of anisotropic moisture movements. Cracks in the radial surface are also smaller than in the corresponding tangential surfaces (Browne 1960; Stamm 1965a, 1965b).

The aim of the present investigation has been to characterize differences in the degradation process on both macro and micro-level between radial and tangential wood surfaces of Scots pine and Norway spruce exposed outdoors above ground.

Material and Method

Star-sawn wood of pine and spruce with a triangular profile has been used in the investigation (Sandberg 1996). The test material was sawn from one pine and two spruce logs. After sawing and drying, some of the triangular profiles have been pressure impregnated with a CCA-agent. From each triangular profile, between 7 and 14 knot-free and defect-free test pieces with a length of 300 mm have been prepared. Figure 1 shows how the samples have been produced.

After being cut into lengths of 300 mm, the samples were planed on all surfaces to facilitate the determination of crack length. The samples were planed with the top end in the planing direction to a depth of 0.5 mm. The final width of the side varied between 75 and 125 mm. The dry density was determined for all samples: pine $475 \pm 25 \text{ kg/m}^3$ and spruce $416 \pm 25 \text{ kg/m}^3$. The end-wood surfaces were sealed with an oil alkyd primer and a silicone-based sealing compound. Some of the samples were brushed with linseed oil before the outdoor exposure. Table 1 presents a summary of the test material.

The samples were exposed in Stockholm for 33 months (September 1993 - May 1996) at an inclination of 45 degrees towards the south.

After outdoor exposure, all the samples were conditioned for two months at a temperature of 24°C and a relative humidity of 66 %. Thereafter, the lengths of all cracks with a crack width greater than 0.25 mm, which was the smallest crack size which could be measured in practice, were determined. Cracks with a width less than 0.25 mm were assessed visually. In the statistical evaluation of the results, a "non-parametric test" has been used with 0.95 confidence limits for the group mean values (Montgomery 1991; Sandberg 1995).

40 samples with an approximate size of $10 \times 50 \times 10 \text{ mm}^3$ (WxLxT) were selected randomly from 158 weathered samples for microscopic studies. To investigate the cross section, the cross section was prepared with the help of UV-laser ablation to minimize the risk of artefacts in the preparation (Seltman 1995, Stehr et al 1998). Otherwise, no preparation of the samples was carried out. Microscopic changes in the wood surfaces were investigated by ESEM (Philips ElectroScan 2020).

Results

Crack formation and colour changes

Cracks wider than 0.25 mm on the exposed surfaces

Table 2 shows mean values for the sum of the crack length per unit area (total crack length on the surface divided by the area of the surface) on the exposed surfaces after 33 months outdoor exposure and subsequent conditioning. The results show a clear difference between radial and tangential surfaces, regardless of impregnation or surface treatment. The difference between radial and tangential surfaces is statistically significant. On the other hand, it is not possible to find any influence on crack length from impregnation or linseed oil treatment.

Figure 2 shows the average of the total crack length for the exposed radial and tangential surfaces in pine and spruce. Pine shows a slightly greater mean crack length than spruce on the tangential surfaces, but a shorter crack length on the radial surfaces. The statistical analysis shows, however, that there is no significant difference in mean crack length between pine and spruce, either on the tangential or on the radial surfaces.

Figure 3a shows the mean value of the number of cracks per unit area which are wider than 0.25 mm. Figure 3b shows the average value of the greatest crack width for the samples, i.e. the maximum crack width has been determined for each test piece. Both quantities have been determined on the exposed surface. The radial surfaces have a significantly smaller number of cracks than the tangential surfaces and the maximum crack width is also significantly smaller. In the case of the radial surfaces, it is not possible to show any significant difference between pine and spruce, either for the number of cracks or the crack width. On the other hand, tangential pine surfaces have significantly more cracks and a smaller maximum crack width than spruce surfaces.

No influence on the crack formation of either surface treatment with linseed oil or impregnation has been found.

Cracks with a width less than 0.25 mm on the exposed surfaces

Cracks with a width less than 0.25 mm are usually short, only a few mm, and numerous. In practice it has not therefore been possible to determine the crack length for these.

Table 3 shows the number of samples with small cracks visible to the naked eye on the exposed surface and where on the surfaces these cracks occur most frequently.

On the radial surfaces, the cracks were primarily found in the annual ring border and in the earlywood. On the tangential surfaces, the cracks appeared in the latewood and across the whole of the exposed surface, i.e. in both the earlywood and latewood.

Cracks wider than 0.25 mm on the non-exposed surfaces

Besides the surface exposed in the southerly direction, each test piece has two adjacent sides which have not been exposed to sunlight to the same degree. These two surfaces have degraded more slowly than the exposed surfaces. Figure 4 shows the crack length for the non-exposed surfaces. In the same way as for the exposed surfaces, the average of the total crack length on the radial surfaces is significantly smaller than that on the tangential surfaces. As can be seen in Figure 2, the average of the total crack length on the non-exposed surfaces is smaller than on the exposed surfaces. For the radial pine surfaces, the average of the total crack length on the non-exposed surfaces is 55 times smaller and on the tangential surfaces 6 times smaller than on the exposed surfaces. The corresponding values for spruce are 23 and 9 times.

Cracks with a width less than 0.25 mm on the non-exposed surfaces

Table 4 shows the number of samples with small cracks on the non-exposed surfaces. On these surfaces, small cracks have not occurred to the same extent as on the exposed surfaces.

On the radial surfaces, small cracks in the annual ring border dominate and, on the tangential surfaces, the cracks are most frequent in the latewood. Table 4 shows that the cracks are not evenly distributed across the whole surface of any test piece, but that the crack formation has begun on parts of surfaces. The tendency is the same as for the exposed surfaces, however, namely that it is on the tangential surfaces that the cracks become visible across the whole surface.

Changes in the appearance of the surfaces

Cracks which develop in wood surfaces during outdoor exposure are, as already shown, particularly visible on tangential surfaces. Figure 5 shows the characteristic appearance of a radial and a tangential surface from the present investigation. On the tangential surface (Figure 5d), cracks are clearly visible. On both the radial and the tangential surfaces, a large number of small cracks can be found which are, however, difficult to see in Figure 5.

The degradation follows the annual ring pattern in such a way that the earlywood degrades more rapidly than the latewood and valleys develop in the wood surface. The surfaces develop a corrugated appearance, which is particularly clear on the radial surfaces.

Figure 5 also shows an example of a colour change in samples after outdoor exposure. This colour change is particularly evident on the exposed surface. The surface changes colour to silver-grey, regardless of whether or not the wood is impregnated, Figure 5.

At the upper edge of the samples in Figure 5b and 5d it is evident that the part of the surface which has been protected against sunlight but exposed to rain and snow has a colour which is different from that of the remaining surface. The influence of the sunlight on the colour change is clarified if the backs of the

samples are studied. Practically no colour change has occurred on these surfaces.

Density

No relationship has been found between crack formation and the density of the samples.

Microscopic Studies - Observations and Comments

In the investigation of the exposed surfaces, the analysis has taken place at three structural levels:

- macroscopic cracks which propagate along practically the whole length (300 mm) of the test body and with a relatively large depth.
- small short cracks, normally with a depth of within one or a few annual rings.
- decomposition of the actual wood fibre and middle lamella.

The first level of degradation occurs primarily in tangential surfaces, as has been shown above. The two subsequent degradation levels occur in both radial and tangential surfaces, with slightly different processes, however, which will be illustrated here. In the analysis of the different surfaces, no significant differences have been found regarding linseed oil treatment, impregnation or type of wood, and the influence of these parameters will not be further discussed.

Figure 6a shows an example of a planed and unexposed wood surface. The surface in the lower part of the picture has been treated by UV-laser ablation to remove the layer of crushed fibres which was a result of planing. Figure 6b shows a corresponding surface after weathering for 33 months. In large parts of the exposed surface, the cell structure is exposed and it is possible to distinguish different structural elements, which it is impossible to see in the unexposed planed wood surface, Figure 6a. Figure 6b shows how the uppermost layer of crushed fibres has cracked as a consequence of the weathering. Sunlight during simultaneous moistening and drying of the surface means that cracks develop and that the fibres which have been partly compressed in the planing operation rise. The surface is opened successively and fibre fragments are broken apart and eroded by rain and wind. In figure 6b, fracture across the fibres as a consequence of tensile stresses is also shown. The fracture region normally stretches 3-10 cell rows down into the surface.

Exposed radial surface

On the radial surfaces, cracks can be found in practically every annual ring border, Figures 7a and 7b. The cracks are usually a few millimetres deep and extend parallel to the annual ring border. The crack extension almost always takes place in one of the first earlywood cell rows and seldom more than two rows from the annual ring border, Figure 7b.

In the earlywood, besides the deep cracks in the annual ring border, relatively small and shallow cracks occur, figure 8. These cracks do not in general become deeper than about 10 cell rows before the surrounding material has eroded away

In the latewood, cracks seldom occur and, in those cases where cracks do appear, they are small, only a few cell rows deep.

The earlywood erodes more rapidly than the latewood, which probably depends on the fact that the latewood has a higher density. Figure 9 shows a latewood strip where the surrounding earlywood has been decomposed and removed by wind and weather. The thin and brittle strips of latewood are broken after some time.

The radial cell walls of the earlywood of both pine and spruce contain a large number of bordered pits. These are degraded at an early stage. The same phenomenon has been observed by e.g. Miniutti (1967) and Borgin (1970, 1971). Figure 10 shows pits at an early stage of degradation. The pit openings have been enlarged and through the pits, diagonally oriented cracks have developed. During the continuing decomposition, these cracks propagate through the cell wall. According to Turkulin and Sell (1997), these are a consequence of stresses which arise in contraction of the actual pit chamber. Torus also erodes at an early stage. Figure 10 also shows that the wart layer is largely lacking and that cracks have begun to develop in the cell wall. This type of crack is found in both the early and latewood. The orientation of these cracks suggests that these follow the fibril orientation in the S2-layer of the cell wall.

In the continuing degradation, the pit openings are further enlarged and the whole pit finally erodes away. The crack formation in the cell wall continues and degradation products are rinsed away until only a close-meshed network of fibril bundles remains, Figure 6b. The microfibrils are thus shown to be the most stable part of the actual tracheid, and the degradation continues with reduced adhesion between microfibrils and between the different cell layers.

Exposed tangential surface

In contrast to the radial wall, the tangential cell wall contains no or very few ring pores and consequently, the degradation pattern for the tangential surfaces becomes different. The tangential surfaces develop more, but also considerably larger cracks than the radial surfaces. Figure 11a shows a typical tangential surface with, on the one hand, a large deep crack and, on the other hand, diagonal cracks in the cell walls, which is also common in the radial cell walls. Failure across the fibre occurs on the tangential surfaces, Figure 11b.

On the tangential surfaces, are initiated in the surface layer, in both the early and latewood, and propagate through the different annual ring layers. Figure 12 shows a crack which has been initiated in the earlywood on an exposed tangential surface. The crack has propagated through the whole earlywood layer and has reached the latewood. The crack propagation in latewood in the outermost exposed surface layer showed a similar development.

Figures 13a and 13b show delamination between fibres in early and latewood for an exposed tangential surface. The delamination is especially clear in the

latewood. The cracks in the latewood extend into the middle lamella with a depth of up to ten cell rows, Figure 13a. In the earlywood, the cracks are shallower and the delineation against adjacent cell walls is not as sharp as in the latewood, Figure 13b.

Figure 14 shows how the different layers in the cell wall are delaminated during the degradation. The different cell wall layers and the fact that the crack propagation has a different orientation in the different layers are evident. Figure 14 also shows a crack running along the length of the fibre which has propagated through the whole thickness of the cell wall.

Discussion

The samples included in this investigation have mainly been exposed to simultaneous photochemical and mechanical degradation.

The chemical reactions in the wood surface initiated by sunlight lead to a change in colour of the surface. This process is similar for radial and tangential surfaces.

The photochemical degradation takes place in a thin layer of the wood surface and this means that the strength of this layer is reduced (Derbyshire and Miller 1981; Derbyshire et al 1995; Raczkowski 1980). When the wood material is exposed to moisture variations, stresses develop in the cell walls and between cells, and these lead to damage and to the propagation of existing cracks. The photochemical reactions which take place in the wood surface during outdoor exposure accelerate this process, but they are not the main reason for the great difference in numbers of cracks between radial and tangential wood surfaces. If the crack length ratio between tangential and radial surfaces is studied for the exposed surfaces (Fig. 2) and for the "non-exposed" surfaces (Fig. 4), it can be established that this ratio is smaller for the exposed surfaces, which implies that the difference in crack development between radial and tangential surfaces is not only a consequence of photochemical degradation. On the other hand, strong exposure to sunlight and rain means that the size and frequency of cracks increase strongly.

The difference in crack susceptibility between radial and tangential surfaces is mainly the result of stresses which arise in the wood as a consequence of anisotropic moisture movements of the wood material and moisture gradients between the surface of the test pieces and its internal region, i.e. mechanical degradation.

The shrinkage and swelling in the tangential direction are about twice as large as the radial moisture movement. Tangential surfaces thus move more than radial surfaces. This means that the stresses become higher in the tangential direction than in the radial direction when the moisture movement in the surface layer is limited by underlying wood which does not have the same moisture content as the wood in the surface layer. This relationship applies in the case of rapid moisture changes in the surface, e.g. when the surface is alternately exposed to rain and dried out in strong sunlight. Moisture gradients then arise between the surface area and the underlying wood material. This results in the formation of more cracks on tangential surfaces than on radial

surfaces.

The latewood shrinks and swells more than the earlywood. In the radial direction, the moisture movement in the latewood is about 3 times higher than in the earlywood and, in the tangential direction, about 1.5 times greater in the latewood (Boutelje 1962; Vintila 1939). When the moisture content in the wood changes, the early and latewood thus move to different extents. In the radial direction, the layers are oriented in series and the early and latewood layers can move practically independently of each other. In the tangential direction, the early and latewood are parallel, which means that the moisture movement is limited by the individual layers and that stresses arise in and between these layers, see e.g. Kifetew (1996). This is a reason why tangential surfaces crack more than radial surfaces.

On the radial surfaces, cracks occur first at the annual ring border (Table 4) and thereafter in the earlywood (Table 3). On the tangential surfaces, cracks appear first in the latewood (Table 4) and then develop across the whole of the exposed surface (Table 3). This agrees with results reported by Coupe and Watson (1967). The fact that cracks do arise at the annual ring border on the radial surfaces is a consequence of the large and abrupt change in density which takes place in the transition from latewood to earlywood. It seems that cracks also arise at an early stage in the latewood on the radial surfaces, but these cracks are difficult to observe because the latewood strips are very thin, about 0.25 mm.

The strains to which the wood material is exposed in pressure impregnation can cause damage to the material, which can mean that impregnated wood may be more susceptible to cracking during weathering than wood which is not impregnated. This hypothesis is not supported by the result of the here reported investigation.

Conclusions

The annual ring orientation in the wood surface has a great influence on the susceptibility of the surface to crack. To avoid cracks occurring on wood used outdoors, wood pieces with annual ring orientation perpendicular to the exposed wood surface should be selected. This is especially important if the wood lacks a covering surface layer, e.g. paint, or if the surfaces are strongly exposed to weather and wind.

For wood of pine or spruce exposed outdoors without a covering surface layer, the annual ring orientation in the wood surface is more important for the crack development than the density of the wood or the type of wood. Impregnation treatment with a CCA-agent or surface treatment with linseed oil has no more than a marginal influence on the crack formation.

On a microscopic level, it is also possible to see clear differences in degradation between radial and tangential surfaces. Tangential surfaces have more and deeper cracks than radial surfaces. The cracks on the tangential surfaces occur frequently in both early and latewood. On radial surfaces, cracks occur primarily at the annual ring border, but to a certain extent also in the earlywood. On an ultrastructural level, decomposition of the pits is the clearest difference between radial and tangential surfaces. In both radial and tangential surfaces, degradation of the cell wall takes place. Cracks arise which follow the fibril orientation in the S2 cell wall layer. Delamination in the middle lamella is especially clear in the latewood on tangential surfaces, but it also occurs in the earlywood. The microfibrils are the parts of the tracheid which are most resistant to weathering.

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Table 1. The extent of the test material. Number of test pieces with different treatments

Treatment of test pieces	Pine		Spruce	
	Radial*	Tangential*	Radial*	Tangential*
Untreated	6	5	16	14
Treated with linseed oil	5	6	5	5
Impregnated with CCA-agent	13	13	4	4
Impregnated and treated with linseed oil	12	13	19	18
Total number of samples	36	37	44	41

* Refers to the annual ring orientation of the surface exposed at an inclination of 45° in a southerly direction, see also Figure 1.

Table 2. Average of the total crack length per unit area (m/m^2) after 33 months' outdoor exposure and subsequent conditioning to a moisture content of 12 %

Treatment of test pieces	Pine		Spruce	
	Radial*	Tangential*	Radial*	Tangential*
Untreated	2.1	25.5	2.9	27.3
Treated with linseed oil	4.1	28.6	6.7	27.2
Impregnated with CCA-agent	1.1	29.8	0.1	31.0
Impregnated and treated with linseed oil	2.7	27.3	6.0	23.9
All samples in the group	2.2	28.1	4.4	26.1

* Refers to the annual ring orientation of the surface exposed at an inclination of 45° in a southerly direction, see also Figure 1.

Table 3. Number of samples with small cracks (crack width less than 0.25 mm) on the exposed surface after 33 months outdoor exposure and subsequent conditioning to a moisture content of 12 %

Main crack orientation	Pine		Spruce	
	Radial*	Tangential*	Radial*	Tangential*
The annual ring border	33	2	40	1
Earlywood	29	1	42	2
Latewood	1	11	2	18
The whole exposed area	3	25	2	23
Total number of samples	36	37	44	41

* Refers to the annual ring orientation of the surface exposed at an inclination of 45° in a southerly direction, see also Figure 1.

Table 4. Number of samples with small cracks (crack width less than 0.25 mm) on the non-exposed surface after 33 months' outdoor exposure and subsequent conditioning to a moisture content of 12 %

Main crack orientation	Pine		Spruce	
	Radial*	Tangential*	Radial*	Tangential*
The annual ring border	26	0	17	1
Earlywood	1	0	0	0
Latewood	0	29	0	22
Part of the surface	1	9	1	15
The whole surface	0	0	0	0
Total number of surfaces	110	36	126	44

* Refers to the annual ring orientation of the surface exposed at an inclination of 45° in a southerly direction, see also Figure 1.

Fig. 1. The star-sawing pattern showing (a) wood with a rectangular cross-section and triangular profiles, (b) production of samples from the triangular profiles. For test piece $a_1, a_3, a_5, \dots$ one of the radial surfaces has been exposed and for test piece $a_2, a_4, \dots$ the tangential surface has been exposed. The length $a_i=300$ mm, $k=\text{knot}$.

Fig. 2. Average of the total crack length per unit area (m/m^2) for pine and spruce after 33 months' outdoor exposure and subsequent conditioning to a moisture content of 12 %.

a)

b)

Fig. 3. Average values for (a) the number of cracks per unit area and (b) the maximum crack width on the exposed surfaces after 33 months outdoor exposure and subsequent conditioning to a moisture content of 12 %.

Fig. 4. Total crack length per unit area (m/m^2). The average value on the non-exposed surfaces after 33 months outdoor exposure and subsequent conditioning to a moisture content of 12 %.

Fig. 5. Colour change of wood surfaces after 33 months outdoor exposure. Radial surface of spruce (a) before and (b) after exposure. Tangential surface of unimpregnated pine (c) before and (d) after exposure.

Fig. 6. (a) Planed radial wood surface of pine with crushed fibres, 213 x magnification. The wood surface in the lower part of the picture has been ablated with UV-laser, which has removed most of the fibre layer which was compressed during the planing. (b) The corresponding surface after weathering for 33 months, 275 x magnification.

a)

b)

Fig. 7. Cracks at the annual ring border on a radial surface. (a) Crack opening at the surface of untreated spruce at 175 x magnification. (b) Crack one millimeter below the surface of impregnated pine at 250 x magnification.

Fig. 8. Crack in the earlywood on a radial surface of impregnated pine at 220 x magnification.

b)

Fig. 9. Latewood strips of untreated pine in 265 x magnification, where the surrounding earlywood has been eroded.

Fig. 10. Early stage of the degradation of a radial cell wall of impregnated and linseed oiled spruce at 1000 x magnification. Torus is destroyed, the pit openings have been enlarged and cracks have arisen through the pits and in the cell wall.

a)

b)

Fig. 11. Exposed tangential surface of linseed oiled spruce in 280 x magnification (a) and 445 x magnification (b). In the weathering, tangential surfaces develop large deep cracks and small cracks in the cell wall (a), and failure across the fibres (b).

Fig. 12. Exposed tangential surface of linseed oiled pine in 235 x magnification with a crack in the exposed earlywood layer and with underlying latewood.

a)

b)

Fig. 13. Delamination cracks in the middle lamella of (a) latewood and (b) earlywood of an exposed tangential spruce surface. Magnification (a) 300 x, (b) 320 x.

Fig. 14. Delamination and crack formation in a tangential cell wall of impregnated pine. Magnification 850 x.