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THE EFFECT OF DRYING AND STORAGE CONDITIONS ON CASE HARDENING OF SCOTS PINE AND NORWAY SPRUCE TIMBER

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ABSTRACT

Case hardening is a feature of dried wood that causes the wood to deform (cup) after re-sawing and equalising the moisture content. VTT has analysed case hardening with the aid of the simulation model PEO and with experimental drying, conditioning and storage tests. Case hardening cannot be predicted by the moisture content gradient alone. However, the case hardening gap after drying to a high final moisture content of 18% is nearly identical to the calculated gap caused by cupping when the moisture gradients of the two halves of the test piece are equalised.

24 hours (proposed in ENV 14464) is too little time to show the total cupping when keeping the sliced specimens in a plastic bag. Thus the test according the standard doesn't show the whole cupping tendency of, for example, panels when the moisture content is equalised after re-sawing the timber and planing the billets.

Increasing the kiln drying rate increases the resulting case hardening tendency. With effective conditioning at the drying temperature, or with steaming after cooling, it is possible to reduce or remove the case hardening. But at normal temperatures in end-use or storage of timber the case hardening diminishes very slowly, despite the equalising of the moisture content in the cross-section.

Keywords: case hardening, cupping, drying, conditioning, re-sawing, simulation, Scots Pine, Norway spruce

INTRODUCTION

Case hardening is a term that is often used to describe the quality of dried wood. The term itself does not unambiguously say what it means. Therefore, a survey has been conducted among internationally renowned experts. The following questions were asked:
- How do you define case hardening?
- What are the disadvantages of case hardening for the end users?
- Do you have measured results to describe the phenomenon of case hardening?

A common feature of the answers is that case hardening is regarded as being related to drying stresses and that it causes deformations after the original dried cross-section has been re-sawn or otherwise machined. The harm is caused by the deformed surface of the final product, by the wasted material when working the re-sawn surface back to a planed form or by the problems with working the wood because of the immediate deformation of the cross-section during planing or sawing.

It was also stated that case hardening is caused by the mechano-sorptive creep deformation during the early part of drying when the surface is under tensile stress. This strain is not recoverable under dry service conditions but can be counteracted by conditioning the wood at the drying temperature: the compressive stress causes compressive creep strain, making the total elongation of the outer surface smaller.

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The term case hardening is often used more loosely, including meanings other than those described above. On the other hand, the term case hardening does not describe the phenomenon. Therefore, it would be better to use distinct well-defined terms for different phenomena, such as:

- residual stress, meaning the physical state of stress after drying, causing deformation immediately the wood is re-sawn or planed.
- stretched surface, elongated surface layer during drying resulting in cupping when re-sawn and equalised.
- dry shell, dry and nutrition-filled cells on the surface, which can slow down the drying process and may explain the origin of the term case hardening. Hardening may also refer to the hardness of the surface because it is dry.

Based on this survey, a definition for case hardening can be suggested: Case hardening is a feature of dried wood that causes it to deform into a cup shape after re-sawing and equalising the moisture content (Ranta-Maunus et al. 2001).

The CEN standard ENV 14464:2002 Sawn timber - Method for assessment of case-hardening gives a method that can be used to measure the tendency for cupping when the product is manufactured by re-sawing dried sawn timber. This method is illustrated in Appendix 1, Figures 1 - 4.

The objective of this research is to experimentally study case hardening as defined above, to verify how well our wood drying simulation software can predict case hardening, and to find ways of minimising case hardening.

MATERIALS AND METHODS

Case hardening measurements were performed on Scots Pine and Norway spruce timber after different drying methods, and also after 1 and 6 months storage in different climates. The material used for the simulations was 50 x 150 mm Scots pine heartwood timber.

CALCULATION OF CASE HARDENING

The numerical analysis of the case hardening tendency has been made with the use of a two-dimensional Finite Element Program called PEO developed by VTT. This calculates the moisture changes and development of stresses during drying. After cooling, the central line element connections are released and cupping of the two pieces is calculated during equalisation of the moisture.

The calculation of the moisture changes in the cross-section is made using a two-dimensional isotropic model for the moisture transfer in the transverse (RT) plane of the wood. The model uses a reduced approach that considers all the different flow components with a single, diffusion-type differential equation. This simplified model uses the diffusion coefficient and the surface emission coefficient as effective model parameters, which take the variations in the flow properties into consideration and whose values are obtained through a comprehensive empirical fit to the experimental data. The model is introduced in more detail in Hukka (1996), Ranta-Maunus (1994), Hanhijärvi and Mackenzie-Helnwein (2003), and Mackenzie-Helnwein and Hanhijärvi (2003).

The spatial discretization is done by the control volume method when calculating the moisture transfer and by finite element method when calculating the mechanical response using a rectangular calculation mesh (Figure 1).

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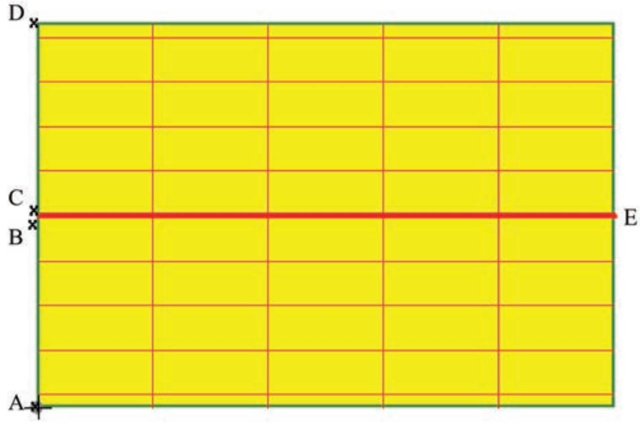

Figure 1. An example of the mesh used in the drying simulations with the PEO program, cross-section size 50 x 150 mm. The figure only shows the right half of the specimen, with the vertical axis of symmetry at the left border of the mesh. The pith of the stud is at point A. Points A–D refer to the results shown in Fig. 3. The vertical position of point E is fixed.

Effect of drying schedule

The material used for the simulations was 50 x 150 mm Scots pine heartwood timber. The pith was on inside face of the studs. The calculation mesh used is presented in Figure 1.

Drying schedules were selected with the following criterion:
- Only minor checking is allowed
- Wet bulb depression is in a fast schedule higher than in a slow schedule

Initially, the fast and slow schedules were the same to avoid checking. In the fast schedules the end phase was speeded up by increasing the wet bulb depression more than in the slow schedules.

Schedules containing additional equalizing phase to reduce moisture content variation and to some extent moisture content gradient were also simulated. In these, the basic schedule was shortened so that after the equalizing phase the average end moisture content was same as after drying without equalizing. The target moisture contents were 18 and 8 %. The drying schedules are specified in Table 1.

Table 1. Drying schedules used in PEO simulations and moisture content gradient after drying, MC_{grad}. The schedules are specified with target moisture content MC_{target}, drying temperature T_{drying}, maximum wet bulb depression WBD_{max}, and duration of drying (t_{drying}) and equalizing ($t_{equal.}$).

Drying schedule	MC_{target} %	T_{drying} °C	WBD_{max} °C	t_{drying} h	$t_{equal.}$ h	t_{tot} h	$MC_{gradient}$ %-unit
18fast60	18	60	14	117		117	5,7
18fast60equal	18	60	14	107	33	140	3
18slow60	18	60	7	157		157	3,9
18slow60equal	18	60	7	122	66	188	2,1
18fast80	18	80	14	78		78	6,5
18fast80equal	18	80	14	72	17	89	3,8
18slow80	18	80	7	96		96	4,6
18slow80equal	18	80	7	66	54	120	2,2
8fast60	8	60	22	256		256	1,8
8fast60equal	8	60	22	240	65	305	0,7
8slow60	8	60	18	309		309	1,4
8slow60equal	8	60	18	292	69	361	0,5
8fast80	8	80	25	150		150	2,1
8fast80equal	8	80	25	142	38	180	0,7
8slow80	8	80	18	180		180	1,4
8slow80equal	8	80	18	177	23	200	0,6

An example of drying curve and tangential stress (relative) development on the surface of the outside face during the drying schedule 18fast60equal is illustrated in Fig. 2.

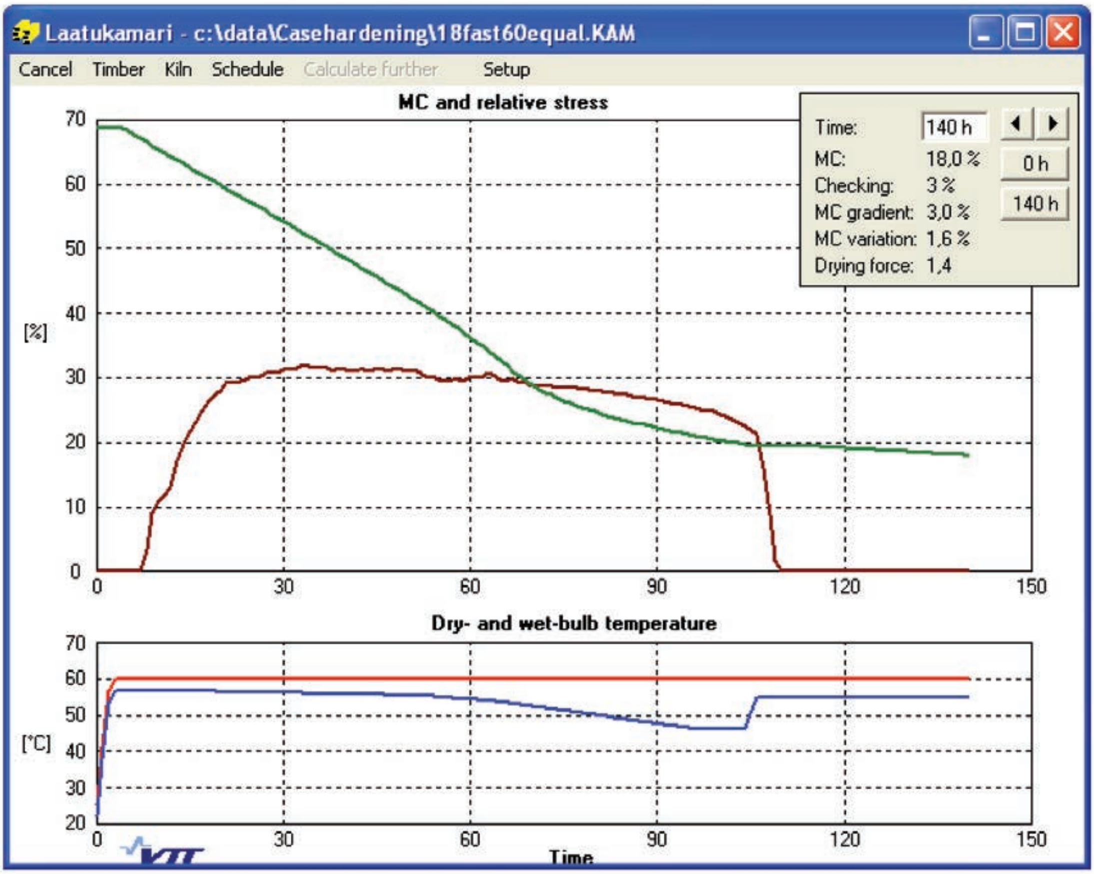

Figure 2. Drying schedule 18fast60equal. Moisture content and drying stress curves in the upper part, dry and wet bulb temperatures in the lower part.

Effect of timber dimension and sawing pattern

The following Scots Pine dimensions were analysed: width 150 mm and thicknesses 25, 32, 50 and 75 mm. The target moisture content was 18%. The basic density was 450 kg/m^3. The initial MC varies in real life according the sawing pattern. Despite that, only the heartwood properties and an initial MC of 35 % were used in the PEO analysis.

Different parts of the log were analysed in the PEO calculations, so the logs were sawn with 2, 3 and 4 ex log (number of central yield pieces); fictional ex log 200 was also used to analyse the situation where the annual rings were parallel to the timber faces.

Effect of conditioning on CEN-gap

The effect of different conditionings after drying on case hardening was also analysed. Table 2 presents the drying schedule and Table 7 shows the different additional conditioning phases and calculated CEN-gap.

Table 2. The drying schedule before conditioning. End MC is 18 %.

Time h	Td °C	Tw °C
0	10	7
3	60	57
50	60	55
90	60	46
112	60	46

The effect of storage time

In analysing the effect of storage time on case hardening with the PEO simulation model it was assumed that the timber was held in 20ºC and 52 % RH for one, two and six months in a room with no air movement before the CEN test.

MEASUREMENT OF CASE HARDENING

Effect of the equalising time after slicing

CEN-test specimens were prepared from 20 spruce battens (32 x 125 mm) dried in a progressive kiln. One specimen from each batten was kept in a plastic bag after the slicing and one parallel specimen in a room atmosphere. Case hardening was measured every 24 hours for one week and at 10 and 20 days after slicing.

Effect of drying schedule, storage conditions and equalizing time after slicing

For the experimental case hardening tests both Norway spruce and Scots Pine timber was selected from industrial production. The nominal timber thickness was 50 mm and the width in most cases was 100 mm. The dryings were selected so that there were fast and slow schedules with and without conditioning. In some cases the industrially dried timber was steam conditioned in VTT´s laboratory kiln. For comparison, two charges of Spruce timber were HT-dried at VTT. One charge was dried with and the other without steam conditioning.

The moisture content and density were measured after drying (and conditioning). The CEN gap was measured according the standard 24 hours after the slicing and storage in a plastic bag. The gap was also measured one week and one month after the slicing in order to obtain the total deformations in the slices.

The timber was cut into 60 cm-long sections for studying the effect of storage. These were conditioned in different climates, as shown in Table 3.

Table 3. Conditioning climate and duration for timber before case hardening test

Climate	1 Month	6 Months
20 °C / 65 % RH	x	x
20 °C / 35 % RH	x	x
Outdoors	x	x

RESULTS AND DISCUSSION

CALCULATED CASE HARDENING

An example of the results of the PEO simulation is presented in Figures 3a - 3d. Figure 3c presents the displacements of points in the middle of the surfaces and just beneath and over the centreline (slicing line, Fig. 1). In the drying and conditioning phase the displacements are due to cupping of the cross-section as one piece. After slicing, the upper and lower parts of the specimen cup in opposite directions when the moisture is equalised. The calculation indicates that the moisture content gradient disappears in one week when conditioning in a plastic bag. The calculated time needed for moisture equalization of the test specimen inside a plastic bag may be inaccurate and has not been verified by tests.

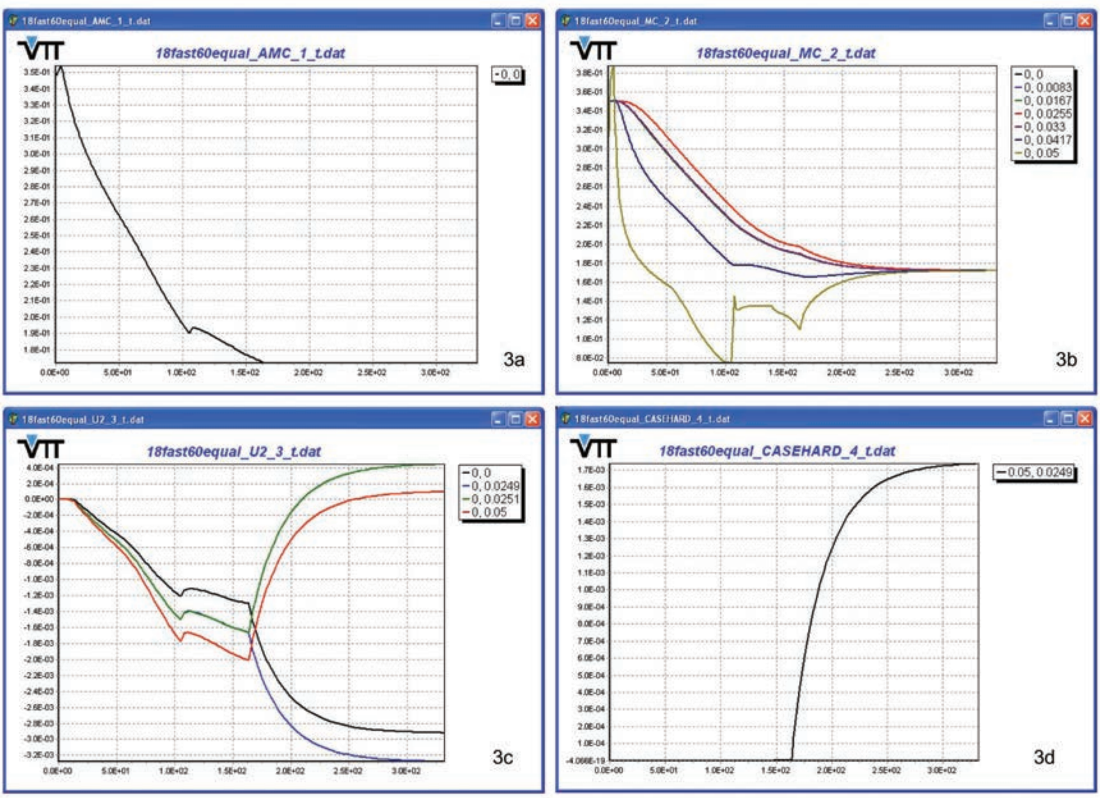

Figure 3. Various calculated variables as function of time [h] (horizontal axis).
Vertical axis: (a) Average moisture content [-]; (b) moisture content on the surfaces and inside the board [-]; (c) vertical displacements of the points A-D [m] , (see Fig. 1) and (d) case hardening opening in the drying phase and after slicing the test specimen [m]. Drying schedule as in Table 1, 18fast60equal.

Effect of drying schedule

The results of the PEO simulations are presented in Table 4. In order to study whether the case hardening gap can be predicted simply by moisture gradient alone, simulated case hardening gap values are compared with the calculated values of the cupping caused only by equalisation of the moisture distribution at the moment of splitting (i.e. freezing creep and elastic deformations to be permanent at the moment of splitting).

Table 4. Simulated CEN gap and gap due to equalising the MC gradient without prior creep history.

Drying schedule	CEN-gap mm	Gap due MC-gradient, mm
18fast60	2,5	2,5
18fast60equal	1,8	1,7
18slow60	1,8	1,8
18slow60equal	1,3	0,7
18fast80	2,5	2,4
18fast80equal	1,7	1,7
18slow80	1,9	1,9
18slow80equal	1,2	1,4
8fast60	2,1	1,4
8fast60equal	1,7	0,8
8slow60	1,8	1,1
8slow60equal	1,4	0,7
8fast80	2,1	1,5
8fast80equal	1,7	1,5
8slow80	1,7	1,1
8slow80equal	1,4	0,8

As expected, the calculated gaps are largest after fast drying without equalizing, smaller when equalized and about equal after slow drying and after fast drying with equalizing. When drying to 18% without equalizing, the case hardening gap is nearly the same as the gap caused by equalizing the moisture content. After equalizing, the gap is smaller but not much different from the pure moisture gradient effect.

When dried to an 8% final MC, the simulated CEN case hardening gaps are about 50% larger than cupping due to the moisture gradient only, when equalizing is not part of the drying. The CEN gap is twice the cupping caused by moisture gradient only in case of schedules with equalizing.

These simulated data show that the case hardening test results and MC gradients are correlated, but are obviously two different measurements that cannot replace each other.

Effect of timber dimension and sawing pattern

The calculated values of the case hardening gap are presented in Table 5.

Table 5. Effect of sawing pattern and dimension on case hardening gap (mm/100mm). Width is 150 mm. Ex log = number of battens in central yield.

D mm	3 ex log inner	2 ex log outer	3 ex log outer	4 ex log outer	200 ex log outer
25				5,5	
32	2,3	3,7	4,3	4,6	4,8
50	1,3	2,5	2,9	3,1	3,3
75	0,8	1,5	1,8	1,9	1,9

The gap does decrease with increasing thickness, partly due to the milder drying schedules for thicker dimensions and partly due to the higher stiffness of the cross-section halves.

Pith boxed pieces (3 ex log inner) cup less after slicing. The cupping does increase with increasing the distance from the pith.

Table 6 presents the effect of the sawing setup on the cupping of the two halves from 32 x 150 mm timber and also the sum of them (CEN gap) after slicing.

Table 6. The effect of sawing pattern on cupping (mm/100 mm) of the halves and the CEN gap. Timber dimension 32 x 100 mm.

batten	outer side	pith side	CEN gap
3 ex log pith boxed	1,1	1,1	2,3
3 ex log outer pcs	3,0	1,5	4,4
4 ex log inner pcs	2,9	0,7	3,7
4 ex log outer pcs	2,8	1,8	4,6
200 ex log	2,4	2,4	4,7

The halves from the pith boxed battens and very far from the pith sawn battens do cup symmetrically. Near the pith the inner slice cups much more than the outer one. The symmetry increases with distance from the pith.

Effect of conditioning on CEN gap

Table 7 shows the different conditioning phases after drying with the schedule presented in Table 2 and simulated CEN gap values.

Table 7. The calculated CEN gap after different conditioning phases. Scots Pine 50 x 150 mm, 2 ex log. The drying schedule is in Table 2.

Conditioning at 60 °C		CEN gap
Tw - Td °C	Time h	mm
	0	2,6
4	6	2,1
4	12	1,9
4	24	1,7
3	24	1,5
2	24	1,2

As expected, the CEN gap decreases with increasing conditioning time and air humidity.

The effect of storage time on case hardening

Table 8 presents the effect of storage time before CEN test on moisture content and case hardening.

Table 8. The calculated effect of storage time on the CEN gap. Scots Pine timber (50 x 150 mm). Storage climate: 20 / 14 ºC (52 % RH).

Storage time months	MC %	CEN gap mm
0	12,0	2,3
1	9,5	1,7
2	9,0	1,5
6	8,7	0,8

The longest storage period reduced the case hardening remarkably. But, compared with the conditioning time, which is needed in the kiln for achieving the same result, the low temperature storage is very time consuming.

EXPERIMENTAL RESULTS

Effect of the equalising time after slicing

The result in Figure 4 shows that the equalisation in plastic bags is slower than in an open space. However it should be noticed that the total cupping in room conditions is higher due to the lower EMC.

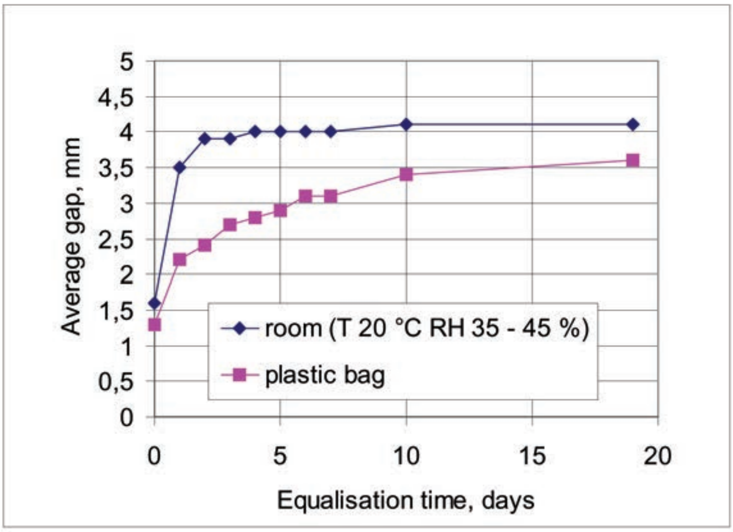

Figure 4. Cupping of sliced specimens in plastic bags and in room conditions. Spruce 32 x 125 mm dried in a progressive kiln for 72 hours (T_{dry} = 64 ºC, T_{wet} = 52 ºC). The points are average values of 20 specimens.

Measured and calculated CEN gap after different dryings and conditionings

Table 9 presents the measured and PEO-model-calculated CEN gap after different dryings and conditionings.

Table 9. Average moisture content as well as measured and calculated CEN gap after different dryings and conditionings. Timber thickness 50 mm.

Drying	Species	MC %	CEN gap (24h) mm		CEN gap (7d) mm	
			meas.	PEO	meas.	PEO
fast	Pine	10,1	0,9	2,0	1,2	2,8
fast + steam cond *	Pine	11,2	-0,1	1,4	0,0	1,9
slow + cond in mill	Pine	9,0	0,6	0,4	0,7	0,4
OTC	Pine	9,1	0,6	1,1	0,8	1,2
OTC + steam cond *	Pine	10,6	0,4	1,0	0,4	1,1
fast	Spruce	10,6	1,4	1,5	1,8	1,7
fast + steam cond. *	Spruce	11,8	0,2	0,7	0,4	1,0
slow	Spruce	8,7		1,0		1,2
HTD	Spruce	11,8	2,1	-	2,5	-
HTD + steam cond. *	Spruce	11,9	1,2	-	1,6	-

** 2.5 h steam conditioning after transport to VTT*

The results show that high-temperature drying without conditioning results in severe case hardening. Slow drying gives better values than fast drying, but with effective conditioning it is possible to remove the case hardening after fast drying.

There is no good correlation between measured and simulated case hardening values. Coefficient of determination is 0.14 for all values and 0.31 in cases without conditioning. One reason for this is that the parameters in the PEO model are not fully correct for the material dried in a particular sawmill. Another reason is that the real drying schedule of each test specimens is not known exactly. Despite of that PEO does show the tendencies how drying schedule affects on case hardening and it is so a useful tool for analysing drying schedules. PEO underestimates the effect of steam conditioning on the CEN gap. So it is necessary to define parameters separately for the situation of moisture intake.

Figures 5 and 6 show the experimental results of the effects of the conditioning climate and time on case hardening, moisture content and moisture gradient. Figure 5 presents the situation after fast drying and Figure 6 after fast drying and additional effective steam conditioning after cooling. The CEN gap was measured 24 h after the slicing as instructed in the standard and also after one and four weeks.

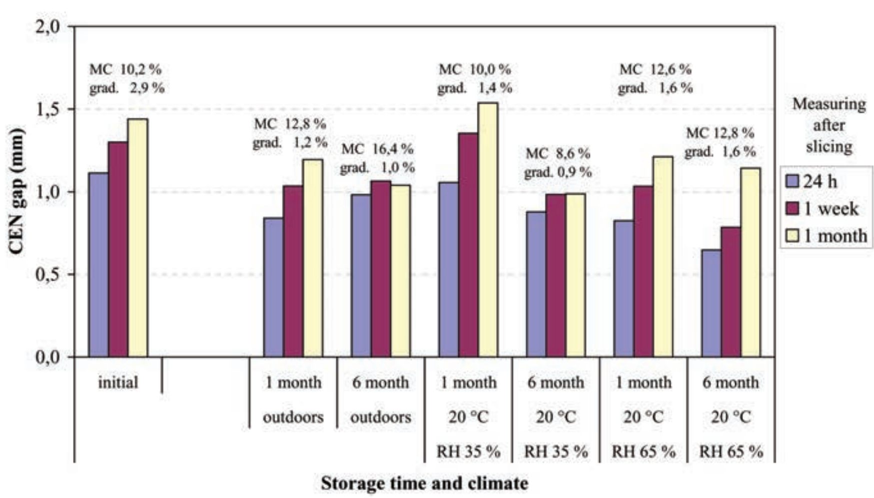

Figure 5. Case hardening, moisture content and moisture gradient after fast drying and after 1 and 6-month storage in different climates. Scots Pine 50 x 140 mm^2. CEN gap is measured 24 h, 1 week and 1 month after the slicing.

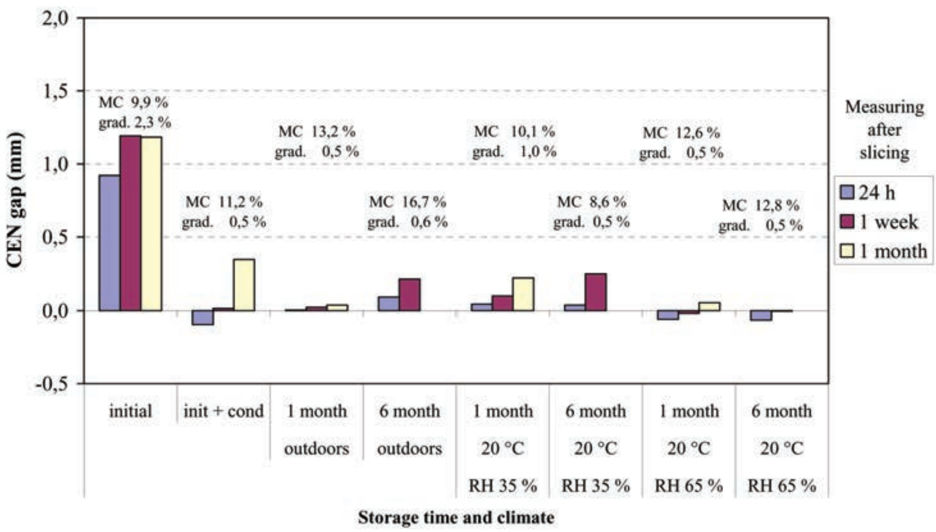

Figure 6. Case hardening, moisture content and moisture gradient after fast drying and steam conditioning, and after 1 and 6-month storage in different climates. Scots Pine 50 x 140 mm^2. CEN gap is measured 24 h, 1 week and 1 month after the slicing.

It can be seen that it is possible to effectively remove case hardening with proper conditioning.

CONCLUSIONS

As a conclusion of the expert interviews, case hardening was defined as follows: Case hardening is a feature of dried wood that causes deformation (cupping) after re-sawing and equalizing of the moisture content.

Analyses with the finite element program PEO have shown that case hardening is not predicted by the moisture content gradient alone. The experimental results give the same conclusion. However, the case hardening gap after drying to a high final moisture content of 18% is nearly identical to the calculatory gap caused by cupping when the moisture gradients of the two halves of the test piece are equalized.

According to the simulations and experiments, the proposed time (24 hours) to keep the sliced specimens in a plastic bag before case hardening measurement is too short to show the total cupping. Thus the test doesn’t show the whole cupping tendency of, for example, panels when the moisture content is equalized after re-sawing the studs and planing the billets. However, the 24 h value is about 70 - 80 % of the value after 1 month, which is enough for a practical test to show the tendency.

The measurements and simulations show that case hardening increases with an increasing drying rate. With effective conditioning at drying temperature, or with steaming after cooling, it is easy to reduce or remove the case hardening. But at normal temperatures in use or storage of timber the case hardening diminishes very slowly, despite equalizing the moisture content in the cross-section.

Correlation between case hardening after industrial drying and simulated values was quite poor. The main reason for that are variations in timber properties and differences between average drying schedule in an industrial kiln and the drying climates just around the measured test specimens.

Despite of the differences of numerical values compared to test values the model may be used as a tool to analyze the tendencies to case hardening after different drying schedules.

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APPENDIX 1 Case hardening test according the CEN standard ENV 14464:2002 Sawn timber - Method for assessment of case-hardening

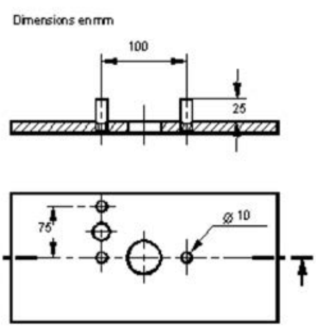

Figure 1: Test jig for assessment of casehardening

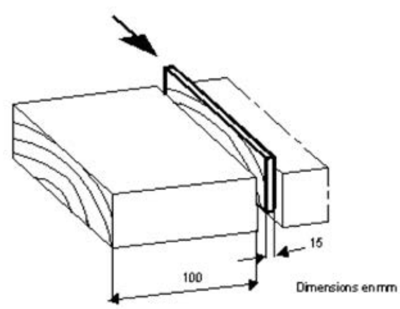

Figure 2: Preparation of test slice

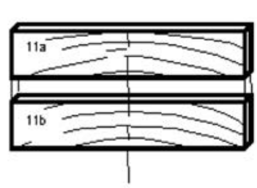

Figure 3: Separation and marking of test slice

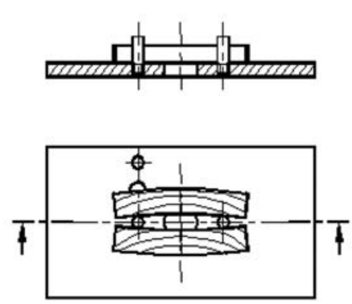

Figure 4: Evaluation of case-hardening with test jig