Almost all wooden pieces have a damaged surface layer - impact on some properties and quality

J.G. Salin

Romensvägen 12 A, FI-02210 Esbo, Finland
jarlgunnar.salin@welho.com

ABSTRACT

There are numerous examples of observations that clearly indicate that the fibre network structure has been more or less damaged in a relatively thin surface layer during preparation of the wooden piece – sawing, planing, sanding, etc. Such examples are the formation of a "dry shell" at an early stage of sapwood drying, "kiln brown stain" formation below the surface especially in Radiata pine at higher drying temperatures, an apparent deviation from the analogy between heat and mass transfer in drying and some phenomena seen in water absorption processes.

These damaged surface layers will have an influence on different properties and on quality. The drying rate for boards should depend on the sawing method and conditions. Checks may be initialized as micro-cracks in the dry shell at an early stage of the drying process. Liquid water absorption may be enhanced. The most critical situation occurs probably in laboratory work with small samples. If the thickness and type of damage is equal in the small sample and in the corresponding full size piece, the high volume ratio of damage in the sample will influence the result. On the other hand, if the sample is prepared too carefully, so that the surface damage is minimized, measurements with the sample may also give biased results.

INTRODUCTION

In the first part of this report some direct or indirect experimental results will be presented, that indicate that the surface layer of almost all machined wood pieces is more or less damaged. These damages may be too small for a direct visual detection, but will change the capillarity of the surface layer and thus influence the interaction with the surrounding air. In many cases a theoretical explanation to the anomalies observed can be found and is included in the presentation. In the second part the impact of the damaged surface layer on the behaviour and properties of the whole wooden piece is discussed. Some remarks regarding laboratory work in this context are further given.

SURFACE LAYER DAMAGE

Deviations from the Analogy between Heat and Mass Transfer

Drying of wood includes transfer of heat to the wood and transfer of vapour (evaporated by that heat flow) from the wooden piece. The fluxes of heat and mass can be modelled using heat and mass transfer coefficients, together with appropriate driving forces. As both the heat and the mass (vapour) have to pass through the same air side boundary layer, it is natural that the transfer coefficients are rather strictly coupled. This so called analogy between heat and mass transfer is a fundamental physical law and is for instant the basis for air humidity measurements with wet and dry bulb thermometers. It is further well known that an only partly wet surface will behave almost like a completely wet surface (or free liquid water surface) as long as the dry spots are not too big.

Especially for sapwood of softwood, with its high initial moisture content, one would thus expect that the analogy between heat and mass transfer should be valid for a rather long time in a wood drying process. Several experimental results indicate, however, that the (apparent) mass transfer coefficient often is considerably lower than expected (Salin 1996). Several explanations have been given (Salin 2002) but the simplest reason is that the moisture evaporation takes place from a front below the surface, i.e. a "dry" shell develops very fast (Fig. 1.). "Dry" in this context means that no free water is present and the assumption of a wet surface is wrong which is seen as an apparent deviation from the analogy. That a dry shell exists has been observed experimentally (Tremblay et al. 2000, Wiberg et al. 2000). The deviation from the analogy above the fibre saturation point is explained by the dry shell - the next question is why the dry shell is formed so rapidly.

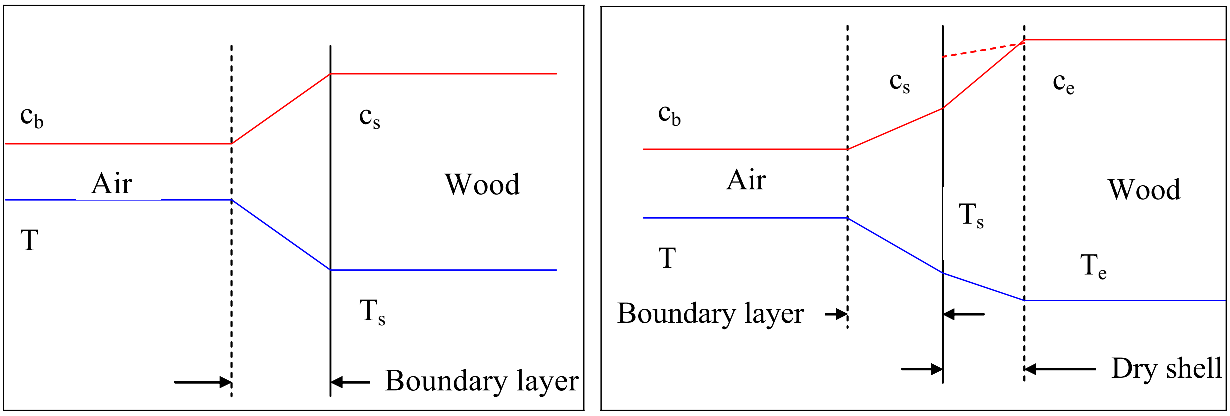

Figure 1: Moisture and temperature profiles in the traditional model to the left and with a dry shell to the right

Kiln Brown Stain

Especially with Radiata pine there is often a problem with discolouration 1-2 mm below the surface of a dried board. This brownish colour - kiln brown stain - may cause a quality loss if uncovered after planing. This phenomenon is explained in the following way (Kreber et al. 1999). Chemical compounds, mainly sugars, originally dissolved in the free water, will precipitate at the point of water evaporation during drying. At elevated temperatures these compounds will then turn dark according to a Maillard chemical reaction - "caramelizing". For other wood species the discolouration may not be a problem, but instead the susceptibility to mould etc. is enhanced due to the local concentration of nutrients at these locations (Terziev 1996).

Anyway, this kiln brown stain phenomenon is another proof that a considerable part of water evaporation takes place below the wood surface. If the drying of free water is (incorrectly) modelled in the traditional way as a diffusion process, then the result is a high evaporation at the wood surface. Recently drying of free water has been more correctly modelled as a process in a capillary network (Salin 2006a,b, 2008a). This theory predicts also that the main part is evaporated from the first layer of fibres at the surface. Why is then the evaporation in reality occurring 1-2 mm below the surface? It has, however, been observed that if a board is very cautiously planed before drying, then the evaporation front will move to the surface, or very close to it (McCurdy et al. 2006). This indicates clearly that the surface layer, 1-2 mm, may have other properties due to the rough sawing process, compared to the bulk of the wooden piece. In the capillary network model for softwood the bordered pits and their size distribution, are key elements. If a gradually increasing equivalent bordered pit opening size distribution towards the surface within the 1-2 mm surface layer is introduced in the model, then the model predicts evaporation at the border between changed and unchanged fibre properties (Salin 2006b, 2008a) as presented in Fig. 2.

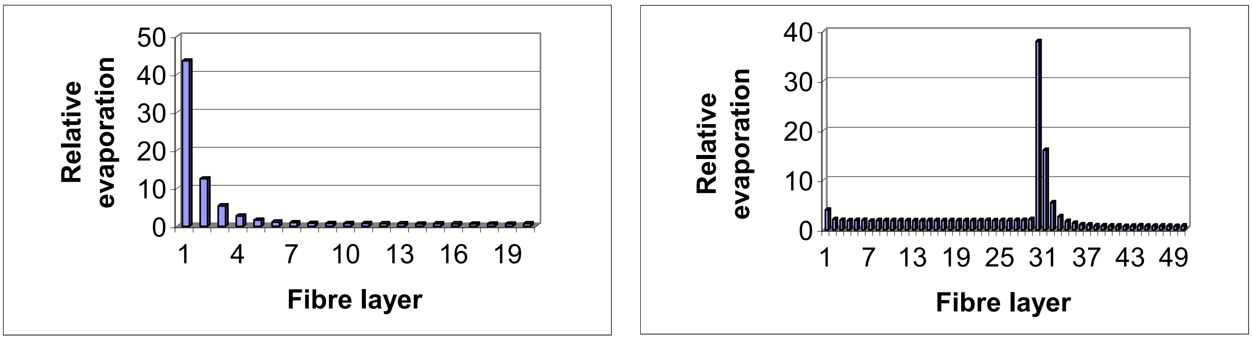

Figure 2: Location of the evaporation front calculated with a capillary fibre network model. To the left the result for an undamaged sample is given and to the right with a 30 fibre thick damaged layer with increasing structure openness towards the surface

It seems thus that a relatively small enlargement of the openings between fibres - in the form of damaged bordered pits, cell wall ruptures etc. - will move the evaporation front inwards. It should be noticed that this damage is directed towards small parts of the fibre, the fibre network as a whole may seem unchanged.

An Unexpected Water Absorption Behaviour

In a paper titled "Unexpected experimental results for capillary suction in wood" (Segerholm and Claesson 2007) the authors describe an absorption experiment that produced a rather surprising result. A stick of pine (*Pinus silvestris)* moisture sealed on four vertical surfaces was kept for a long time with one (open) end just below a water surface. This resulted of course in absorption of water, upwards in the fibre direction. After 1000 or 1900 hours the stick was sliced and the moisture content determined as a function of the height above the water surface. In the case of a 100 mm long stick the moisture content was naturally very high in the lower end and decreased gradually upwards. However, about halfway up the moisture content started to increase again and reached a maximum at the upper end (Fig. 3.). For 200 and 300 mm long sticks the same general result was found, except that the maximum value at the upper end decreased as the sample length increased. For a 400 mm stick a steadily decreasing moisture content was found all the way up to the end. The result for the shorter sticks contradicts of course the basic understanding of an absorption process of this kind.

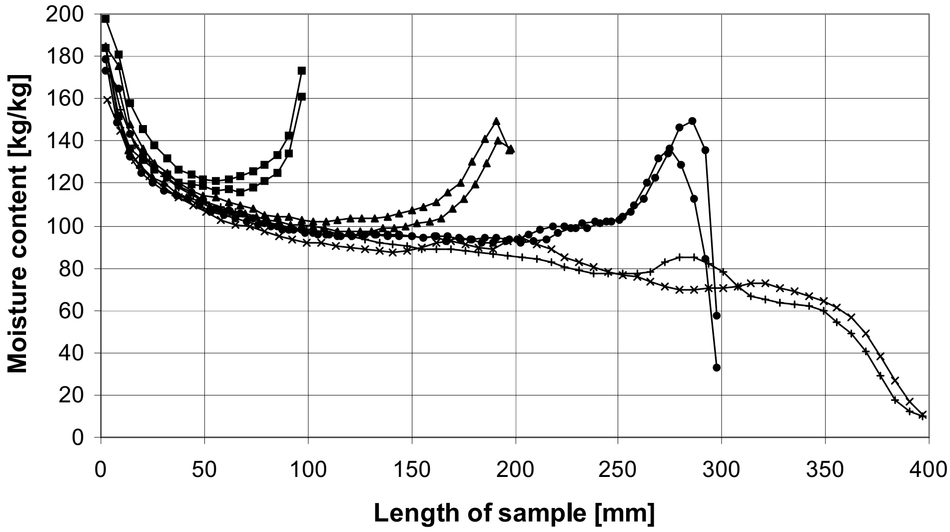

Figure 3: Moisture profiles in the vertical direction for different sample lengths. From (Sederholm and Claesson 2007)

The authors explained the result by suggesting that the water had spread laterally when it reached the top and then had penetrated the stick downwards. The result would thus resemble a situation where water is absorbed from both ends of the stick. This suggestion requires that the uppermost fibre network is more open than in the rest of the sample - otherwise the lateral spread had occurred earlier. Taking into account that the upper surface was obtained by sawing perpendicularly to the fibres, it is no surprise that a damaged surface layer is found here again, as in the other experiments mentioned above.

A water absorption model for wood has been developed based on a capillary fibre network concept (Salin 2008b). This model has been used for the simulation of the experiment above, assuming that the uppermost fibre layer has a more open structure than the rest. The results from the simulations are very similar to the experimental results presented in Fig. 3. It turns out that the shape of the moisture content profile in the vertical direction depends strongly on the relation between the sample length and the rate of evaporation from the upper surface. For short samples and/or a low evaporation rate a U-shape curve is obtained (equal 100 mm length in the experiment). For long samples and/or a high evaporation rate a steadily decreasing moisture content is obtained (400 mm sample). Fig. 4 presents examples of simulation results when the rate of evaporation from the upper surface is varied (instead of the sample length). It turns further out that for a wood species with a more open structure a very “shallow” U-shape is obtained - probably not seen as a “U” at all. For a more closed structure all water paths would stop at dead ends even before reaching the upper end. Only in a rather narrow interval the behaviour seen in the experiments will occur, which perhaps explains why such a phenomenon has not been reported earlier.

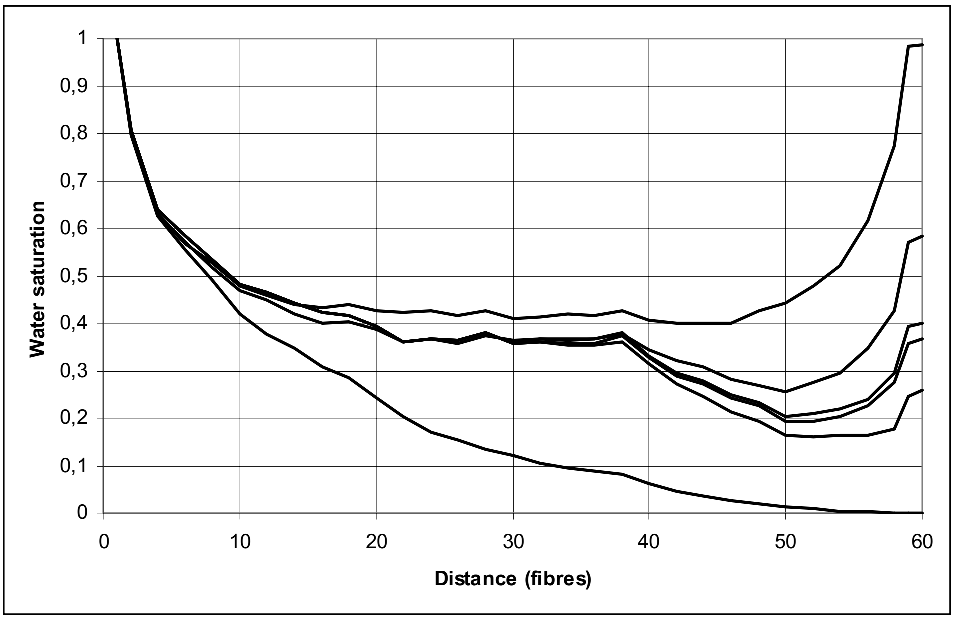

Figure 4: Calculated moisture profiles in the vertical direction for different rates of evaporation from the upper surface. The uppermost curve represents a very low evaporation rate and the lowest curve a very high (infinite) rate

Anyway, the assumption of a damaged surface layer gives, in this case also, a reasonable explanation to the behaviour seen in the experiment. This is the basis for the statement that almost all wooden pieces have a damages surface layer.

In the previous discussion the main focus has been on a changed capillary structure and its influence on free water behaviour. However, the damage in a surface layer can also be viewed as a re-opening of aspirated bordered pits, making the layer more open for gaseous phase flow. The damaged surface layer may thus have an influence below the fibre saturation point also, i.e. where there is no free water present.

THE IMPACT OF DAMAGED SURFACE LAYERS

Heat and Mass Transfer

Up to date the apparent deviation from the analogy between heat and mass transfer (especially for sapwood of softwood) has been accounted for by introducing correction factors. If the thickness of the damaged surface is known, then an analytical expression can be given for the correction factor. However, in most individual cases this thickness is not known, but an analytical expression with a few (partly known) parameters is better than a plain correction factor with an unknown background. This discussion concerns modelling free water behaviour in the traditional way (incorrectly) as a diffusion process - in which case a correction factor is needed. If a capillary network model is employed then no correction factor should be needed, but such models require very heavy calculations and cannot in practice be used for board scale analyses. An approximate model between these two levels of accuracy is thus needed and is the target for work in this area.
It is known that planed boards dry faster than sawn boards with the same thickness (Wiberg et al. 2000). This is surprising as a rough surface should enhance the heat and mass transfer due to higher turbulence. The result indicates that the evaporation front is closer to the surface in the

planed case and that this effect is stronger than the effect of turbulence. Accordingly one would expect that there should be a small difference in drying behaviour for instance between boards from a band saw and a frame saw. The author is not aware of any such results. Anyway, there should perhaps be a new correction factor introduced in drying models that takes into account how the board has been produced.

A more serious problem arise from the fact that a lot of wood property parameters have been determined using very small (centimetre size) laboratory samples. There are two important factors in this context. If the damaged layer thickness is the same in the laboratory samples and in reality, then the volume ratio damage/undamaged wood is quite different in these two cases, which may give a biased result. On the other hand, in most cases the laboratory samples are very carefully prepared and probably the damaged layer is much thinner than in industrially produced wooden pieces. Many researchers that have developed drying models using "small scale" property parameters have found that such models do not always fit full scale processes very well.

An extreme example is related to the "surface emission coefficient" concept. This concept was introduced almost 80 years ago (Newman 1931) in order to simplify the modelling of external mass transfer and to make analytical solutions available for the diffusion equation. The concept is not physically correct, but has especially in wood science been used for a long time - too long. The traditional way to determine the surface emission coefficient is to use laboratory scale samples with *different thicknesses* and the coefficient can then be extracted from a combination of these results. It would thus be no surprise if the damaged surface layer feature has influenced these experiments. In a survey of published numerical values for the surface emission coefficient (Söderström and Salin 1993) the ratio between the highest and the lowest value was 500000. Although part of the spread could be due to the approximate nature of the concept, the damaged layer may very well have influenced the result even more. Despite a tremendous amount of work, the surface emission coefficient concept never reached a level that could be used in full scale modelling of timber drying.

Kiln Brown Stain

If the kiln brown stain discolouration and the local high concentration of nutrients (susceptibility to mould etc.) are determined primarily by the thickness of the damaged surface layer, then changes in drying conditions should have only a minor influence on the problem. An exception could be high temperature drying in order to create an internal vapour overpressure that "pushes" the evaporation front outwards. On the other hand, a higher temperature would enhance the Maillard colour producing chemical reaction. The insight into the real cause of the problem, results in a negative feeling regarding the existence of simple solutions to the kiln brown stain problem.

Water Absorption

In the example above with the remarkable moisture profile in a stick with one end in water, it was concluded that the damaged nature of the upper surface had a high impact on the result. One could expect that the vertical surfaces were more or less damaged also. If so, then the more open structure of the vertical surface layers would increase the water absorption rate, and water redistribution laterally higher up in the sample. A higher moisture content in a thin surface layer is very difficult to verify experimentally. It is almost impossible using gravimetrical methods.

CT-scanning can provide a high resolution, but the general problem to reproduce abrupt density changes (transition air/wood) may mask the phenomenon.

In the actual experiment mentioned, the vertical surfaces were moisture sealed. It is possible that the sealant had penetrated the damaged surface layer, counteracting the increase in absorption rate. In the case of unsealed surfaces the evaporation of free water from the surfaces will make the situation more complicated.

There are several standardized test procedures involving absorption of water or other liquids into (treated or untreated) wood samples. It is suggested that the influence of damaged surface layers on the test results should be considered and evaluated.

Other Impacts

If a dry shell (no free water) rapidly develops in sapwood, this shell will start to shrink although there is a lot of free water (and no shrinkage) in the bulk part of the piece. This creates tension stress in the shell - balanced by compression stress in the bulk. An interesting question is whether this tension stress can be high enough to create checks (cracks) in the surface layer. According to order of magnitude calculations reported in (Salin 2006b) checking seems to be possible. Experimental observations of checking in sapwood at a very early stage may be seen as a confirmation (Morén 2008). The depth of the crack can hardly be deeper than the thickness of the dry shell, i.e. the result is a micro-crack hardly visible to the naked eye. Such a micro-crack may by capillary suction attract colour pigments into the crack, forming a clearly visible coloured line at the surface, in a surface treatment. The micro-crack may also act as an initialisation for bigger "normal" drying checks later in the drying process.

Coating, surface treatment and gluing are all processes where the condition of the wooden surface is important. There is thus a need to investigate how the surface layer influences the results in these processes. Again attention should be given to the possibility that laboratory test samples have different surface properties compared to full scale boards, etc. In gluing the "weak boundary layer", WBL, concept has been used to describe a decreased strength of the joint. This concept was extended in (Stehr 1999) for wood by defining a chemical (CWBL) and a mechanical (MWBL) boundary layer. It seems however that this kind of damage is concentrated to an only 0,1-0,2 mm thick layer, where on the other hand a more extensive damage in the fibre structure is found. Especially regarding the capillary behaviour the impact may be similar to the cases discussed above, but the main focus in this report is on a thicker layer but with a damage of a more microscopic nature.

CONCLUSIONS

Based on experimental evidence it has been concluded that almost all wooden pieces have a damaged surface layer and that this damage results in different properties within the layer compared to undamaged (bulk) wood. These differences will influence the behaviour of the piece, especially in cases where the interaction with the surrounding air (or other media) is important.

One aim of this study is to point out the importance of recognizing problems that may arise from such surface layers. Transforming measurement data on small laboratory samples to full scale situations represents a particular challenge in this respect.

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