INFLUENCE OF TEMPERATURE ON CRACKING AND MECHANICAL PROPERTIES OF WOOD DURING WOOD DRYING – A REVIEW

Laura Oltean, [a] Alfred Teischinger, [a,b] and Christian Hansmann [a,b*]

The occurrence of cracks and loss of mechanical properties are major problems in wood drying, and careful control of drying conditions is necessary in order to avoid this form of defects. Wood drying at different temperatures, especially high temperatures, has gained much interest in the last several decades. Some solutions for minimizing drying defects, such as cracks and decrease of mechanical properties due to the increase of drying rates, decrease of drying time and thus cost, must be acknowledged and understood. The present review tries to summarize the influence of temperature during kiln drying on the mechanical properties of wood and on the occurrence of cracks.

Keywords: Wood, Drying temperatures, Kiln drying, Cracks, Mechanical properties

*Contact information: a: Institute of Wood Science and Technology, Department of Material Sciences and Process Engineering, University of Natural Resources and Applied Life Sciences, Peter Jordan Strasse 82, 1190 Vienna, Austria; b: Wood K plus, Competence Centre for Wood Composites and Wood Chemistry, St.Peter Strasse 25, 4021 Linz, Austria; *Corresponding author: hansmann@boku.ac.at*

INTRODUCTION

Kiln drying of wood within different ranges of temperatures, especially at high temperatures, has gained much interest over the last several decades. Drying at elevated temperature is one way to reduce drying time, and this reduction may in turn reduce manufacturing costs and improve kiln throughput. According to Thiam et al. (2002), drying affects the mechanical properties of wood in three ways: the direct effect of moisture loss, the internal drying strain and stresses, and the direct influence of temperature on wood components. Milota (2000) suggested that by increasing the temperature (from 82°C to a range of 116°C-132°C) during drying of western hemlock and fir timber, the time required decreases by almost 50 %. Similar results were found for western hemlock by Kozlik and Ward (1981) and Thiam et al. (2002). Kozlik and Ward (1981) found that high temperature (HT) drying intensified internal cracking and collapse in wood. However, it was suggested that not all of these defects degrade the timber in industrial practice. Similar work was performed by Thiam et al. (2002), who found that western hemlock and fir timber showed a decrease of warp, particularly bow and crook, by applying a high temperature drying schedule (116°C), compared to a conventional drying schedule (82°C). A decrease in mechanical properties was in this case recorded.

Strength is not permanently affected by short exposures to temperatures below 100°C, but may be reduced permanently by extended exposures to temperatures greater than 65°C. The magnitude of this permanent strength reduction depends on the heating medium, temperature (Kudela and Laurová 2006; Lagana et al. 2006; Popović et al.

2006), the moisture content (MC) (Bastendorff and Polensek 1984; McCollum 1986; Popović et al. 2006), the exposure period (Kudela and Laurová 2006; Lagana et al. 2006), species, and specimen size (Tsoumis 1991; Junkkonen and Heräjärvi 2006). The effect is greater when the MC is high (Bastendorff and Polensek 1984; McCollum 1986). Detailed information concerning the direct influence of moisture and temperature on some mechanical properties of beech wood is given by Popović et al. (2006). In the study performed, they stated that each increase of hygroscopic moisture, depending on wood temperature, causes a decrease of modulus of elasticity (MOE) and modulus of rupture (MOR) by 1.3-3.3% and by 2.1-7.1%, respectively. It was also found that, depending on the moisture and anatomic directions, an increase of temperature by 1 °C causes a decrease of MOE and MOR by 0.17-0.59% and by 0.40-0.59%, respectively.

According to Brunner (1987) there are three ranges of temperature that are nowadays used in the industry for wood drying, namely low temperature (LT) drying (15-45°C), normal temperature drying (40-90°C), and high temperature drying (90-130°C). Also combinations of the LT/HT drying schedules are used, while higher ranges of temperature (160-260°C) are considered as thermal treatments (Hill 2006). The drying schedule is chosen according to several parameters, wood species dried, initial MC, mechanical properties desired, and final application of the product.

Thermal treated wood is used in indoor or outdoor applications such as furniture, paneling, or flooring. Recent work on heat treatment processes of timber (known as Thermowood® in Finland, “Thermoholz”® in Austria, “Plato wood” in the Netherlands, “Retification” and “Perdure process” in France, and “Oil heat treatment”, “Lignostone” and “Lignofol” in Germany, and “Staypak” and “Staybwood” in the United States) has shown that such types of processes can improve the performance of timber considerably in several respects (Patzelt et al. 2002; Hill 2006). The main effects gained by heat treatment of wood are distinct improvements in hygroscopicity, dimensional stability, and biological durability, and in some cases control of color changes.

Dimensional stability is strongly connected to the hygroscopicity of wood (e.g., Wang and Cooper 2005). When wood is exposed to elevated temperatures, the hemicelluloses are partially decomposed, resulting in reduced hygroscopicity (Stamm 1956; Espenas 1971; Sehlstedt-Persson 1995), and thus influencing the wettability of wood (Hakkou et al. 2005a,b; Johansson et al. 2006; Sehlstedt-Persson et al. 2006; Esteves et al. 2007). Yet, undesirable side effects have been observed, in particular the loss of strength and increased brittleness of the treated wood (e.g. Tjeerdsma et al. 1998).

The decomposition of cellulose, hemicellulose, and lignin, which are the principal organic components of wood, is the main cause of degradation during elevated temperature drying. Within hemicellulose, the reaction of acetyl groups is one possible cause of permanent strength reduction by high-temperature drying. After the acetyl groups form acetic acid, cellulose is depolymerised. After the depolymerisation of cellulose, the tensile strength of Douglas fir is more sensitive to changes in moisture content in comparison to wood having cellulose of long-chain structures (Ifju 1964). The acid hydrolyzes the bonds that connect the glucose monomers. The rate of strength losses increases as the production of acid is accelerated by high temperature and high MC (Mitchell and Barnes 1986; Tjeerdsma et al. 1998).

Another negative outcome of elevated temperature drying schedules which affects the loss of mechanical properties of wood is the occurrence of cracks, i.e. "checking." There are several types of wood cracking due to drying, as presented by Simpson (1991), such as surface cracks, end cracks and splits, collapse and honeycomb.

It is generally considered (Schniewind 1963) that cracks occur during the initial stages of drying because moisture gradients lead to high tensile stresses on the face of the drying board. These are generally named surface cracks and they can be removed by machining if the final application requests it and/or allows for it. The width limit for the visibility of cracks by the naked eye is stated by Hanhijärvi et al. (2003) as being 0.1 mm.

A honeycomb is described as an internal crack caused by a tensile failure across the grain of the wood that usually occurs in the wood rays (e.g. Simpson 1991). This defect occurs when the core is still at relatively high moisture content above fiber saturation point (FSP), while the surface is starting to dry and the drying treatment is being carried out at excessively high temperatures for too long periods of time. Severely honeycombed timber frequently has a wavy appearance on the surface, and the defect is often associated with severe collapse (Simpson 1991). Collapse is a deformation caused by flattening or crushing of wood cells. It may be caused by compressive drying stresses in the inner part of the boards that exceed the compressive strength of the wood or liquid tension in cell cavities that are completely filled with water. Collapse is usually associated with excessively high dry-bulb temperatures (DBT) early in kiln drying, but this type of defect is not usually visible on the wood surface until later in the process (Simpson 1991). It is usually seen to occur in the sapwood part of the boards (Innes 1996). Therefore, low initial dry-bulb temperatures in species which are susceptible to collapse are recommended by Simpson (1991).

Hart (1984) stated that the relationships between the relative humidity (RH), moisture content, and shrinkage in the early stages of drying are of particular importance, because of the collapse-type shrinkage that may occur with some species of wood, in particular, species such as oak in which the honeycomb appears to be one of the most serious drying defects. Regular high humidity treatments at low temperatures have a significant influence in reducing cracks (Neumann and Saavedra 1992); a possible explanation might be that they can avoid or continuously recover from the collapse, especially with respect to the surface cells, and thus prevent the formation of micro-cracks, which might extend to visible surface cracks. This would also increase the surface permeability and thus reduce the moisture gradients. Another possible reason is that there might be a hysteresis effect that retards the contraction of the surface layers at lower MCs after the high humidity treatments. A reduction of cracking might be obtained if the boards are pre-steamed (Neumann and Saavedra 1992) or if a reconditioning step follows the HT drying process (Innes 1996).

THE OCCURRENCE AND DEVELOPMENT OF CRACKS DURING DRYING

General Considerations

The concept of fracture mechanics was used for a long time in order to characterize the failure of wood under load. Research has been performed by several scientists to determine the fracture mechanics parameters for a variety of wood species and for different grain orientations (Johnson 1973; Schniewind and Lyon 1973; Mindess and Bentur 1986). Wood drying has also consequences at the micro-scale, e.g., at the cell wall level. The wood cell is a natural composite made up of middle lamella, primary wall, and three secondary cell wall layers with different orientations of microfibrils in relation to the fiber direction (Kifetew et al. 1998). According to Côté and Hanna (1983), three types of cell fracture are recognized: intercell failure, which is the separation of cells at the middle lamella; intrawall failure, which occurs within the secondary cell wall; and transwall failure, which is the fracture across the cell walls. These terms are shown in a schematic diagram in Fig. 1.

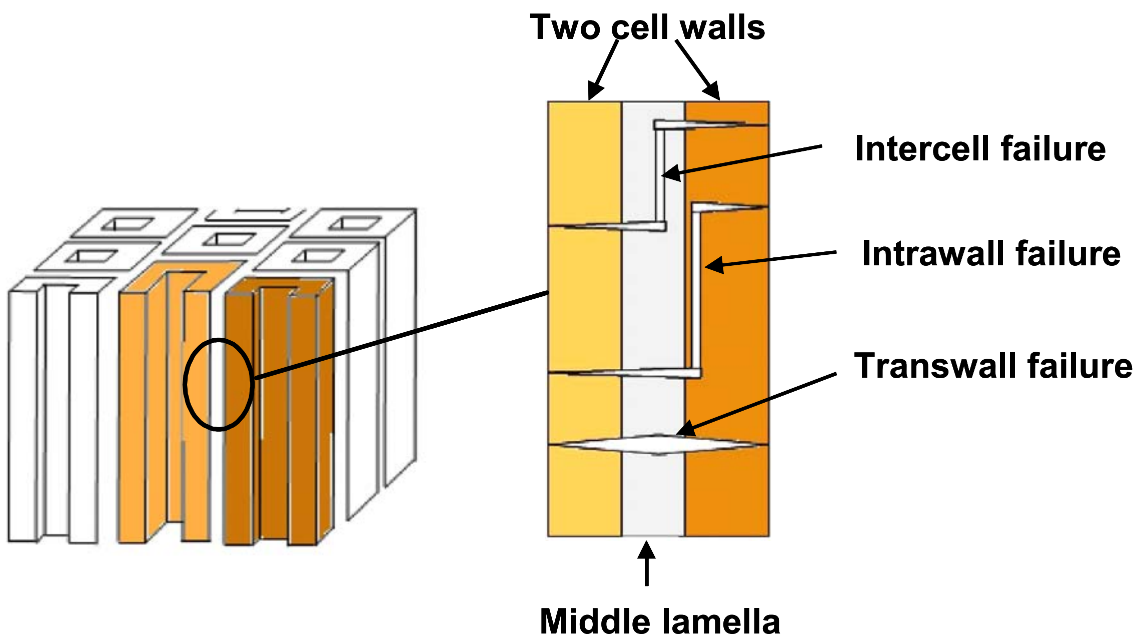


Fig. 1. Schematic diagram showing the different types of failures at the cell wall level (according to Kifetew et al. 1998)

The effect of drying on wood fracture surfaces of thin specimens of Scots pine subjected to uni-axial tensile tests in wet conditions was studied by Kifetew et al. (1998). One set was in a green state, while the other one was dried and then re-soaked to wet conditions to test the material at the same MC. The dried/resoaked specimens showed a flatter and more brittle appearance, which leads to the hypothesis that drying is responsible for cell wall damage.

Subsequent studies (Triboulot et al. 1984) employing finite element calculations, showed that at least some of the assumptions underlying the use of the linear elastic fracture mechanics (LEFM) for wood, namely, the assumption of plane strain, and orthotropic and linear elastic behavior, may be considered valid. Specific attention was given by Mindess and Bentur (1986) to the microscopic details of the physical process that takes place during crack propagation in Douglas fir by compact tension loading. In general, the pattern of crack propagation was found to be a straight path, parallel to the direction of the grain. At the microscopic level, the crack could not be described as an ideal straight, parallel-sided crack. Its path was characterized by various irregularities, such as branching, bridging, and discontinuities, and in some regions of the crack its walls were inclined. When the crack became stable and had to be induced to propagate beyond it, this implied that the stable crack tip had been arrested at a zone of high toughness; in order to propagate further, the crack preferred the path of the least resistance, which bypasses the tough zone.

Several studies have been performed concerning the occurrence and development of cracks during drying (Schniewind 1963; Mackay 1972; Kozlik and Ward 1981; Kozlik and Boone 1987; Hanhijärvi et al. 2003), but not many studies were found in the literature on the development of cracking during the variation of drying temperatures and their effects on mechanical properties (Schneider 1973; Terziev and Daniel 2002; Poncsák et al. 2006). The latter topic will be discussed in the last section of this review, "Influence of occurring and developing cracks on the mechanical properties of wood during kiln drying."

Crack formation in wood during drying might differ due to different parameters, such as the kiln drying schedule, the moisture gradient within the wood, but also due to the micro-structure of different wood species and dimension of specimens.

The work done by Schniewind (1963) on the mechanism of crack formation in wood confirmed the theory that for Californian black oak, rays are the sites of maximum tensile stresses in the early stages of drying, and therefore, cracks would be expected to first develop in the rays. In the case of Tasmanian Eucalyptus oblique, Mackay (1972) found that after initiating at vessel sites, cracks spread in a radial direction not necessarily along a ray but frequently between them. In addition, one common pattern of crack development was through nearby vessels aligned radially. After breaking through a vessel element wall, the zone of failure was in the middle lamella, causing a separation of adjacent cells rather than a fracture of cell walls. Furthermore, it was found that the occurrence of end cracks started and spread in and along a ray.

Increased internal cracking and collapse in sapwood of young-growth western hemlock dimension timber occurred during drying at HT (110°C) compared to LT drying (82°C) (Kozlik and Ward 1981). During HT drying at a DBT of 110°C of red alder timber, Kozlik and Boone (1987) observed that excessive cracking of board ends, areas surrounding knots, and cracks in large rays decreased as the wet-bulb temperature (WBT) decreased. A detailed investigation of 12 wood species dried at 110°C HT drying or a combination of conventional drying, below 82.2°C, from green to 20% MC and then dried at 110°C to final MC of 6-8%, was performed by Boone (1984). The results of HT drying are summarized in Table 1, indicating the location of drying defects in relation to sapwood, heartwood, natural defects, and severity of defects in unacceptable boards. The combination of the conventional with HT drying decreased the drying degradation, but increased kiln residence time over the HT drying schedule alone.

In the case of Scots pine sapwood boards dried at HT in the range of 110-180°C, Schneider (1973) found no surface cracking on the longitudinal surfaces without collapse and without warping, but internal cracking occurred in many cases. In the case of beech wood, the occurrence of internal cracking was much higher, compared to pine wood.

Table 1. Location of Drying Defects in Relation to Sapwood, Heartwood, and Natural Defects; Response to High-Temperature (ht) Drying from Green and Severity of Defects in Unacceptable Boards by Percentage (Boone 1984)

Wood species	Ratio sapwood and heartwood in boards	Primary defect and location	Response to HT Drying from green	Severity in un-acceptable boards % rated as slight (1)
Fraxinus americana	Mostly heartwood	Honeycomb (HC) around knots in sapwood and heartwood	Suitable	75
Tilia americana	Mostly sapwood	HC around knots	Suitable	75
Fagus grandifolia	Mostly heartwood	HC all surfaces	Unsuitable	76
Prunus serotina	Mostly heartwood	HC all surfaces especially around knots	Unsuitable	51
Nyssa sylvatica	40:60	HC; more in sapwood; around knots	Intermediate	85
Populus deltoides	80:20	HC and collapse	Intermediate	74
Ulmus americana	Mostly heartwood	HC in heartwood, around knots; warp in heartwood	Intermediate	51
Acer saccharum	50:50	HC in sapwood and heartwood, slightly more in sapwood	Unsuitable	64
Acer rubrum	50:50	HC in sapwood and heartwood, slightly more in sapwood	Suitable	75
Carya sp.	Mostly heartwood	HC all surfaces	Unsuitable	81
Liquidambar styraciflua	Mostly sapwood	HC more in sapwood than in heartwood, around knots	Suitable	96
Liriodendron tulipifera	50:50	HC in heartwood around knots, pin knots and pith	Suitable	74
(1) Slight equals 1% severity of defects related to 25 % area of board				

Collapse and internal cracking are important defects often found after drying in the timber of several wood species. Using a stress and drying model it has been demonstrated by Innes (1996) that in order to avoid collapse cracking, the timber of *Eucalyptus regnans* should be dried at temperatures below the critical temperatures for collapse of both the earlywood (26°C) and the latewood (could not be determined, but it collapsed at an ambient temperature of 20°C) until all parts of the wood were below the fiber saturation point (FSP). This comes in accordance with the study performed by Neumann and Saavedra (1992), who found that cracking inside the boards of *Eucalyptus globulus* wood dried from a green state will be reduced significantly if the initial drying temperature is as low as possible, preferably below 30°C. A study performed by Ilic

(1999) contradicts the concept of critical collapse temperature (Innes 1996), while for drying *Eucalyptus regnans* below temperatures of 24-30°C, the collapse and cracking were not eliminated.

A one dimensional stress model incorporating the various strain components was developed by Chen et al. (1997) based on a physically realistic model of HT drying behavior of *Pinus radiata*. The drying of sapwood is assumed to be characterized by two principal stages, first dominated by an evaporative front receding into the board, and the second dominated by bound water and vapor diffusion. As the drying proceeds, a progressive fall in the relative liquid permeability of wood is observed. The sapwood consistently loses liquid continuity at about 60% of the local MC, which is significantly higher than the FSP. The moisture in the evaporative zone is driven by a small, but adequate vapor pressure difference between irreducible saturation and the FSP, which corresponds to an equilibrium moisture content (EMC) of 99%. The wood is assumed to be a viscoelastic material with its mechanical properties varying with both temperature and MC. Also under HT conditions the wood may be capable of sustaining some extent of the plastic strain after passing through the yield point, without cracking. Cracking is assumed to occur only after the ultimate stress is exceeded.

Hanhijärvi et al. (2003) found a way to detect the development and growth of micro-cracks on the wood surface during early stages of drying by applying focused laser beam reflected intensity measurements on Scots pine (*Pinus sylvestris L.*). The results showed that by increasing the temperature from 30°C (for 24 h) to 50°C (for 6h) and 80°C (for 6h), the development of cracks increased compared to air drying at room temperature (20°C, for 26h). Furthermore, results showed that drying under dry conditions produces more cracks than drying under humid conditions. The development of internal cracking of spruce wood (*Picea abies*) heat treated at 212°C with several steps applied at different temperatures and time durations was also studied (Johansson 2006). Boards pre-dried to initial 18% MC, and dried in the secondary step at 212°C for 12h showed severe internal cracking, compared to 18 or 24h duration or pre-dried to lower initial MC (6%). Problems in terms of internal cracking can be encountered in the case that pith is present in the cross section of the board.

Possible Pre-treatments to Reduce Cracking

The steaming or pre-heating of wood prior to drying has generally been considered to reduce drying time and increase drying rate (Mackay 1971; Alexiou et al. 1990; Ananias et al. 1995; Chafe and Ananias 1996). It was suggested that after high temperature drying, collapse might be recovered by steam reconditioning (Chafe 1995; Innes 1996). Mackay (1971) stated that these treatments have a double effect. First, chemical changes take place due to acid hydrolysis, which causes re-crystallization of cellulose and relocation of extractives. Second, the physical collapse and recovery of individual cell walls would respectively decrease and then increase porosity through closing by a crumpling action and re-opening by an expansion of the cell cavities through which the diffusion occurs. The duration of steaming is also important. A longer steaming period was found to lead to a decreased equilibrium moisture content (EMC) of red oak (Kubinsky and Ifju 1974) and European beech wood (Schmidt 1982a, b), because the degradation processes of hemicelluloses already had occurred due to the influence of elevated temperatures.

Esteves et al. (2007) tested pine (*Pinus pinaster*) and eucalyptus (*Eucalyptus globulus*) wood by steaming it for 2 to 12 hours at 190-210°C and found the MOE to be very little affected by steaming, but the bending resistance was reduced. Chafe and Ananias (1996) found that the steaming of green boards of *Eucalyptus regnans* at 100°C for 1, 2, 4, and 8 hours caused an increase in the drying rate during HT drying. For *Eucalyptus globulus* no significant increase was evident. For *Eucalyptus regnans* wood species boards of radial/intermediate grain orientation, a positive relationship between average evaporable moisture available during drying and basic density showed density to be a negative influence on the drying rate. In the case of tangentially oriented material, both the size and number of internal cracks declined after the first preheating step (50°C), whereas in radial/intermediate material the size and number of internal cracks increased at 50°C before subsequently decreasing. These patterns were evident for a pre-steaming period up to 2 to 4 hours.

A high external shrinkage is associated with higher internal cracking, which is reversed in the study performed by Chafe (1995), where increased shrinkage was accompanied by a decrease in internal cracking. The difference might be due to the severity of drying conditions in the study performed by Chafe and Ananias (1996), while in Chafe (1995) the drying was done more gradually (30°C and 67% RH), and preheating was carried out at various temperatures in water rather than by pre-steaming.

In the case of *Eucalyptus pilularis* heartwood boards steamed in saturated conditions at 100 C for 3 hours after a one hour heating-up period, the drying rate was increased by 7-16%. A partial removal of extractives during pre-steaming was found, which allowed greater access of water molecules to cell walls resulting in rapid radial and tangential diffusion during drying. Longitudinal permeability was not found to be influenced significantly by the pre-steaming treatment, as tyloses appeared unaltered and also volumetric shrinkage was unchanged by pre-steaming (Alexiou et al. 1990).

For the Chilean eucalyptus species (*Eucalyptus globulus*), preheating in a water-saturated atmosphere at 80°C can have a beneficial effect in collapse recovery and relief of drying stresses. The drying rate is also increased by about 7% in the preheated material. Initial MC and/or the MC at the moment of reconditioning also appear to be of importance (Ananias et al. 1995).

Ward and Groom (1983) studied bacterial infected heartwood of red oak (*Quercus rubra L.*) and concluded that, compared to the normal wood, it is more prone to develop surface defects, honeycombing, and ring failure when kiln dried (at 52-82.2°C) or under mild heating conditions (40.5-82.2°C) to 8% MC from green state. In order to minimize the weight losses, pre-drying should be applied down to 25% MC with mild conditions of drying at 32.2°C and 60% RH.

Barnes and Taylor (1985) found no correlation between cracking patterns of southern pine veneer cores and drying schedules such as conventional schedule (82.2°C), HT drying (DBT=118.3°C, WBT=74°C), or HT drying in superheated steam (118.3°C) at atmospheric pressure. The number of cracks, length and width were weakly correlated with specific gravity, and their magnitude was reduced after three month's storage.

Wood species density might influence the occurrence of internal cracking and collapse. In the case of *Eucalyptus regnans F.Muell.*, Ilic (1999) found that material with high mean basic density above 530 kg/m³ was associated with low levels of internal cracking and collapse. However, the highest expected density (640 kg/m³) corresponding to the complete elimination of collapse and hence of internal cracking in *Eucalyptus regnans*, is greater than the highest naturally occurring density of species (580 kg/m³). This provides support for the proposition that other eucalypt species of similar structure, but of higher density are less collapse prone.

In the case of small diameter wood, Chestnut (*Castanea sativa Mill.*) presents good mechanical properties, but shows cracking during drying. Even though previous studies showed that lower temperatures of hot oil bath treatments of 110°C increased the shrinkage values and above 140°C lead to critical collapse, the study performed by Berard et al. (2006) showed different results. Green logs of chestnut wood (with 55-75% MC) with a diameter of 70 and 160 mm were subjected to hot oil bath treatments for 1 hour at 130°C temperature in rapeseed and linseed oil (boiling points near 400°C). A 75% reduction of cracks with a better efficiency for small diameter logs was observed. In the case of treated logs with a greater diameter very narrow end cracks located at the heart were observed. Moreover, this heart cracking occurs during oil treatment due to hydrothermal recovery phenomena, thus the surfaces generated by this cracking process will also be protected against tannin leaching by a thin oil impregnation (Berard et al. 2006).

INFLUENCE OF TEMPERATURE ON THE MECHANICAL PROPERTIES OF WOOD DURING DRYING

Kiln drying of wood is one of the most important drying methods used in commercial applications throughout the world. The behavior of wood during the drying process depends on the drying conditions in the kiln (e.g. ambient temperature, relative humidity, and air velocity) and on the properties of the wood itself (e.g. density, chemical composition) (Möttönen 2006). Some problems related to air drying methods, such as long drying times, costs, and drying defects, can be overcome by alternative methods, such as low-temperature (LT) drying and high-temperature (HT) drying (Bekhta and Niemz 2003).

The influence of the drying temperature during conventional and high temperature drying on mechanical properties has been investigated for a long time. A summary of these results is presented in Table 2.

Thompson (1969) found that the clear size specimens of Southern pine wood kiln dried at temperatures of 66.7°C and 83.3°C showed a reduction of MOE and compression strength up to 1.6% and up to 6.1%, respectively, for an 83.3°C kiln drying schedule compared to a 66.7 C kiln drying schedule.

Drying at high temperatures may result in hydrolysis of the cellulose and other chemical compounds in wood, and subsequently in a permanent reduction of mechanical properties. A summary of the work done until 1969 is presented by Salamon (1969) concerning the effect of temperature on the strength properties of wood. It is shown that the effect of elevated drying temperature on wood strength varied among species and strength properties, namely some species did not lose strength when dried at high temperatures, while others lost 7 to 20% compared to conventionally dried samples. Several findings were apparent, namely decrease in shear or tensile strength perpendicular to the grain, unchanged static bending strength, or influence of high temperature drying on toughness, which can be higher or lower compared to conventional drying.

Early research studies (Ladell 1953; Combem 1955; Petri and Ananyin 1960; Schneider 1973; Yao and Taylor 1979; Gerhards 1983) showed that an increase of temperature will not affect the mechanical properties of wood (hardwoods and softwoods) significantly; but later intensive studies (Hillis 1984; Zhou and Smith 1991; Sehlstedt-Persson 1995; Kubojima et al. 2000; Terziev and Daniel 2002; Thiam et al. 2002; Bekhta and Niemz 2003; Müller et al. 2003; Junkkonen and Heräjärvi 2006; Poncsák et al. 2006; Frühwald 2007) proved the influence of temperature on the mechanical properties of wood.

Schneider (1973) found a slight reduction in the compression strength parallel to the grain of Scots pine sapwood samples dried at HT in the range of 130-180°C, but an increase was detected in the case of beech wood samples. In the case of modulus of rupture (MOR), a reduction was observed for both species with increasing temperature (Table 2). Teischinger (1992) found that MOE and MOR of spruce wood (*Picea abies*) show a less significant influence of the drying temperature during drying. However, conventional drying schedules at 50°C and HT drying (100-110°C) showed a significant influence on the EMC and shrinkage behavior of wood. No effect of HT drying (115°C) on the strength properties (MOE, MOR) of red alder (*Alnus rubra Bong*.) compared to conventional drying (54.4-71.1°C) was found by Layton et al. (1986).

A survey of papers is presented by Teischinger (1992) concerning the temperature influence during drying on mechanical properties of wood, which includes the work performed by several scientists: Salamon (1969); Gerhards (1979); Yao and Taylor (1979); Gerhards (1983) and Zhou and Smith (1991). In Table 2 an up-to-date summary is presented according to the softwood and hardwood species tested.

Gerhards (1979) dried Douglas fir by using three different kiln schedules. It was found that average tensile strength was 10% lower with progressive LT-HT schedules (up to 110°C) and 18% lower with constant HT (110°C) than with conventional schedules (not exceeding 85°C). The study shows that tensile strength is significantly affected by the type of kiln schedule, while MOE is not. This agrees closely with the results from other studies reviewed by Gerhards (1979) or some having somehow different experimental design and longer kiln schedules (Kozlik 1976). Kifetew et al. (1998) and Thuvander et al. (2001) reported a higher loss in tensile strength of about 50% due to drying. Millett and Gerhards (1972) observed that long exposure (60 days) at high temperature drying (110°C) leads to strength and mass loss of about 15% and 2%, respectively, represented by a clear reduction of MOR.

Kubojima et al. (2000) performed bending strength tests on Sitka spruce wood (*Picea sitchensis Carr.)* to determine the influence of heat treatment at 160°C for 0.5 hours up to 16 hours in nitrogen gas and air on the mechanical properties of wood. The results showed that MOE, the bending strength, and the energy absorbed in impact bending increased at the onset of the heat treatment and decreased later. The MOR decreased steadily as the heat treatment time increased, which was thought to be the cause of the plastic and not the elastic behavior of wood.

Table 2. Strength Properties Reduction (%) of Different Wood Species Influenced by Temperature during Drying (according to Teischinger 1992 and updated) #

Botanical Name	T(°C)	MOR	MOE	CS	SS	Reference
Softwoods						
Abies balsamea	116	16				Cech, Huffman (1974)
Larix decidua	120	0	0			Frühwald (2007)
Larix decidua	170	0	0			Frühwald (2007)
Larix decidua	190	0	0			Frühwald (2007)
Picea abies	103	9.1	7.1	6.7		Müller et al. (2003) *
Picea abies	110	0	0			Teischinger (1992)
Picea abies	115	9.5	0			Bengtsson, Betzold (2000)
Picea abies	116	s.r.		s.r.		Egner (1952)
Picea abies	120	11.5	0			Bengtsson, Betzold (2000)
Picea abies	120	5.5	0			Frühwald (2007)
Picea abies	170	7.4	0			Frühwald (2007)
Picea abies	190	2.3	0			Frühwald (2007)
Picea abies	200	44 - 50	0			Bekhta, Niemz (2003) **
Picea abies	210	16	d.r.			Frühwald (2007)
Picea glauca	116	4	3			Cech, Huffman (1971)
Picea glauca	116	10				Cech, Huffman (1974)
Picea glauca	160-180	13.7	15			Zhou, Smith (1991) **
Picea sitchensis	138	d.r.		0		Köhler (1933)
Picea sitchensis	160	s.r.	s.r.			Kubojima et al. (2000)
Pinus banksiana	116	16				Cech, Huffman (1974)
Pinus contorta	104	5	i. 2		2.5	Troxell, Luza (1972)
Pinus contorta	104	10	3		9.6	Troxell, Luza (1972)
Pinus palustris	100	8	i.6			Thompson Stevens (1972)
Pinus palustris	107	14	i.13			Thompson Stevens (1972)
Pinus palustris	110	0				Comstock (1963)
Pinus palustris	116	4				Koch (1971)
Pinus palustris	116	0	0			Yao, Taylor (1979)
Pinus palustris	83.3		1.6	6.1		Thompson (1969)
Pinus sylvestris	60	17.2	12.8			Terziev, Daniel (2002)
Pinus sylvestris	100				3	Sehlstedt-Persson (1995)
Pinus sylvestris	110			→9	→12	Leont'ev et al. (1957)
Pinus sylvestris	110	3		0		Schneider (1973)
Pinus sylvestris	115				17	Sehlstedt-Persson (1995)
Pinus sylvestris	115	7.8	5.4			Terziev, Daniel (2002)
Pinus sylvestris	116	0	0			Comben (1955)
Pinus sylvestris	121		0			Petri, Ananyin (1960)
Pinus sylvestris	130	0		i. 1		Schneider (1973)

Pinus sylvestris	130	8		6		Schneider (1973)
Pinus sylvestris	150	7		i. 2		Schneider (1973)
Pinus sylvestris	150	30		7		Schneider (1973)
Pinus sylvestris	180	19		2		Schneider (1973)
Pinus sylvestris	180	32		2		Schneider (1973)
Pseudotsuga menziesii	94	3	1			Graham (1957)
Pseudotsuga menziesii	104	7	8			Graham (1957)
Pseudotsuga menziesii	107	10	5	i.6		Eddy Graham (1955)
Pseudotsuga menziesii	110	→15				Comstock (1963)
Pseudotsuga menziesii	110	→20	0			Kozlik (1968)
Pseudotsuga menziesii	110	5	12		15-20	Kozlik(1967)
Pseudotsuga menziesii	110	17		→14		Salamon (1963)
Pseudotsuga menziesii	121	13	2	12		Eddy Graham (1955)
Tsuga canadensis	71-113	0-s.i.		0-s.i.		Salamon (1965)
Tsuga canadensis	107	0		0		Salamon (1965)
Tsuga canadensis	>100	0				Ladell (1953)
Tsuga heterophylla	110	0	0			Kozlik (1968)
Tsuga heterophylla	110	12	4		8	Kozlik(1967)
Tsuga heterophylla	116	8.1	0		14	Thiam et al. (2002)
Hardwoods						
Alnus rubra	115	0	0			Layton et al. (1986)
Betula alleghaniensis	102-104		s.r.			Ladell (1956)
Betula papyrifera	200-230	d.r.	0			Poncsák et al. (2006)
Fagus sylvatica	110	4		i.3		Schneider (1973)
Fagus sylvatica	116	s.i.	s.i.	s.i.		Keylwerth (1952)
Fagus sylvatica	130	7		i.3		Schneider (1973)
Fagus sylvatica	150	9		i.16		Schneider (1973)
Fagus sylvatica	180	23		i.4		Schneider (1973)
Liriodendron tulipifera	113	0	i.4			Gerhards (1983)
P. tremula x tremuloides.	180	13.7	i. 2.5	i. 13		Junkkonen, Heräjärvi (2006)
Populus tremula	180	8.5	i. 12.7	i. 12.5		Junkkonen, Heräjärvi (2006)

Legend: SS-shear strength; CS-compression strength; MOR-modulus of rupture; MOE-modulus of elasticity; d.r.-definite reduction; d.i.- definite increase; s.r.-slightly reduced; s.i.-slightly increased; i. -increased; → up to
Values given are compared to low or normal temperature drying (exceptions: *-compared with DIN 68364 (1979); **-compared with HT-drying). Due to incomplete information, strength adjustments for moisture content differences were not made.

The influence of high temperature drying on the mechanical properties of Norway spruce was also studied by Bengtsson and Betzold (2000), who used three drying schemes, high temperature (HT-115°C), low/high temperature (L/HT-70 C/120°C), and low temperature (LT-75°C). Four-point bending tests were performed in order to observe the influence of temperature during drying on the bending strength and stiffness of wood. The results showed that, on the average, the bending strength decreased by 11.5% and 9.5% for the specimens dried by a combined L/HT drying scheme and a HT drying scheme, respectively, compared to a LT drying scheme. No effects of HT drying on the bending stiffness were found.

Western hemlock was dried using conventional (82°C) and accelerated (116°C) kiln schedules to determine the influence of temperature on the mechanical properties of wood. The accelerated drying schedule reduced the base design bending stress by 8.1 % and shear stress by 14.0 %, while the allowable stiffness was not affected (Thiam et al. 2002).

The effect of HT drying on mechanical properties, dimensional stability, and color of spruce wood were investigated by Bekhta and Niemz (2003). The wood specimens conditioned at different RH (50, 65, 80 and 95%) were subjected to heat treatment at 100, 150, and 200°C for different time periods. The results showed that heat treatment mainly resulted in a darkening of wood tissues (the greatest darkening occurred in the first 4h of exposure), improvement of dimensional stability of wood, and reduction of its mechanical properties. The average decrease in bending strength of samples dried at 200°C compared to samples dried at 110°C was about 44-50%, while MOE was not affected in this case. It was found that the treatment time and temperature were more important than the relative humidity regarding the color responses. Strong correlations between total color differences and both MOE and bending strength were found.

Müller et al. (2003) tested macroscopic spruce samples (*Picea abies L.*) in bending and compression parallel to the grain in green state and oven dried (103°C)/re-moistened by three vacuum cycles (25 mbar, with a MC higher than 160%). In bending, a highly significant reduction of 10% for MOE and 16.5% for MOR was found for dried/re-moistened samples, compared to fresh ones. Compression tests showed 15% lower compression strength for spruce samples, compared to fresh ones, while the MOE was not altered. In the case of microscopic spruce samples, tensile and compression tests were performed with samples oven dried (103°C) and air dried (for 3 days at 20°C)/re-moistened by two cycles of water vacuum impregnation (10 min, 25 mbar, resulting in an MC=210-220%). The oven dried/re-moistening procedure leads to a 9.8% and 14.9% lower tensile and compression strength respectively compared to the air dried/re-moistening procedure. For air dried/re-moistened samples, compared to fresh ones, no difference in tensile strength was found, but for the compression strength a 10% reduction was observed. The results of this study compared to the ones of DIN 68364 (1979) shows strength losses of 9.1% for bending, 6.7% for compression, and 7.1% for tensile strength testing.

Frühwald (2007) kiln dried spruce and different larch species to 6% MC at 80, 120 and 170°C. The experiment was complemented by heat-treated spruce (Thermowood®), which had been treated at 190 and 210°C in an industrial process. The results (Table 2) showed that the temperature affects some properties; however, the results were not equal for all species; e.g., with larch MOE and MOR were not influenced by the drying temperature, which was probably due to the small sample size, resulting in high variation.

INFLUENCE OF OCCURRING AND DEVELOPING CRACKS ON THE MECHANICAL PROPERTIES OF WOOD DURING KILN DRYING

Generally speaking, the mechanical properties of wood are influenced by the occurrence of internal cracks during drying at different levels of temperature. There are few research papers which deal with the correlation between these two issues (Graham and Womack 1972; Schneider 1973; Kozlik 1982; Terziev and Daniel 2002; Hanhijärvi et al. 2003; Poncsák et al. 2006).

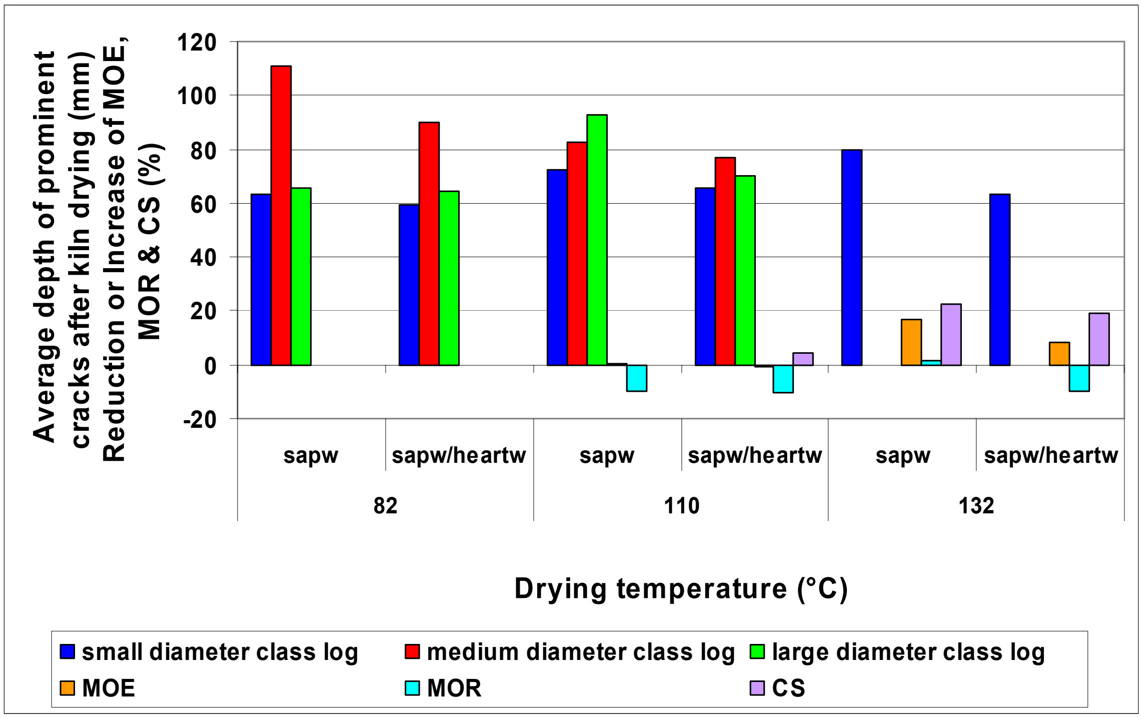
Douglas fir was dried using different drying schedules in order to establish the effect of the drying temperature on the mechanical strengths and cracking (Graham and Womack 1972, Kozlik 1982).

Graham and Womack (1972) dried 2.4 m length Douglas fir timber at high temperatures (104°C, 124°C, 143°C) and the width of the cracks that occurred after drying were 2.5 mm, 7.2 mm and 5.5 mm, respectively. The size of surface cracks was believed to be caused by the stress relieving effect of internal cracks formed just beneath the wooden surface. A strength reduction of at least 10% was assumed to be expected (real value not given). Similar results were recorded by Kozlik (1982), who studied the effects of three drying schedules on the occurrence of cracks in Douglas fir logs and the changes in mechanical properties of clear wood specimens. The results of his work are summarized in Fig. 2.

Recent studies of Terziev and Daniel (2002) showed that conventional kiln drying had only minor effects on the microstructure of Scots pine wood (*Pinus sylvestris*). The HT drying (115°C) partly damaged the apertures of some bordered pits, provoking nano- (10-20 nm) and micro-cracks (1-2 μm) in the warty and S3 layers of cell walls, and probably modified the structure of the polymer structure in order to facilitate the penetration of liquids. Impact bending strength, hardness, MOE, and MOR tended to decrease regardless of the drying method, while only the MOR was significantly reduced in the case of conventional drying.

Poncsák et al. (2006) studied the effect of high temperature with humid (100 g water vapor/m³) and dry gases on the mechanical properties of birch wood (*Betula papyrifera*). Birch wood dried at HT (220°C) in water vapor showed no failure, such as crack formation during drying. In the absence of humidity in the heating gas, one to three cracks per samples were observed and also an increase in the weight loss rate. The reason might be that if the humidity of gas is low, then the difference between the moisture content of the gas and the initially humid wood (moisture concentration gradient) is high.

This increases the moisture removal rate and might cause crack formation in wood, especially around the knots. The influence of drying temperature and the occurrence of cracks on the MOE and MOR of several wood species is shown in Table 4.



Legend: MOE-modulus of elasticity; MOR-modulus of rupture; CS-compression strength; sapw, sapw/heartw – sapwood, sapwood in combination with heartwood

Figure 2. Effect of temperature drying schedules on the occurrence of cracks in different log diameter classes of Douglas fir, on sapwood or combination of sapwood and heartwood and the increase or decrease in mechanical properties after drying compared to conventional drying (82 °C) (Kozlik 1982)

As was shown by Hanhijärvi et al. (2003), an increase in temperature of 30°C up to 50°C and 80°C for different time periods increases the development and occurrence of cracks, compared to air drying at room temperature (20°C). Furthermore, results showed that drying under dry conditions produces more cracks than drying under humid conditions.

Table 4. Research Work Concerning the Occurrence and Development of Cracks and Changes in Mechanical Properties of Wood during Drying at Different Temperatures

Author	Wood species	Drying Temperature	Cracking	Mechanical properties
Schneider (1973)	*Pinus sylvestris* (20 mm sapwood)	110-180°C	no surface cracking on the longitudinal direction, no warping or collapse, but internal cracking occurred in many cases	no reduction in compression strength
	Fagus sylvatica (20 mm sapwood)	110-180°C	no surface cracking on the longitudinal direction, no warping or collapse, but internal cracking occurred in many cases	small increase in compression strength compared to control samples
	Pinus sylvestris and *Fagus sylvatica* (40 mm)	110-180°C	for beech wood a higher number of internal cracks occurred compared to Scots pine	5% decrease in compression strength
Terziev and Daniel (2002)	*Pinus sylvestris*	60°C	no micro-cracks are observed, or damage of pit apertures	reduces MOR significantly
		115°C	provoke nano (10-20 nm) and micro-cracks (1-2 μm) in the warty and S3 layer of cell walls	no critical reduction of impact bending, strength, hardness, MOE and MOR
		<100°C		reduces MOR significantly
Poncsák et al. (2006)	*Betula papyrifera*	200-230°C (in humid inert gas)	no cracks were detected	MOR decreases with an increase in temperature
		220°C (in dry gas)	one to three cracks/sample occurred	MOE is not affected significantly

CONCLUSIONS

This review attempted to summarize the work done on the influence of temperature and the occurrence of cracks during drying on the mechanical properties of wood. Due to large differences in the conditions under which temperature levels were compared and the variety of wood species tested in the different studies, it was possible to show a general trend, but not a universally valid picture to what extent the properties will change at a certain temperature level and what the impact is on the occurrence and development of cracks in timber during drying.

Negative outcomes during elevated temperature drying processes are the depolymerization of hemicellulose resulting in reduced hygroscopicity and further loss of strength and increase in brittleness of treated wood. By increasing the drying temperature, the moisture gradients increase, which leads to high internal stresses that are released as cracks. The crack formation in wood during drying might differ due to different parameters such as the drying schedule, moisture content of wood, the microstructure of different wood species, and dimension of samples tested.

In general, it could be concluded that drying temperature has a greater effect on the reduction of the modulus of rupture compared to the modulus of elasticity, which is only slightly reduced. A different behavior of hardwood and softwood species in general could not be noticed, but it should be elaborated more widely due to the fact that most of the papers mainly focused on high temperature drying of softwoods.

A critical general temperature when the mechanical properties start to decrease could not be stated, due to the time dependence behavior during wood drying, but also due to wood species behavior. It is generally known that mechanical properties depend on the time duration of the high temperature drying process, but information of the influence of time at lower temperature ranges could hardly be found in the literature concerning mechanical properties or cracking behavior. In general, conservative drying schedules (e.g., low temperatures and low drying rates) would affect the mechanical properties to a lesser extent compared to severe drying schedules, but the longer drying durations used would not lead to economical processing. An optimum compromise has to be found for each specific wood species and product.

Surprisingly, only few papers dealt with the influence of temperature during drying on both the mechanical properties of wood and on the occurrence of cracks. Usually research was conducted either on one issue or the other, but the important correlation between the influence of temperature and the occurrence of (micro-) cracks and their influence on the mechanical properties was seldom found as the main focus of the research. It is evident that both degradation of wood components by temperature and cracking could have a distinct influence on the mechanical properties of wood. As both factors can occur together or separately, it would be important to know to which extent both of them are responsible for any change in mechanical properties. Of course it is known that the problems of degradation and cracking increase with increasing temperature, but the majority of studies which examine that problem deal with high temperature drying or even thermal treatment. In the lower or normal temperature region for wood drying these effects have not been analyzed in a very detailed way up to now, which would be especially important for the upper region of normal temperature drying. This would be an interesting direction for further work.

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