21 Wood Modification

Throughout history, wood has been used for the construction of homes and other structures, furniture, tools, vehicles, and decorative objects. Wood is used to produce a variety of products, including cut and dressed poles, sawn and dressed planks, veneers, laminated products, particleboard, fiberboard, paper and cardboard.
The anatomy and growth behaviour of trees clearly influences the properties and behaviour of wood. A cross section of a tree trunk (Figure 21.1) shows the well defined features of most trees (Forest Products Laboratory 1999):

1. ***bark***, which may be divided into an outer corky dead part, whose thickness varies greatly with species and age of trees, and an inner thin living part, which carries food from the leaves to growing parts of the tree;
2. ***wood***, which in merchantable trees of most species is clearly differentiated into sapwood and heartwood; and
3. ***pith***, a small core of tissue located at the center of tree stems, branches, and twigs about which initial wood growth takes place.

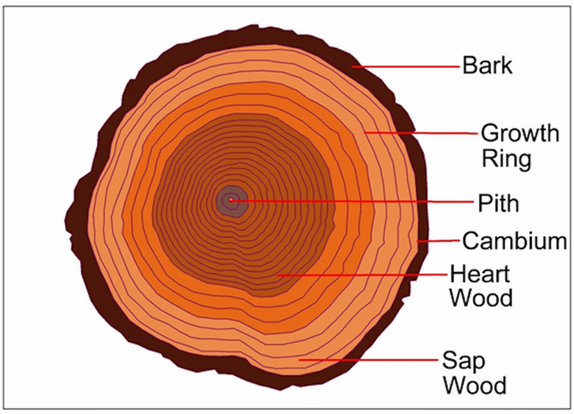

Figure 21.1: Cross section of tree trunk (Source: Brodie 2008).

Sapwood contains both living and dead tissue and carries sap from the roots to the leaves (Jackson and Day 1989, Forest Products Laboratory 1999). Heartwood is formed by a gradual change in the sapwood and is inactive (Jackson and Day 1989, Forest Products Laboratory 1999). Rays, which are horizontally oriented tissue running from the pith to the cambium, vary in size from one cell wide and a few cells high to more than 15 cells wide and several centimetres high (Jackson and Day 1989, Forest Products Laboratory 1999). The cambium layer is inside the inner bark and forms both wood and bark cells. The cambium layer can only be seen with a microscope (Jackson and Day 1989, Forest Products Laboratory 1999).

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The macroscopic structure of wood can be described in terms of early wood and later wood, longitudinal tracheids, rays, resin channels in softwoods and vessels in hardwoods (Meyland and Butterfield 1972, Jackson and Day 1989, Torgovnikov 1993). Some of these elements are illustrated in Figure 21.2.

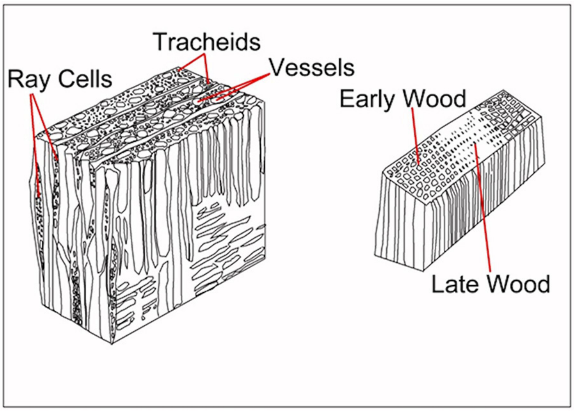

Figure 21.2: Macro-structural elements of wood (Source: Brodie 2008).

The appearance of growth rings, associated with the deposition of early and late wood, is due to structural changes in the wood cells produced by the cambium through the growing season (Jackson and Day 1989). Cells produced at the beginning of the growing season are usually larger, and so this early wood appears less dense than the late wood produced towards the end of the season.

Although all trees produce concentric layers of wood, not all trees produce visible growth rings, neither are all growth rings necessarily annual (Jackson and Day 1989). In some trees seasonal changes in wood structure may be so slight that growth rings are not evident. Under conditions of severe drought a visible growth ring may not be produced at all. On the other hand, under continuously favourable conditions, such as in the tropics, several growth rings may be produced in a single year (Society of Wood Science and Technology 2001).

Moist wood is essentially a heterogeneous mixture of solid, liquid and gaseous materials. Wood cells are built up as a honeycomb like structure oriented along the stem, except in the case of ray cells. The cell wall is a composite material consisting of partly crystalline cellulose micro-fibrils embedded in an amorphous matrix made up of hemicelluloses and lignin (Torgovnikov 1993, Forest Products Laboratory 1999).

At the micro-structural level, wood can be described in terms of longitudinal tracheids, pit pairs, which connect between tracheids, the primary cell walls and the secondary cell walls (Meyland and Butterfield 1972, Hofstetter, *et al.* 2007). Hardwoods

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contain vessel elements (Forest Products Laboratory 1999) while softwoods often contain resin channels (Jackson and Day 1989). The orientation of wood cells profoundly affect all the measurable properties of wood (Torgovnikov 1993).

A vessel is a wood cell with open ends. When vessel elements are set one above another, they form a continuous tube (vessel), which serves as a conduit for transporting water or sap in the tree. Vessels may extend to the full height of the tree; however they more commonly only extend over short distances (< 200 mm) in most species (Forest Products Laboratory 1999). Tyloses are balloon-shaped intrusions (Meyland and Butterfield 1972) that appear in hardwood vessels at the time of heartwood formation. They extend from the parenchyma cells into the vessels and have the effect of blocking or clogging vessels that have been damaged by cavitation in the water column inside the vessel (Forest Products Laboratory 1999, Jackson and Day 1989).

At the molecular level, wood must be described in terms of polymers, free and bound water, extractives, minor amounts (5% to 10%) of extraneous materials contained in a cellular structure and air (Meyland and Butterfield 1972, Hofstetter, *et al.* 2007). The polymers of wood can be classified into three major types: cellulose, hemicellulose, and lignin. The proportion of these three polymers varies between species (Society of Wood Science and Technology 2001). Variations in the characteristics and volume of these components and differences in cellular structure make woods heavy or light, stiff or flexible, and hard or soft (Forest Products Laboratory 1999).

Cellulose is the most important single compound in wood. It provides wood's strength. Cellulose is a product of photosynthesis (Knox, *et al.* 2001). In photosynthesis, glucose and other sugars are manufactured from water and carbon dioxide. The glucose is chemically changed to glucose anhydride by the removal of one molecule of water from each glucose unit. These glucose anhydride units then polymerize into long chain cellulose molecules that contain from 5,000-10,000 glucose units (Society of Wood Science and Technology 2001).

Hemi-celluloses are a group of compounds similar to cellulose, but with a lower molecular weight. The number of repeating end-to-end molecules in hemi-cellulose is only about 150 compared to the 5,000-10,000 of cellulose (Society of Wood Science and Technology 2001). Lignin is a complex, high molecular weight polymer whose exact structure varies. It is an amorphous polymer that acts as a binding agent to hold cells together. Lignin also occurs within cell walls to impart rigidity (Society of Wood Science and Technology 2001).

When timber is harvested, it is usually sawn before further processing takes place. There are several methods of sawing timber (Figure 21.3). in most cases, freshly sawn timber needs to dry before it can be used.

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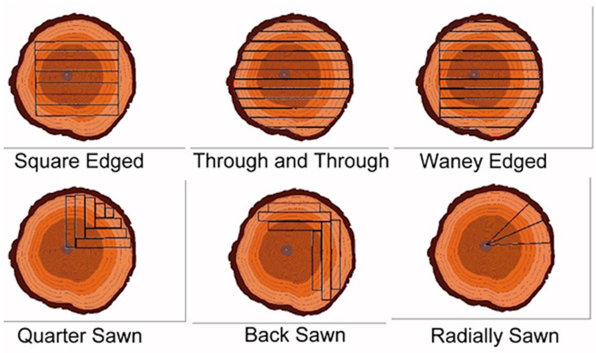

Figure 21.3: Various methods of sawing timber (Source: Brodie 2008).

21.1 Applications of Microwave Modification in Wood Drying

Emphasis in the Australian hardwood industry is shifting away from structural-grade timber toward the production of high-value products (Vermaas 2000). This is also true in China, Chile, Brazil, and South Africa, all of which have substantial eucalyptus-based hardwood industries (Vermaas 2000). The high shrinkage, low diffusivity, and highly refractory properties of many hardwoods and some softwoods make them extremely difficult to dry without drying defects, especially in back-sawn boards (Rozsa 1998). Drying defects include: splitting (often referred to as checking), warping, twisting, and collapse. To facilitate this shift in industry emphasis toward high-quality products, drying technology is once again becoming an important focus of research and development.

The first stage in the drying of timber from eucalypt species is usually a slow process involving a long period of air drying or pre-drying under mild conditions until the moisture content of the board approaches the fibre saturation point (FSP). However, even under the best controlled conditions surface checks, collapse of the cross section and internal collapse checks degrade a significant proportion of timber that would otherwise be used for appearance grade products (Rozsa 1995).

As wood dries below fibre saturation, the various polymers loose bound water and shrink. The drying rate varies across a sawn board's cross section; therefore the rate of shrinkage also varies. This induces drying stresses in the timber. When the local drying stress exceeds the tensile strength of wood perpendicular to the grain, the timber fibres separate. This is commonly referred to as checking. There are two types of checks that can develop: surface checks, which develop on the surface of a board and internal checks (or honeycombing), which develop within the board. Both types of defects can occur concurrently.

Surface checking usually develops during the early stages of drying when wood in the outer part, or case, of a section is low in moisture relative to the inner part, or core.

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Under these circumstances, shrinkage in the case leads to tension stress, which in turn may lead to surface checking. In some circumstances, readily observable surface checks may be removed by planning (Standards Australia/New Zealand 2001).

Refractory species are difficult to dry and are prone to surface checking, particularly when back-sawing techniques are used to produce usable boards. For example, checks in mature messmate (*Eucalyptus oliqua*) begin to appear on the surface after the loss of only a small proportion of moisture (Mackay 1972). The rate of moisture movement out of wood during drying is influenced by the permeability of the wood, which in turn is affected by the availability of unobstructed pathways from the core of the sawn timber to the surface. The presence of vessels in hardwood provides longitudinal pathways for moisture movement, chemical impregnation, drying, gluing, painting, cutting and other processes (Hillis and Brown 1984); however the presence of tyloses and incrustations in the vessels inhibits moisture and solvent movement through the material. The extent of direct contact between vessels and other elements is also important and is influenced by the nature of pits, which varies according to the contiguous elements.

Kanagawa, et al. (1992) developed an effective method to improve the permeability of Japanese cedar wood (*Cryptomeria japonica*) by generating steam inside the wood cells. The method, which is called Local Steam Explosion, heats and softens wood in a chamber using high-pressure super-heated steam and then instantaneously exhausts the steam from the chamber. The sudden release of pressure instantaneously boils free water in the wood cells. Permeability of the woody material is significantly increased due to the creation of local fractures in the wood cells. Steam pre-conditioning has also been used for some time to increase the permeability of *Pinus radiata* (D. Don); however, a substantial strength loss is often incurred (Vinden and Torgovnikov 2000).

Research into the application of microwave pre-treatment to green wood, as an alternative to steam pressure treatment (Vinden and Torgovnikov 2000, Vinden, *et al.* 2010, 2011), found that intensive short duration microwave irradiation can be used to modify the structure of refractory hardwoods by bursting the tyloses (increasing longitudinal permeability), rupturing ray cells (increasing radial permeability) and creating micro-voids at the fibre/ray intersection (also improving the radial permeability of timber). This modification results from a build-up of steam pressure in the moist green wood. The improvement in wood permeability facilitates faster drying, with potentially fewer drying defects.

Vinden et al. (2003) were granted a patent for this process, which describes a method for increasing the permeability of timber by applying microwave energy with power densities between 10 W cm^{-2} and 100 kW cm^{-2} for durations of between 0.05 and 600 seconds resulting in a permeability increases of at least 500% compared to that of untreated wood. The preferential Electric field orientation is perpendicular to the grain and aligned with the radial direction of the timber. Preheating the timber to a temperature of between 80 and 110°C before final microwave treatment also seems to be beneficial. A study carried out by Manríquez and Moraes (2010) showed

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that the molecular structure of moist lignin is modified and moist hemi-cellulous begins to soften when the temperature rises above 55 °C; therefore pre-heating of the green timber softens and weakens the cells that are targeted by the microwave preconditioning technique.

Vinden et al. (2007) described seven changes that occur in timber during microwave modification. Some of these included microscopic rupturing of pit membranes, tyloses, inter ray tissue and fibres, as well as macroscopic expansion of voids, resulting in an expansion of the cross section and a spongy wood product. Where these types of modification are not present after microwave treatment, the wood has simply been heated, but not modified, which still has applications for wood bending, sterilisation, drying, etc.

They later defined three levels of modification (Torgovnikov and Vinden 2008). Low level modification increases the permeability by 1.1 to 1.5 times; moderate modification increases the permeability by about a thousand times; and high modification converts wood to a highly permeable material with permeability increased by millions of times that of normal wood. Using a frequency of 2.45 GHz requires a power density of between 13,000 and 89,000 kW m^{-3} and energy densities between 270 and 1080 MJ m^{-3} to obtain the varying degrees of modification.

Any improvement in wood permeability has an impact on capillary flow of moisture (Hillis and Brown 1984). By increasing the permeability of wood, moisture is able to move more freely, ensuring the evaporative front is maintained close to the case of the board for a longer period during drying; therefore reducing tension stress in the wood and in turn preventing surface checking.

Harris et al. (2008) found that there was a significant reduction in surface checking, both in number and depth, in microwave modified messmate boards compared to the controls. Check assessment was carried out by comparing the total number of checks (including both internal/honeycombing and surface checks) per specimen. In addition a check area ratio (CAR) was calculated for each sample by dividing the total area of checks by the total sample cross sectional area (including the area occupied by the checks). The results indicate that microwave pre-treatment, prior to conventional drying, significantly reduced the total number of checks per specimen as well as reduced the CAR.

Brodie (2007) demonstrated that microwave treatment of *Populus alba* and *Eucalyptus regnans* prior to solar drying reduced drying time, compared with solar drying without microwave treatment, by 17% and 33%, respectively. This acceleration in drying may be attributed to a combination of the 8% to 9% reduction in wood density and a substantial improvement in moisture permeability associated with the internal fractures created in the wood structure.

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21.2 Improving Wood Impregnation

Vinden and Torgovnikov (2000) also developed a product formed under intense microwave irradiation which they named Torgvin. In this process, larger cavities are formed in the longitudinal-radial plane, expanding the cross section of the timber, resulting in a reduced oven dry density of up to 15% and increasing the radial permeability by 170 to 1200 times. The main application of this material is a composite product where resin is introduced and the wood is compressed back to its original dimensions (Torgovnikov and Vinden 2002).

Microwave energy between 1 MJ m^{-3} and 4,000 MJ m^{-3} was applied to moist wood, increasing the permeability and creating cavities. This was followed by drying, impregnation of the cavities with resin and compression of the wood to close the voids left by the microwave treatment and bond the resin to the fibres (Torgovnikov and Vinden 2002). The resulting composite material has a high strength and dimensional stability while in most cases looking like normal wood.

Vinden and Torgovnikov (2000) also found that moderate modification could improve preservative uptake. A 60kW, 922 MHz microwave source was used to treat softwood as it was fed through on a conveyor. While modification of 90mm x 90mm heartwood was achieved using 7.5 kW, they demonstrated that using between 54 and 57 kW gave the best results. Energy densities of 421 MJ m^{-3} were required to make Douglas fir heartwood permeable, increasing preservative uptake by a factor of 5 to 6.

Similar results were reported in hardwoods, where intensive microwave treatment resulted in rupture of tracheids and libriform fibres in the ray tissue, formation of micro-checks at the interface of the ray tissue and longitudinal fibres and formation of voids in the longitudinal-radial plane. They found the resultant increase in permeability accelerated the drying process, relieved stresses, reduced check formation and improved impregnability.

21.3 Stress Relief

Carter et al. (2003) investigated the effect of a microwave treatment on growth stress in large rounds of *Eucalyptus globulus*. Microwave treated logs displayed considerably less crack formation than the control samples after air drying. They also showed negligible deformation in a prong test, indicating that internal stresses were relieved by microwave treatment. While the actual mechanism leading to the stress relief was not detailed, it could be due to a more even moisture gradient, or increased permeability, or heat softening of the timber to relieve the stresses.

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21.4 Industrial Scale Pilot Plant

Vinden et al. (2006) used a 300 kW microwave system consisting of three 100 kW applicators arranged radially around a conveyor for continuous processing of logs and sleepers. They found that power densities up to 30 kW cm^{-2} produced more consistent modification. They also found that energy requirements for commercial scale applications were lower than expected from laboratory experiments. This may have been due to the larger cross sections facilitating the build-up of higher pressures and temperatures within the wood structure, leading to a higher degree of modification, with a lower portion of the energy lost to vaporisation of the surface moisture. Energy densities of between 273 and 1,080 MJ m^{-3} were required depending on species, moisture content and degree of modification.

Further details were provided on the 300kW, 0.922 GHz, microwave plant for modification of sawn and round timber (Torgovnikov and Vinden 2006b). Power densities of between 0.05 and 30 kW cm^{-2} were reported to produce modification, with higher power intensity providing better control. Energy densities ranged between 300 and 2000 MJ m^{-3}. High velocity heated air flow and a cyclonic separator were used to remove moisture and wood particles from the applicator and prevent condensation. The costs of microwave modification were assessed and found to be acceptable to industry.

Torgovnikov and Vinden (2006a) reported further on their research into the microwave modification of timber. A conveyor style 57 kW microwave treatment plant was used to treat timber to create Torgvin from a number of species, with electrical energy consumption ranging between 432 and 1,080 MJ m^{-3}. Volumetric expansions of up to 15% and preservative uptakes of 10 times greater than control samples were achieved.

The strength of the timber in the tangential and radial direction was reduced as a function of the treatment energy density, with losses of up to 80% and 70% respectively in the modulus of rupture (MOR). A reduction in the tangential MOR of between 15% and 23% was required to achieve significant increases in permeability. Microwave treatment energy densities of between 288 and 576 MJ m^{-3} were suitable for a pre-drying treatment of Messmate (*Eucalyptus obliqua*). These treatments reduced the drying time for Messmate, using conventional drying systems, by up to 90%. All microwave treatments were performed at atmospheric pressure.

Vinden et al. (2010) utilised a 300 kW, 0.922 GHz conveyor fed microwave plant, to treat *Pinus radiata* railway sleepers up to 130mm x 260mm in cross section. Permeability was increased (measured by preservative uptake) allowing for subsequent impregnation of both the sapwood and heartwood with preservative. Microwave treatment power densities were in the range of 5000 to 8800 kW m^{-3} and energy densities were in the range of 250 to 550 MJ m^{-3}, with the wood starting at a moisture content of 31 to 35%. They found proper treatment required an energy density of 270 to 395 MJ m^{-3}, with higher energy densities leading to significant strength

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loss and deformation. Preservative uptakes, relative to control samples, increased by 1.7 to 4.5 fold, depending on preservative type.

21.5 Pre-treatment for Wood Pulping

Akhtar et al. (2004) were granted a patent on their invention of microwave treating logs prior to mechanical pulping, resulting in a decrease in pulping energy and increase in paper strength. They found that the microwave treatment of logs at 50 kW for five minutes resulted in increased porosity, with jets of steam escaping from the wood during treatment, suggesting a concurrent increase in permeability.

Lawrence (2006) demonstrated that application of intense microwave energy can reduce the density of *Eucalyptus obliqua* wood by up to 12 %, depending on microwave energy absorbed by the samples. Softwoods such as *Pinus radiata* can experience a more substantial change in density when exposed to the same energy levels (Lawrence 2005). This change in density associated with microwave treatment can reduce wood hardness by up to 54 % (Awoyemi 2003) compared to untreated wood. Brodie et al. (2011) found that microwave pre-treatment of sugar cane reduced the compressive strength of the cane to about 18 % of its original strength (the control samples). Scott and Klungness (2005) showed that using microwave preconditioning on logs, before reducing them to paper pulp, reduced total energy consumption in the wood pulping process by 15%.

Compere et al. (2004) also investigated the application of microwave pre-treatment to pulping logs and chips. They found that pulping energy and chemical consumption was reduced and up to 30% oversized chips could be processed, suggesting greater chemical penetration due to increased permeability from the microwave treatment.

This chapter has explored how microwave pre-treatment can rupture plant cells to facilitate faster movement of water, resins or solvents into or out of woody material. It has also shown how microwave pre-treatment can be used to soften woody material to reduce the energy required for down-stream processing. These same features can also be used to enhance extraction of other valuable products from plant materials. This will be briefly explored in the next chapter.

References

Akhtar, M., Lentz, M., Horn, E., Klungness, J. and Scott, C. 2004. *Microwave pre-treatment of logs for use in making paper and other wood products*. Patent No. US2004238134

Awoyemi, L. 2003. Effects of microwave modification on the hardness of *Eucalyptus obliqua* wood. *Journal of the Institute of Wood Science*. 16(3): 186-188.

Brodie, G. 2007. Microwave treatment accelerates solar timber drying. *Transactions of the American Society of Agricultural and Biological Engineers*. 50(2): 389-396.

Unauthentifiziert | Heruntergeladen 21.02.20 22:34 UTC

Brodie, G., Jacob, M. V., Sheehan, M., Yin, L., Cushion, M. and Harris, G. 2011. Microwave modification of sugar cane to enhance juice extraction during milling. *Journal of Microwave Power and Electromagnetic Energy*. 45(4): 178-187.

Brodie, G. I. 2008, *Innovative wood drying: Applying microwave and solar technologies to wood drying*, Saarbruecken, Germany: VDM Verlag.

Carter, P., Hutchings, P. and Tran, V. 2003. Microwave technology for heating large diameter logs for sapstain treatment and stress relief. *Proc. Third World Conference on Microwave and Radio Frequency Applications*. 341-348.Sydney, Australia

Compere, A., Gardner, W., Griffith, W., White, T., Jameel, H., Argyropoulos, D. and Fricke, A. 2004. Microwave pre-treatment to decrease pulping energy and chemicals. *Proc. TAPPI Paper Summit - Spring Technical and International Environmental Conference*.

Forest Products Laboratory 1999, *Wood Handbook—Wood as an engineering material*, Madison, Wisconsin: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Harris, G. A., Torgovnikov, G., Vinden, P., Brodie, G. I. and Shaginov, A. 2008. Microwave pretreatment of backsawn messmate boards to improve drying quality: Part 1. *Drying Technology*. 26(5): 579 - 584.

Hillis, W. E. and Brown, A. G. 1984, *Eucalypts for Wood Production*, Australia: CSIRO Publications and Academic Press.

Hofstetter, K., Hellmich, C. and Eberhardsteiner, J. 2007. Micromechanical modeling of solid-type and plate-type deformation patterns within softwood materials. A review and an improved approach. *Holzforschung*. 61(4): 343-351.

Jackson, A. and Day, D. 1989, *Wood Worker's Manual*, Sydney: William Collins Sons & Co. Ltd.

Kanagawa, Y., Hayashi, K. and Yasiizitna, M. 1992. Improvement of dryability by local steam explosion for Japanese cedar. *Proc. 3rd lUFRO Wood Drying Conference*. 269-276.Vienna, Austria

Knox, B., Ladiges, P., Evans, B. and Saint, R. 2001, *Biology*, 2nd edn, Roseville, Australia: McGraw-Hill.

Lawrence, A. 2005. Differential response of hardwood and softwood to microwave modification. *Journal of the Timber Development Association of India*. 51(3/4): 49-53.

Lawrence, A. 2006. Effect of microwave modification on the density of *Eucalyptus obliqua* wood. *Journal of the Timber Development Association of India*. 52(1/2): 26-31.

Mackay, J. F. G. 1972. The occurrence, development and control of checking in Tasmanian Eucalyptus oliqua. *Holzforschung*. 26: 121-124.

Manríquez, M. J. and Moraes, P. D. 2010. Influence of the temperature on the compression strength parallel to grain of paricá. *Construction and Building Materials*. 24(1): 99-104.

Meyland, B. A. and Butterfield, B. G. 1972, *Three-dimensional Structure of Wood: A Scanning Electron Microscope Study*, Reed Education.

Rozsa, A. 1995. Moisture movement in eucalypt timbers during microwave vacuum drying. *Proc. International Conference on Wood Drying*. 289-294.Slovak Republic

Rozsa, A. 1998. *Processing Green Timber from South-East Australian Ash-Type Hardwoods*. CSIRO Forestry and Forest Products

Scott, C. T. and Klungness, J. 2005 Microwaving logs for energy savings and improved paper properties for mechanical pulps. In *Microwave and Radio Frequency Applications: Proceedings of the Fourth World Congress on Microwave and Radio Frequency Applications*, 75-82. Schulz, R. L. and Folz, D. C. eds. The Microwave Working Group: Arnold MD.

Society of Wood Science and Technology. 2001. *Structure of Wood*. Society of Wood Science and Technology

Standards Australia/New Zealand. 2001. Assessment of drying quality. AS/NZ 4787:2001:

Torgovnikov, G. and Vinden, P. 2002. *Modified wood product and the process for the preparation thereof*. Patent No.

Unauthentifiziert | Heruntergeladen 21.02.20 22:34 UTC

Torgovnikov, G. and Vinden, P. 2006a Microwave Method for Increasing the Permeability of Wood and its Applications. In *Advances in Microwave and Radio Frequency Processing*, 303-311. Springer Berlin Heidelberg.

Torgovnikov, G. and Vinden, P. 2006b. New 300KW plant for microwave wood modification. *Proc. IMPI 40th annual international microwave symposium*. Boston, USA

Torgovnikov, G. and Vinden, P. 2008. Main aspect of microwave wood modification applicable to the timber industry. *Proc. Global congress on microwave energy applications*. 407-410.

Torgovnikov, G. I. 1993, *Dielectric Properties of Wood and Wood-Based Materials*, Springer Series in Wood Science, Berlin: Springer-Verlag.

Vermaas, H. F. 2000. A review of drying technologies for young fast-grown eucalypts. *Proc. International Conference of IUFRO*. 193-203.Tasmania, Australia

Vinden, P., Romero, F. J. and Torgovnikov, G. 2003. *Method for increasing the permeability of wood*. Patent No. 6,596,975

Vinden, P. and Torgovnikov, G. 2000. The physical manipulation of wood properties using microwave. *Proc. International Conference of IUFRO*. 240-247.Tasmania, Australia

Vinden, P., Torgovnikov, G., Blackwell, P., Hann, J. and Shaginov, A. 2006. Microwave processing of wood: the design of commercial plant. *Proc. European Panel Products Symposium*. Llandudno, Wales, UK

Vinden, P., Torgovnikov, G. and Hann, J. 2010. Microwave modification of Radiata pine railway sleepers for preservative treatment. *European Journal of Wood and Wood Products*. 1-9.

Vinden, P., Torgovnikov, G. and Hann, J. 2011. Microwave modification of Radiata pine railway sleepers for preservative treatment. *Holz als Roh- und Werkstoff: European journal of wood and wood industries*. 69(2): 271-279.

Vinden, P., Torgovnikov, G., Przewloka, S., Hann, J. and Shaginov, A. 2007. The Manufacture of Solid Wood Composites from Microwave Modified Wood. *Proc. International Panel Products Symposium*. Cardiff, Wales, UK

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