Microwave Wood Modification Technology and Its Applications

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Abstract

The use of microwave (MW) technology is growing in all industries. This increased use has resulted from the high efficiency of converting electricity into MW energy; energy savings associated with rapid, in-depth heating of materials; specific interactions that can be achieved between MW energy and materials; radical acceleration of technological processes; reductions in MW equipment costs; and improvements in the reliability of industrial MW equipment. The new technology of MW wood modification is based on the supply of high-intensity MW power, up to 135,000 kW/m^3 at frequencies of 0.922 and 2.45 GHz. Such power induces significant changes to the microstructure of wood and a dramatic increase in wood permeability. A number of commercial applications have been developed based on the fundamental changes in wood structure. These include the treatment of refractory wood species with preservatives, rapid drying of hardwoods, relief of growth and drying stresses in timber, manufacture of the new wood materials Torgvin and Vintorg, and modification of logs, sawn timber, and woodchips for pulping. MW equipment and processing parameters have been developed for three applications that are ready for commercial use. The technology provides significant material and energy savings and will give a new impetus to product development in a very traditional industry. The costs of microwave timber processing range from AU\$22 to AU\$69 per m^3. These costs are acceptable to industry and potentially provide wide appeal for use in the timber, biocomposite, and pulp and paper industries.

Microwave (MW) processing technologies are developing rapidly in all industries. This use of MW arises from the high efficiency of converting electricity into MW energy; energy savings associated with rapid, in-depth heating of materials; specific interactions that can be achieved between ME energy and materials; radical acceleration of technological processes; reductions in MW equipment costs; and improvements in the reliability of industrial MW equipment.

A number of wood species have a very low permeability that causes problems during timber processing. These problems include very long drying times, large material losses after drying, expensive drying processes, and difficult impregnation with preservatives and resins. Furthermore, growth stresses in wood and collapse often lead to drying defects and high material losses in the recovery of sawn timber. In the wood pulping industry, low wood permeability results in shallow chemical penetration of pulping liquids into wood. This requires the use of small-sized chips, high chemical usage, and high energy consumption. MW wood modification can provide an increase in wood permeability that solves many wood processing problems.

Intensive MW power applied to green wood generates steam pressure within the wood cells. Under high internal pressure, the pit membranes in cell walls, tyloses in vessels, and weak ray cells are ruptured to form pathways for easy transportation of liquids and vapors (Vinden et al. 2003). An increase in the intensity of the MW energy increases the internal pressure, resulting in the formation of narrow voids in the radial and longitudinal planes (Torgovnikov and Vinden 2003). The number of cavities, their dimensions, and their distribution are controlled by the intensity of MW energy supplied. A several thousand-fold increase in wood permeability in the radial and longitudinal directions can be achieved in species previously found to be impermeable to liquids and gases. Other physical properties and technological attributes are also changed (Vinden and Torgovnikov 2003). Structural changes in wood after MW modification, their effect on wood properties, and the process parameters required for different degrees of wood modification are described by Torgovnikov and Vinden (2009).

MW wood modification technology provides a number of commercial applications:

- Treatment of refractory wood species with preservatives
- Rapid drying of hardwoods

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- Growth and drying stress relief in timber
- Manufacture of the MW-modified wood Torgvin
- Production of the new wood-based material Vintorg
- Increased permeability of logs, sawn timber, and woodchips for pulping

This article describes, analyzes, and provides estimates for each of these applications, including research completed, plant requirements, potential throughput, and cost. Three technologies are ready for commercialization. These technologies include MW timber modification for impregnation with preservatives and resins as well as pretreatment of hardwood sawn timber for fast drying and MW processing of timber and woodchips for pulping.

Background (MW Wood Modification, Process Parameters, and Equipment)

When intense MW power is applied to moist wood, the internal water content heats to the boiling point, generating steam pressure within the wood cells. The pressure increases up to 6 bar within 0.3 to 6 seconds, and the pressure gradients rupture the weakest elements of wood structure, increasing the permeability of wood for liquids and gases. Three levels of MW modification of wood have been defined (low, moderate, and high), depending on the MW processing conditions used (Torgovnikov and Vinden 2009).

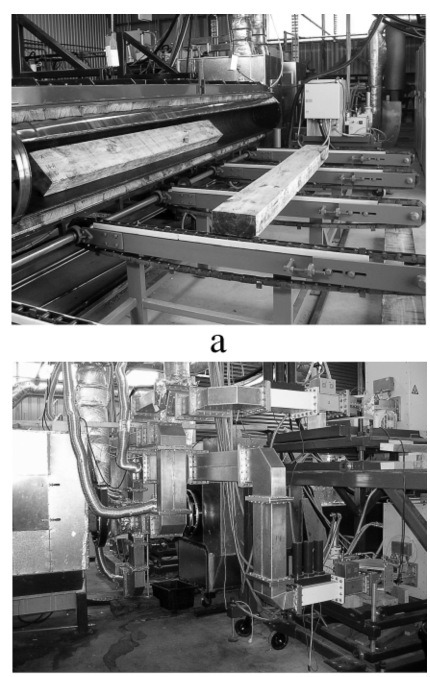
A low degree of MW modification can increase the permeability of wood by a factor of 1.1 to 1.5. A low degree of MW modification has no statistical effect on wood density or strength properties. Such wood modification takes place at an applied MW energy of 250 to 350 MJ/m^3. A moderate degree of modification increases the permeability a thousand-fold and, at the same time, reduces the strength properties, such as the modulus of elasticity (MOE) and modulus of rupture (MOR), by 12 to 26 percent. A high degree of modification can convert wood into a highly porous material with numerous cavities, mainly in the radial–longitudinal planes. Permeability of this modified wood increases dramatically compared with that of natural wood, and this porous material is called Torgvin. A high degree of wood modification leads to substantial reduction of MOE and MOR (17% to 65% of the initial MOE and 15% to 80% of the initial MOR), depending on processing conditions and MW processing parameters (Torgovnikov and Vinden 2000). Such wood modification requires applied MW energy levels up to 1,200 MJ/m^3. In some instances, the strength reduction can be acceptable, bearing in mind the strength variability range of natural wood ($\pm$20%). A high degree of MW modification generates numerous voids in the wood and changes many wood properties, such as porosity, permeability, density, strength, flexibility, shrinkage and swelling, heat and sound conductivity, and dielectric properties.

MW timber modification is a continuous conveyor process and occurs where the green timber or logs move through an MW field in an MW applicator (an MW applicator is a device in which MW energy interacts with timber). MW applicators focus high-intensity MW energy into a limited volume of wood. The main processing parameters that are adjusted to provide different levels of MW wood modification comprise MW frequency, specific power applied to the wood, energy supplied to the wood, MW applicator configuration, timber feed speed through the MW applicator, and air flow parameters (temperature and speed).

The depth of MW penetration into the wood depends on MW frequency. A lower frequency provides deeper penetration. A frequency of 2.45 GHz can be used for processing sawn timber with thicknesses up to 90 mm or for surface treatment of thicker wood samples, while 0.922 GHz (or 0.915 GHz in some countries) can be used for timber up to 450 mm thick. To achieve the required degree of wood modification, MW energy needs to be applied to the wood with enough intensity to create high steam pressure within the cells for rupturing the wood microstructure. However, too much MW power can initiate wood burning. The specific power applied to the wood at 2.45 GHz needs to be in the range from 13,000 to 135,000 kW/m^3. At 0.922 GHz, power needs to be in the range of 5,000 to 25,000 kW/m^3. The MW energy for timber modification supplied to the wood needs to be in the range from 250 to 1,200 MJ/m^3 (70 to 330 kWh/m^3; Torgovnikov and Vinden 2009).

All commercial MW plants for timber modification (Fig. 1) consist of four main components:

1. The MW system, which includes generators with tuners and product-specific MW applicators.
2. The timber feeding system, which provides mechanisms for centering and moving timber through the applicator at controllable speeds.
3. The air dynamic system, which removes vapors, water, and wood particles from the applicator and prevents water condensation on the internal surfaces of the applicator.
4. The process control and monitoring system, which



a

b

Figure 1.—A 300-kW MW plant (frequency, 0.922 GHz) for large cross-section round and sawn timber modification: (a) general view from the out-feed side; (b) four-port MW applicator with waveguides for MW power supply to the applicator from generators.

provides centralized operation of the timber modification process.

Different MW applicator configurations can be used to provide the desired wood modification. This includes the use of round applicators with two to four ports for energy supply and rectangular applicators with one to four ports for energy supply (Torgovnikov and Vinden 2005, 2006, 2007). The power of the MW plant is determined by the required output of the commercial plant and can range from fifty to thousands of kilowatts.

Industrial Applications of MW Wood Modification Technology

Preservative treatment and resin impregnation of wood

Many wood species have low durability and cannot be used without preservative treatment. The very low permeability of some of these species compounds the problem. MW wood modification overcomes this issue and facilitates a very high standard of treatment. Typical commodities include poles, posts, lumber, railway sleepers, peeler cores, garden sleepers, cross-arms, bridge timbers, etc. Experiments with hardwood species, such as blue gum (*Eucalyptus globulus*), shining gum (*Eucalyptus nitens*), stringybark (*Eucalyptus muellerana*), messmate (*Eucalyptus obliqua*), and Paulownia (*Paulownia fortunei* and *Paulownia elongata*), as well as softwood species, such as Sitka spruce (*Picea sitchensis*), radiata pine (*Pinus radiata*), and Douglas-fir (*Pseudotsuga taxifolia*) heartwood, show that full cross section preservative penetration can be achieved.

Improvements in permeability have been obtained in the radial, tangential, and longitudinal grain directions. Figures 2 and 3 illustrate the significant difference in impregnation of MW-treated and untreated Douglas-fir and Paulownia samples, respectively. Refractory or impermeable wood species become permeable and can be easily impregnated with preservatives, resins, and other chemicals after MW modification.

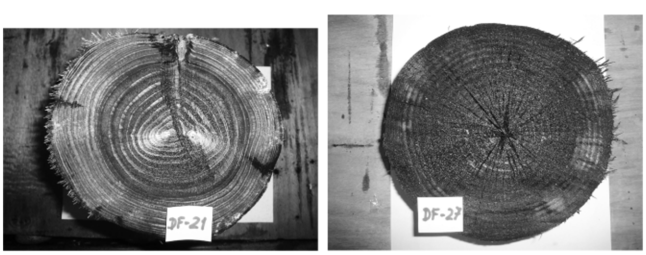


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Figure 2.—Chromated copper arsenate distribution in Douglas-fir log cross sections after impregnation: (a) control (no MW processing); (b) after MW modification.

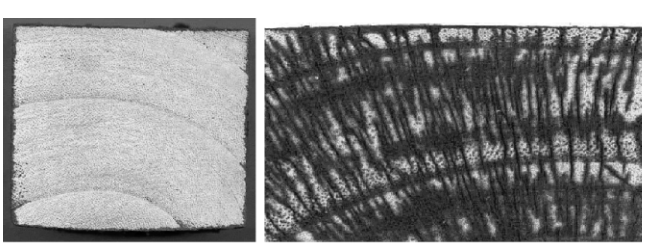

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Figure 3.—Paulownia wood after MW treatment and pressure impregnation with resin: (a) control (non–MW-treated sample); (b) MW-modified sample.

MW processing of heartwood of radiata pine, Douglas-fir, and Sitka spruce species using MW energy ranging from 250 to 400 MJ/m^3 (69 to 111 kWh/m^3) facilitates an increase in uptake of water-based preservatives by a factor of 2.9 to 5.3 compared with non–MW-treated timber. Highly refractory hardwood species, such as messmate, stringybark, and blue gum, achieve increases in uptake of water-based preservative by a factor ranging from 8 to 14 following MW modification using an applied MW energy of 570 to 850 MJ/m^3 (158 to 236 kWh/m^3; Torgovnikov and Vinden 2009).

Experiments with the MW processing of Norway spruce (*Picea abies*) demonstrated a significant increase in the uptake of a 2 percent copper-based preservative after wood modification at an applied MW energy of more than 50 kWh/m^3 at a frequency of 2.45 GHz (Treu and Gjolsjo 2008). Larch (*Larix olgensis*) wood modification by applying intensive MW irradiation (Hong-Hai et al. 2005) showed a 2.5- to 3.3-fold increase in water uptake compared with untreated wood, while the MOE and MOR remained practically unchanged.

For preservative treatment, a moderate degree of MW modification is used. This applies particularly to sawn timber because of limitations in check sizes that can appear on the timber surface. MW frequency also influences the width of surface checks. Experiments show that at a high degree of modification, using a frequency of 2.45 GHz results in smaller surface check sizes in timber compared with using a frequency of 0.922 GHz.

Radiata pine railway sleepers need to be preservative treated to provide the required durability. However, a large part of the sleeper cross section usually comprises impermeable heartwood. MW processing of freshly sawn sleepers allows impregnation with any preservative. A special four-port MW applicator was designed and built for a 300-kW (0.922-GHz) plant specifically for the modification of radiata pine railway sleepers. The objective was to determine the optimum processing parameters for the plant. More than 3,500 sleepers (130 by 260 by 2,700 and 130 by 225 by 2,100 mm) were MW processed and successfully impregnated with copper naphthenate preservative. Figure 4a shows the difference in the impregnation of MW-treated and non–MW-treated sleepers. The top row of sleepers comprises controls. The light color indicates unimpregnated areas. The MW-conditioned sleepers achieved complete impregnation of preservative (Torgovnikov et al. 2009). A 400-kW, commercial MW plant has now been designed that is capable of an output of 100,000 sleepers per annum.

MW energy consumption for softwood (heartwood) timber modification ranged from 65 to 110 kWh/m^3, depending on wood moisture content (MC), and from 130 to 250 kWh/m^3 for hardwoods, depending on the required degree of modification. Techniques have also been developed for the surface modification of timber to increase the permeability of the timber shell (Sugiyaento et al. 2008). Technical aspects of the technology have been completed, and it is ready for commercialization.

a

b

Figure 4.—Radiata pine railway sleepers (130 by 260 by 2,700 mm) after MW processing using a 300-kW MW plant and pressure impregnation with copper naphthenate preservatives: (a) top row are controls without MW conditioning, and the other rows are MW modified; (b) sleepers stockpiled for industrial testing.

Rapid drying of hardwoods

Many commercial hardwood drying operations impose an extended period of slow air drying to reduce the incidence of drying defects (checking and collapse) before kiln drying. MW conditioning of hardwoods provides an opportunity for kiln drying immediately after sawing. The reduction in drying time for hardwoods provides a reduction in associated capital, space, energy, and labor costs, while the reduction in drying defects can increase yields. Intensive MW conditioning increases the permeability of the green wood, overcoming the propensity of the hardwoods to collapse during kiln drying.

MW pretreatment of Victorian (Australia) grown messmate timber provides a reduction in drying times by a factor of 2 to 10 compared with unmodified wood (Vinden and Torgovnikov 2000). MW lumber predrying treatment experiments were carried out in Oak Ridge National Laboratory (Compere 2005) with white oak (*Quercus alba* L.), red oak (*Quercus rubra*), and hard maple (*Acer saccharum* Marsh). In that study, a low degree of MW wood modification did not affect timber quality and reduced drying time.

Analysis of the dried quality of a number of hardwood species, including messmate, black butt (*Eucalyptus pilularis*), Sydney blue gum (*Eucalyptus saligna*), mountain ash (*Eucalyptus regnans*), jarrah (*Eucalyptus marginata*), and shining gum, demonstrated that a low degree of MW wood modification does not provide any significant difference in the quantity and sizes of checks between MW-pretreated and control samples after drying under similar conditions (Harris et al. 2008). Standard commercial kiln schedules were used for lumber drying in this research. Predrying MW treatment schedules are summarized in Table 1. On-going research into MW conditioning is evaluating the use of more aggressive drying schedules to achieve reductions in drying time.

Compere (2005), working with red oak, hard maple, and yellow poplar (*Liriodendron tulipifera* L.) as shown that a low degree of MW wood modification does not give any statistically significant difference in strength, stiffness, hardness, or glue shear between untreated and pretreated lumber. In addition, no difference was found in the machinability, gluability, or finish quality of MW-treated boards compared with controls.

A low degree of MW modification reduces the kiln drying time of 30- to 50-mm-thick hardwood boards by approximately 50 percent. MW pretreatment increases the drying rate by decreasing the MC of wood (immediately by 4% to 11%) and by increasing the rate at which boards of a given MC dry in a kiln. Moderate degrees of modification facilitate a 5- to 10-fold acceleration in drying, depending on lumber species, thickness, and initial MC (Vinden and Torgovnikov 2000). Initial MC losses can range from 12 to 32 percent. However, the probability of developing internal and external checks increases. Thus, the MW pretreatment schedule and kiln drying schedules need to be matched.

The probability of check development in back-sawn boards is higher compared with boards in which annual rings are oriented 40° to 45° to the board width. MW energy consumption for hardwood timber conditioning before drying ranges from 70 to 110 kWh/m^3 for a low degree of modification and from 100 to 180 kWh/m^3 for a moderate degree of modification, depending on wood species and MC (Torgovnikov and Vinden 2009).

The propensity for microvoid formation during MW irradiation differs between hardwood species. Every species has an optimum level of energy needed to achieve specified levels of modification. For example, MW energy of up to 130 kWh/m^3 can be applied to messmate boards without the appearance of visible internal microvoids, while mountain ash boards undergo extensive modification if more than 90

Table 1.—MW predrying treatment parameters for some Eucalyptus species lumber and check appearance.

Timber species	Timber size (mm)	Frequency (GHz)	MC (%)	Specific applied MW power (kW/m^3)	MW energy applied (MJ/m^3)	Difference in check appearance in control and MW treated samples
Messmate back-sawn	32 by 110	2.45	70–90	24,400	270	Check number reduction
Messmate quarter-sawn	32 by 112	2.45	92–118	27,000	280–300	No difference
Sydney blue gum	45 by 108	2.45	65–80	14,300	270	No difference
Back butt	45 by 108	2.45	50–74	14,300	310	No difference
Jarrach	45 by 107	2.45	81–112	13,000	270	Check number reduction
Shining gum	28 by 100	2.45	70–130	32,000	320–350	No difference
Mountain ash quarter-sawn	45 by 180	0.922	95–112	6,200	280–320	No difference

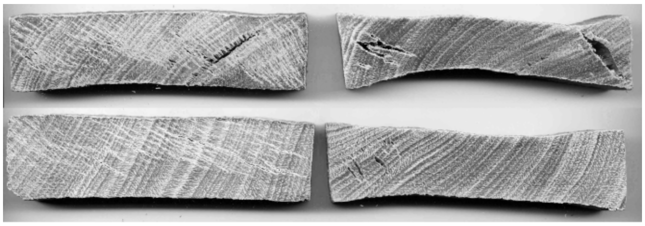


Figure 5.—End-matched messmate after drying under similar conditions (air temperature, 70°C; relative humidity, 51%): (a) MW-modified samples, with minimal changes in the shape; (b) unmodified control samples.

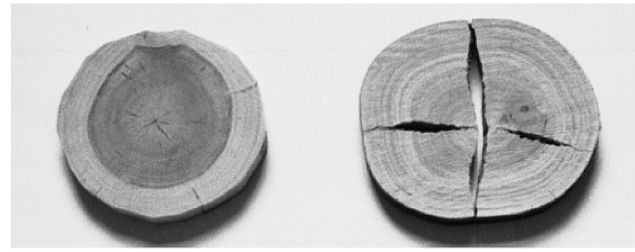


Figure 6.—Stringybark posts after drying: (a) MW-modified log has a large number of micro- and macrochecks, which reduces stress and maintains the integrity of the post; (b) unmodified control log that splits because of growth and drying stresses.

kWh/m^3 is applied. Similarly, more aggressive drying schedules can be applied to messmate compared with mountain ash without degrade.

In summary, MW timber conditioning before kiln drying demonstrates the potential to increase the drying rate of hardwood timbers and reduce drying defects, thus increasing the yield of usable timber. MW conditioning overcomes the propensity of the hardwoods to collapse during kiln drying and reduces the losses of timber because of long storage times. MW pretreatment substitutes the lengthy 3 to 6 months of air drying for eucalyptus lumber conventionally applied before kiln drying and reduces kiln drying by up to 2 to 3 weeks. Results of a study by Compere (2005) in which the overall mill retention times for predried and MW-pretreated red oak lumber were examined indicated that MW pretreatment could reduce overall inventory and processing time from 60 days to around 12 days, with concomitant reductions in lumber handling, inventory, and operating costs. Drying time reduction leads to significant reduction in energy consumption. According to Compere (2005), this can save the United States up to 41 trillion Btu of petroleum energy used in drying. Most of the technical aspects relating to the technology are now completed, and it can be used advantageously even in sawmills with low capacities of 3,000 m^3/y.

Growth and drying stress relief in timber

The development of growth stresses in plantation eucalypts leads to losses in sawn timber production and lower quality. The problem remains largely unsolved and costs the Australian timber industry approximately AU$1.4 billion each year. Drying stresses in wood also lead to high material losses and down-grade because of wood quality issues. It is important that these issues are addressed.

MW-pretreated eucalyptus timber has different shrinkage behavior compared with nonmodified samples. For example, modified messmate samples after drying have lower shrinkage than controls. The probability of cell collapse after drying is also lower (Fig. 5).

The influence of MW heating is twofold. First, the temperature increases in the moist wood, generally within the range of 110°C to 158°C. This softens the lignin, hemicellulose, and cellulose, and it provides stress relaxation (Kubler 1987). Second, steam pressure generates inside the wood. This ruptures the softer tissue in wood, creating micro- and macrochecks, which leads to improved permeability and internal stress reduction. This process requires the provision of a high degree of modification and MW energy in the range 300 to 1,200 MJ/m^3, depending on wood species, density, and MC (Torgovnikov and Vinden 2009).

Experiments show that MW irradiation of small thicknesses of yellow stringybark and blue gum posts can provide relief of both growth and drying stresses. The formation of micro- and macrochecks in the posts results in stress relief and maintenance of the post integrity (Fig. 6).

MW heating of bent boards up to 140°C for subsequent straightening has been studied by the Forest Products Laboratory in Madison, Wisconsin. In that study, Hunt et al. (2005) demonstrated successful straightening of highly bowed lodgepole pine (*Pinus contorta*) boards without any damage (cracking or end splitting). This highlights the opportunities available for using MW technology to alleviate stress in wood. The technology requires further study and development to assess the engineering and economic feasibility of processing options.

Drying tests of MW-modified sawn timber show that the wood behaves differently during convectional drying; there is reduced collapse and reduced shrinkage. These properties of MW-modified wood have not been thoroughly studied. However, the visual qualitative assessment of many samples indicates that MW modification has a very positive affect on the timber. The reduction of timber splitting reduces material losses.

Torgvin and Vintorg material manufacturing

A high degree of MW modification converts wood into a highly porous material, called Torgvin. The special physical properties of Torgvin open up a number of new fields for the application of wood materials. One application for Torgvin is the production of a new composite material called Vintorg. Vintorg is manufactured from Torgvin by impregnating the modified wood with resin, followed by pressing and curing (Torgovnikov and Vinden 2002, Vinden et al. 2007). The process is suitable for any wood species. Very intensive steam pressure generated inside the timber ruptures the weaker, softer tissue and expands the cross section of the wood. During impregnation, the resin penetrates the ruptured sites, including expanded microvoids in the wood, which are subsequently bonded with resin under pressure to provide a stronger material.

Vintorg has a number of advantages compared with normal wood. These advantages include higher strength properties than the parent wood, natural appearance and structure, good dimensional stability, decay resistance, fire resistance, and conversion of low-grade material into value-added products. Paulownia wood that normally has very low

Table 2.—Summary of the improvement obtained following Vintorg manufacture from Paulownia compared with natural wood as a function of resin content.

Material	Resin (%)	MOR (MPa)	MOR increase (%)	MOE (MPa)	MOE increase (%)	Hardness (MPa)	Hardness increase (%)
Natural wood	0	40.1		3,425		11.4	
Vintorg with resin Rubinate 1780 (PMDI, diphenylmethane-4,4′-diissosyanate)	10	45.9	14	5,260	53	24.6	116
	20	52.8	32	5,920	73	27.2	139
	30	59.8	49	6,590	92	29.8	161
Vintorg with resin Sylvic M550 (melamine formaldehyde)	10	45.3	13	5,510	61	22.1	94
	20	50.7	26	5,615	64	23.7	108
	30	56.1	40	5,720	67	25.3	122

density (ovendry density of 250 to 300 kg/m^3) and low strength has been converted into Vintorg (Vinden et al. 2008), with significant improvements in MOR, MOE, and hardness compared with natural wood (Table 2).

Clearly, the increases obtained in each of the strength properties are proportional to the percentage of resin content after Vintorg manufacture. Surface hardness is improved significantly. The improvement obtained in MOE for both the Rubinate 1780 (an increase in MOE of 53% to 92%) and Silvic M550 resin (an increase in MOE of 61% to 67%) expands the utility of this wood species significantly.

The cost of resin forms 23 to 46 percent of the total Vintorg production costs, assuming a resin consumption of 15 to 20 percent of the weight of wood (at a wood MC of 8%). Both resin consumption and cost could be reduced if MW modification was limited to an envelope or shell treatment.

Torgvin manufactured from different wood species has also been pressure impregnated with metal alloys. The alloy (''Cerrobend'') is selected based on its low melting point (<230°C; Shaginov et al. 2005). Vintorg-metal has a number of advantages compared with natural wood, including higher strength properties, dimensional stability, electric conductivity, and original appearance. Figure 7 illustrates the structure of Vintorg-metal made from three wood species. The physical properties of Vintorg-metal require additional study to determine the potential fields of application.

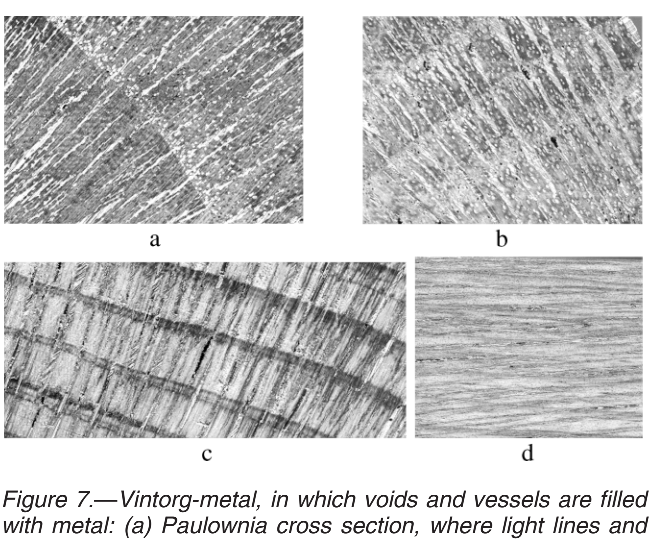


Figure 7.—Vintorg-metal, in which voids and vessels are filled with metal: (a) Paulownia cross section, where light lines and dots are metal; (b) mountain ash cross section, where light lines and dots are metal; (c) radiata pine cross cut, where dark lines are metal; (d) radiata pine radial section, where dark areas are metal.

Increasing permeability of logs, sawn timber, and woodchips for pulping

Increasing the permeability of wood through MW modification opens up new opportunities for pulping wood by providing fast chemical penetration into wood and delignification. Logs, sawn timber, and woodchips can be MW treated on a conveyor before pulping. This technology improves both economic and environmental performance of pulping operations.

MW pretreatment for pulping requires a high degree of modification and is not limited by check size requirements, which are critical for other applications of the technology. MW pretreatment provides instant penetration of pulping liquor into the chip and direct contact with the lignin. Paper manufacturing tests using radiata pine heartwood (90 by 90 by 3,000 mm and an MC of 30% to 35%) MW modified at a frequency of 0.922 GHz in a conveyor applicator demonstrated the following advantages: screened yield was improved by 7 percent, reduction of pulping chemical use by 22 to 31 percent, improved paper properties, and lower processing time. The MW energy consumption needed to achieve a high degree of heartwood timber modification is approximately 340 MJ/m^3.

Investigations by Scott et al. (2002) into the processing of black spruce (*Picea mariana*) logs and the manufacture of chips and paper identified the following advantages for mechanical pulping: energy savings of up to 15 percent and an increase in handsheet properties (by 35% burst index, 20% tear index, and 13% tensile index). There was, however, a reduction in brightness of 10 percent. An economic assessment of the value of MW pretreatment by those authors showed that for a pulp mill output of 800 t/d, annual pulp cost savings of US$10 million to US$15 million would accrue.

A comprehensive study of MW wood modification for pulping has been carried out by the Oak Ridge National Laboratory (Compere 2006). This investigation showed significant advantages for MW-modified wood use in pulping (including kraft and soda-anthraquinone pulp mills as well as sulfite and chemithermomechanical pulping mills). These advantages (US Department of Energy 2006, 2007) include improved yield and throughput of up to 40 percent, a reduction of chemical use of up to 40 percent, a reduction of wood loses associated with oversized chips, and energy savings from natural gas reduction of up to 40 percent.

Table 3.—MW power for MW plant outputs of 1 and 5 m^3/h working two and three shifts per day at a frequency of 2.45 or 0.922 GHz.

Sawn timber and logs	MC (%)	MW energy consumption (kWh/m^3)	Output (m^3/h)	Annual plant capacity at 2 shifts per d/3 shifts per d (m^3/y)	Plant MW power (kW)
Softwoods, heartwood	30–40	75–110	1	4,000/6,000	75–110
			5	20,000/30,000	375–550
Softwoods, sapwood	80–120	125–180	1	4,000/6,000	125–180
			5	20,000/30,000	625–900
Hardwoods	30–120	100–220	1	4,000/6,000	100–220
			5	20,000/30,000	500–1,100

Technical aspects associated with the MW processing of wood for pulping have been established for both softwood and hardwood species by developing and testing high-power MW plants of up to 300 kW (Torgovnikov and Vinden 2005, 2006). MW wood processing for pulping requires energy consumption (at frequencies of 2.45 or 0.922 GHz) in the range 340 to 1,080 MJ/m^3, depending on species, wood density, and MC.

MW wood modification allows a larger range of woodchip sizes or wood pieces to be used for pulping. The use of MW-modified wood for pulping can radically change pulping technology and bring significant economic benefits to the industry. It also improves environmental performance. The market potential for this technology has been estimated by the US Department of Energy (2007) as comprising 75 percent of chemical pulping mills.

Plant Capacity Calculations

MW plant specifications depend on industrial capacity that may range from 3,000 m^3/y (for a small sawmill) to 120,000 m^3/y (for a pulp mill). MW power calculations are usually based on output in cubic meters per hour. In this case, it is easy to calculate output for plants working one (2,000 h/y), two (4,000 h/y), or three (6,000 h/y) shifts per day. The MW power of the plant is determined from energy consumption and the required output and can be calculated using following formula:

$$P = E \times O$$

where

P = MW power of the plant (kW),

E = energy consumption (kWh/m^3) determined experimentally from the MW processing of different wood species and sizes, and

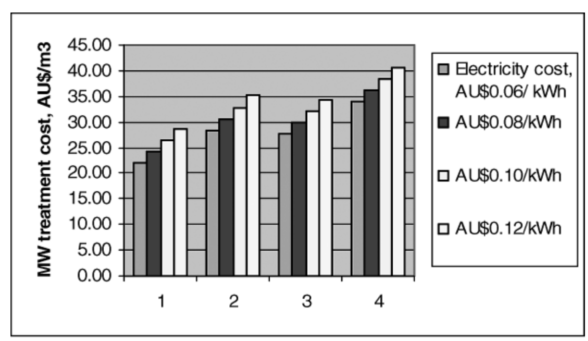
O = required output of the plant (m^3/h).

Table 3 displays MW power ranges required for plant outputs of 1 and 5 m^3/h at plants working two and three shifts per day at frequencies of 2.45 or 0.922 GHz.

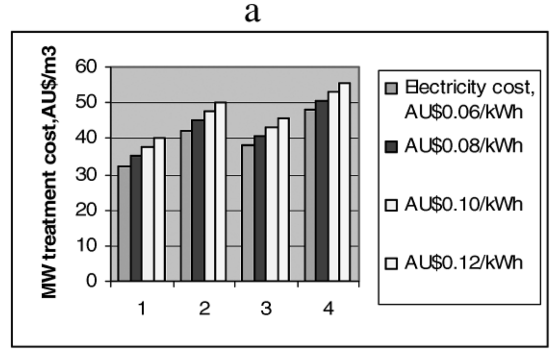
MW generators used for industrial applications utilize magnetrons (electronic devices that convert electricity into MW energy). Magnetrons are a cheaper option compared with other devices. Currently, the maximum commercial MW single-generator (magnetron) power available is 30 kW at a frequency of 2.45 GHz and 100 kW at a frequency of 0.922 GHz. To provide an MW plant power of 300 kW requires ten 30-kW generators at a frequency of 2.45 GHz or three 100-kW generators at a frequency of 0.922 GHz. The efficiency of electricity transformation into MW energy is 76 percent at a frequency of 2.45 GHz and 87 percent at a frequency of 0.922 GHz. Thus, the use of MW generators at a frequency of 0.922 GHz can save about 10 percent of the energy used by generators with a frequency of 2.45 GHz. The cost for 1 kW of power from a 30-kW MW generator at a frequency of 2.45 GHz is AU$3.2, while at a frequency of 0.922 GHz, the cost is AU$1.4. Therefore, in the case when, from the technological point of view, both frequencies can be used, it is cheaper to use generators with a frequency of 0.922 GHz. If timber is preheated using steam or hot air up to 90°C before MW modification, the electrical energy consumption can be reduced up to 30 percent.

Costs of MW Wood Modification

A costing of MW wood modification for different applications is presented below. The assessment is based on technical data from experiments and tests and worldwide prices of the equipment. Figure 8 provides a cost analysis



a



b

Figure 8.—MW lumber predrying costs depending on plant output and electricity costs: (a) frequency of 0.922 GHz; (b) frequency of 2.45 GHz. 1 = automatic plant, three shifts per day, output of 24,000 m^3/y; 2 = automatic plant, two shifts per day, output of 16,000 m^3/y; 3 = one plant operator per shift, three shifts per day, output of 24,000 m^3/y; 4 = one plant operator per shift, two shifts per day, output of 16,000 m^3/y.

for MW hardwood lumber predrying treatment under the following conditions:

1. MW plant output of 24,000 m^3/y at 6,000 working hours per y (three shifts per day) and 4 m^3/h, or 16,000 m^3/y at 4,000 working hours per y (two shifts per day) at 4 m^3/h.
2. MW power of the plant of 360 kW.
3. MW plant costs of AU$1,428,000 at a frequency of 0.922 GHz and AU$2,348,000 at a frequency of 2.45 GHz.
4. MW plants that work automatically (no operator) or with an operator (one worker per shift).
5. Electric energy consumption of 113 kWh/m^3 at a frequency of 0.922 GHz and 127 kWh/m^3 at a frequency of 2.45 GHz.
6. Electricity cost ranging from AU$0.06 to AU$0.12 per kWh.
7. Depreciation rate of 17%.

The estimated specific costs include costs associated with capital, maintenance, magnetron replacement, labor, floor space cost, and electricity costs. These costs do not include costs of mechanical installation, electrical connections, or overhead and taxes.

The calculations show that the MW predrying treatment costs for an automatic plant with a frequency of 0.922 GHz and electricity costs of AU$0.06 per kWh compared with AU$0.12 per kWh grow from AU$22.0 to AU$28.8 per m^3 for three shifts per day and from AU$28.3 to AU$35.1 per m^3 for two shifts per day. At a frequency of 2.45 GHz, MW predrying costs (under similar conditions) grow from AU$32.5 to AU$40.1 per m^3 for three shifts per day and from AU$42.4 to AU$50 per m^3 for two shifts per day. The increase in electricity costs (from AU$0.06 to AU$0.12 per kWh) leads to an increase in MW predrying treatment costs from 16 to 29 percent. For an MW plant operated by a worker, MW predrying treatment costs increase from 11 to 17 percent for a frequency of 2.45 GHz and by 16 to 25 percent for a frequency of 0.922 GHz compared with an automatic plant. For a frequency of 2.45 GHz, the MW predrying treatment costs are higher compared with those for a frequency of 0.922 GHz, because capital costs and electricity consumption are higher.

MW predrying treatment costs for plant with an output of 24,000 m^3/y (three shifts per day) and 16,000 m^3/y (two shifts per day) at an electricity cost of AU$0.08 per kWh are summarized in Table 4. The capital costs comprise the largest proportion of total costs (34% to 49%), followed by electricity costs (20% to 30%) and labor costs (11% to 19%). The costs reduce significantly when equipment is used on a three-shifts-per-day basis.

The heartwood of many softwood species is low compared with sapwood. Radiata pine and Douglas-fir peeler cores, for example, have low wood MC, ranging from 30 to 45 percent. MW modification is required in the shell areas only for preservative treatment of hazard classes H3, H4, and H5 (Standards Australia 2000). In this case, MW processing requires less energy and is relatively low in cost at a frequency of 2.45 GHz. The costs of automatic MW conditioning of peeler cores (diameter, 130 mm) range from

Table 4.—MW predrying treatment costs for plant with an output capacity of 24,000 m^3/y (three shifts per day) and 16,000 m^3/y (two shifts per day) at an electricity cost of AU$0.08 per kWh.

	Frequency, 0.922 GHz				Frequency, 2.45 GHz			
	3 shifts/d, 24,000 m^3/y		2 shifts/d, 16,000 m^3/y		3 shifts/d, 24,000 m^3/y		2 shifts/day, 16,000 m^3/y	
Cost items	AU$/$m^3$	%	AU$/$m^3$	%	AU$/$m^3$	%	AU$/$m^3$	%
Capital	10.12	34	15.17	42	16.63	41	24.95	49
Magnetron replacement	2.67	9	2.70	7	5	12	5	10
Maintenance	1.19	4	1.79	5	1.96	5	2.94	6
Electricity	9.04	30	9.04	25	10.16	25	10.16	20
Labor	5.63	19	5.63	16	5.63	14	5.63	11
Floor space	1.25	4	1.88	5	1.25	3	1.88	4
Total	29.89	100	36.20	100	40.62	100	50.54	100

Table 5.—Costs of timber modification in the MW plants operated by one worker per shift for different applications at an electricity cost of AU$0.08 per kWh.

Process and timber	Plant output (m^3/y)	Shifts/d	Frequency (GHz)	MW power of the plant (kW)	MW plant cost (AU$)	Energy consumption (kWh/m^3)	Specific MW treatment cost (AU$/$m^3$)
Predrying treatment of hardwood lumber	24,000	3	2.45	360	2,348,000	127	40.6
	16,000	2					50.5
	24,000	3	0.922	360	1,428,000	113	29.9
	16,000	2					36.2
Radiata pine, Douglas-fir peeler core for preservative treatment	24,000	3	2.45	270	1.790,000	95	28.7
	16,000	2					37.3
Douglas-fir logs for preservative treatment	24,000	3	0.922	520	1,735,000	173	32.6
	16,000	2					40.2
Radiata pine railway sleepers for preservative treatment	24,000	3	0.922	480	1,585,000	155	31.4
	16,000	2					39.2
Hardwood post and poles for preservative treatment	24,000	3	0.922	900	2,363,000	283	49.4
	16,000	2					59.8

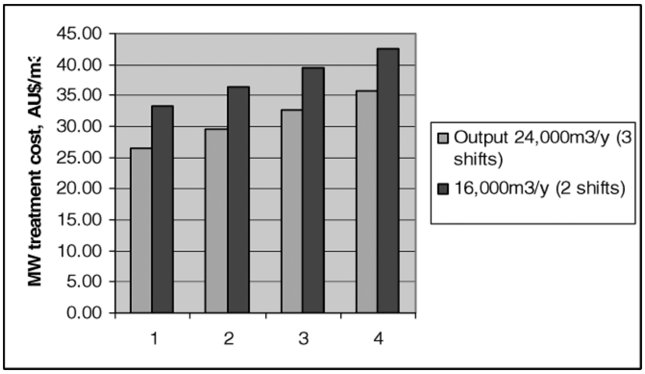


Figure 9.—MW modification costs of radiata pine sleepers using a frequency of 0.922 GHz as a function of electricity charges. Assumptions in the use of an automatic plant include output of 24,000 m^3/y (three shifts per day) or 16,000 m^3/y (two shifts per day), MW plant power of 480 kW, MW plant cost of AU$1,585,000, electric energy consumption of 155 kWh/m^3, and depreciation rate of 17 percent. 1 = AU$0.06 per kWh; 2 = AU$0.08 per kWh; 3 = AU$0.10 per kWh; 4 = AU$0.12 per kWh.

AU$26.8 to AU$34.5 per m^3. Cost calculation assumptions include an automatic MW plant, output of 24,000 m^3/y (three shifts per day), 16,000 m^3/y (two shifts per day), MW plant power of 270 kW (2.45 GHz), MW plant cost of AU$1,790,000, electricity energy consumption of 95 kWh/m^3, electricity cost of AU$0.08 per kWh, and a depreciation rate of 17%.

Table 5 summarizes the costs of timber modification in the MW plant operated by a worker for different applications. The cost analysis assumes an electricity cost AU$0.08 per kWh.

In Australia, high-quality indigenous hardwood lumber from mountain ash costs AU$730 to AU$1,300 per m^3 depending on quality. MW predrying treatment costs range from AU$30 to 36 per m^3, thus forming 4.1 to 4.9 percent of low-grade lumber price and 2.3 to 2.8 percent of high-grade lumber price. The additional expense is not significant and is low compared with the significant benefits accruing to MW processing.

The MW modification of radiata pine railway sleepers for preservative treatment requires a frequency of 0.922 GHz. This arises because the sleeper cross section is large (130 by 260 mm). The costs of sleeper processing using an automatic MW plant ranges from AU$26.4 to AU$42.6 per m^3 (Fig. 9), assuming electricity charges ranging from AU$0.06 to AU$0.12 per kWh.

The MW modification of hardwood poles for preservative treatment requires a frequency of 0.922 GHz. The costs of pole processing using an automatic plant range from AU$42.9 to AU$69.1 per m^3 for electricity charges ranging from AU$0.06 to AU$0.12 per kWh. Assumptions include an output of 24,000 m^3/y (three shifts per day), 16,000 m^3/y (two shifts per day), MW power of the plant 900 kW (at 0.922 GHz), MW plant cost AU$2,363,000, electricity consumption 283 kWh/m^3, and a depreciation rate of 17%.

Capital costs (at depreciation rate of 17%) and electricity charges (AU$0.08 per kWh) comprise 30 to 49 percent and 19 to 41 percent, respectively, of total production costs. Labor costs are responsible for another 9 to 19 percent of total costs. A significant reduction in MW energy costs can be achieved if steam or hot air is used for timber preheating before MW wood modification. The costs of MW timber modification range of AU$22 to AU$69 per m^3, depending of the wood species and particular application.

Conclusions

The application of high-intensity MW power to moist wood changes the physical properties of the wood, resulting in a dramatic increase in wood permeability. Impermeable species can be transformed into highly permeable materials that allow the flow of liquids and gases within its structure. MW wood modification can be applied to any wood species.

The main commercial applications for this new technology have been identified and studied. These applications include the treatment of refractory wood species with preservatives, rapid drying of hardwoods, relief of growing and drying stresses in round wood and timber, manufacture of new wood materials Torgvin and Vintorg, and modification of logs, sawn timber, and woodchips for pulping.

A number of MW applications are ready for commercial use. These applications include MW timber modification for impregnation with preservatives and resins as well as pretreatment of hardwood sawn timber for fast drying and MW processing of timber and woodchips for pulping. Promising applications for MW technology requiring further research include relief of growing and drying stresses and manufacture of the wood materials Torgvin and Vintorg, imparting new physical properties. Relief of growing and drying stresses is very important for fast-growing plantation timber and can bring significant benefits in terms of preventing log splitting, reducing collapse damage in timber, diminishing drying defects, and improving recovery.

MW wood modification technology provides significant material and energy savings and improves both economic and environment performance of a very traditional industry. The costs of MW timber processing for different applications are in the range of AU$22 to AU$69 per m^3. This low-cost technology should find wide commercial appeal and use in the timber, biocomposite, and pulping industries.

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