Eur. J. Wood Prod.
DOI 10.1007/s00107-010-0428-8

ORIGINALS ORIGINALARBEITEN

Microwave modification of Radiata pine railway sleepers for preservative treatment

Peter Vinden · Grigory Torgovnikov · Jeff Hann

Received: 9 November 2009

Abstract The use of hardwood railway sleepers in Australia is limited by hardwood timber resources, thus softwood sleepers made from plantation Radiata pine (*Pinus radiata*) may replace them. Low permeability pine heartwood does not allow for good impregnation with preservatives. Microwave (MW) wood modification increases heartwood permeability and improves preservative distribution and uptake. The experimental study of MW sleeper modification and impregnation, allows for the rational MW process parameters and preservative treatment schedules to be determined, with an estimate of the effect of MW treatment on sleeper quality, and for recommendations to be provided to industry. On the basis of the research results a 400 kW commercial MW plant capable of an output of 100,000 sleepers per annum has been designed. The costs of MW sleeper processing are acceptable to industry and provide good opportunities for the commercialization.

Verbesserung der Imprägnierung von Eisenbahnschwellen aus Radiatakiefer mittels Mikrowellen

Zusammenfassung In Australien ist aufgrund der Laubholzressourcen die Verwendung von Laubholz für Eisenbahnschwellen beschränkt. Als möglicher Ersatz sind Schwellen aus in Plantagen angebauter Radiatakiefer (*Pinus radiata*) denkbar. Wegen der geringen Durchlässigkeit des Kiefernkernholzes kann dieses nicht gut imprägniert werden. Mit einer Mikrowellen- (MW) behandlung des Holzes wird die Durchlässigkeit von Kernholz erhöht und die Schutzmittelaufnahme und -verteilung verbessert. In dieser Studie über Mikrowellenbehandlung und Imprägnierung von Schwellen konnten die Parameter der Mikrowellenbehandlung und der Schutzmittelbehandlung bestimmt werden. Weiterhin konnten der Einfluss einer MW-Behandlung auf die Qualität der Schwellen geschätzt und Empfehlungen an die Industrie gegeben werden. Aufbauend auf den Forschungsergebnissen wurde eine kommerzielle 400 kW MW-Anlage mit einer Jahreskapazität von 100.000 Schwellen entworfen. Die Kosten der MW-behandlung von Schwellen sind für die Industrie annehmbar und die Chancen für eine Vermarktung stehen gut.

P. Vinden · G. Torgovnikov (✉) · J. Hann
Forest and Ecosystem Science, Melbourne University, 1 Water St, Creswick, Victoria 3363, Australia
e-mail: grigori@unimelb.edu.au

1 Introduction

The use of hardwood railway sleepers in Australia is limited by hardwood timber resources, and thus softwood sleepers made from plantation grown Radiata pine (*Pinus radiata*) timber may replace them. Radiata pine sleepers must be impregnated with preservatives to have high durability. But a part of the sleeper cross section consists of heartwood (central part of the tree stem) which is practically impermeable, and preservative solutions do not penetrate this timber. MW modification of wood structure can increase the wood permeability and open new opportunities for increasing timber durability by impregnation with preservatives.

Green or freshly sawn Radiata pine wood has moisture contents ranging from 35 to 160%. Due to its high moisture content, green wood readily absorbs microwave energy. Intense MW power applied to the wood generates steam pressure within the wood cells. Under high internal pressure the weak ray cells are ruptured to form pathways for easy transportation of liquids and vapors in the radial direction. An increase in the intensity of the MW energy applied to the wood

Published online: 01 April 2010

increases the internal pressure, resulting in the formation of narrow voids in the radial-longitudinal planes, and 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 (Vinden et al. 2004; Torgovnikov and Vinden 2009).

The study of MW timber processing of softwood species for preservative impregnation showed that Radiata pine, Douglas fir, Sitka spruce heartwood sawn timber with sizes up to 100 × 100 mm^2 and peeler cores up to 130 mm diameter can be MW modified and preservative treated according to standard requirements (Sugiyanto et al. 2008). Railway sleepers have large cross sections (130 × 260 and 130 × 225 mm^2) and MW process parameters for increasing wood permeability and special equipment were required.

New MW technology for wood modification required the establishment of new techniques and MW equipment to provide the required degree of wood modification and satisfy the special demands of the timber industry. To reach the required quality of wood modification for different applications, the MW equipment must have the ability to control the following operating parameters: frequency, MW intensity (flux), energy absorbed by wood, mode of energy application to wood (pulse or continuous), vector electric field strength "E" orientation relative to wood grain, energy distribution in timber cross section, MW applicator configuration, speed of timber through applicator, air flow parameters (temperature and speed), MW leakage protection (Torgovnikov and Vinden 2009).

The difficulties for MW sleeper processing are due to the differing amounts and location of sapwood and heartwood throughout a cross section. Heartwood and sapwood have distinctly different moisture contents (MC). MC of sapwood can be in the range between 120 and 160%, while heartwood MC is in the range of 35–55%. This difference in MC causes a significant difference in dielectric properties of moist wood and wood MW absorption ability. Also the different ratio of heartwood/sapwood creates high variability of energy release within a sleeper cross section. To develop rational process parameters for getting required preservative distribution and uptake in sleeper cross section it is necessary to study experimentally the MW modification process.

The research objectives include:

- an experimental study of the MW interaction with Radiata pine sleepers using a four port MW applicator,
- a study of the effect of MW process parameters on preservative distribution and uptake in sleepers and determination of the rational process parameters of modification,
- a determination of the effect of MW modification on the sleeper strength properties,
- a study of impregnation process parameters to get required preservative distribution in sleepers and uptake,
- recommendations for MW process parameters and technology for commercial MW modification of sleepers.

2 Materials and methods

Radiata pine railway sleepers from plantation grown timber measuring 130 × 260 × 2700 mm^3 (550 sleepers) and 130 × 225 × 2100 mm^3 (595 sleepers) were used in the experiments. Every sleeper consisted of sapwood and heartwood with different ratios, densities and moisture content. Variants of the heartwood position in sleeper cross section are shown in Fig. 1. Measurements taken showed that 83% of the 130 × 225 mm^2 sleepers had 70–100% of heartwood in the sleeper cross section, 15% had 50–69%, and 2% had less than 49% of heartwood. In 130 × 260 mm^2 sleepers, 84% of sleepers had 40–69% of heartwood, 13% had 70–79%, and only 3% had less than 40% of heartwood. Sapwood moisture content was in the range of 70 to 120% and heartwood in the range of 20 to 45%. Oven dry density of sapwood and heartwood were in the range of 350–600 kg/m^3 with an average of 480 kg/m^3.

Because of a very high difference in MC, the wood MW energy absorption ability at a frequency of 0.922 GHz and oven dry density of 480 kg/m^3 differs 4 times (compare wood dielectric constant at temperature of 90°C and 20% MC is $\varepsilon = 3.5$ and $\mathrm{tg}\,\delta = 0.14$, at 100% MC it is $\varepsilon = 13.1$ and $\mathrm{tg}\,\delta = 0.15$). High variability in the heartwood/sapwood ratio, their position in the sleeper cross section, MC, density and large differences in MW energy absorption ability of different sleeper areas did not allow accurate modeling of the energy release in sleepers and wood modification. Therefore, an experimental study was carried out to determine possibilities of the practical use of the MW process of

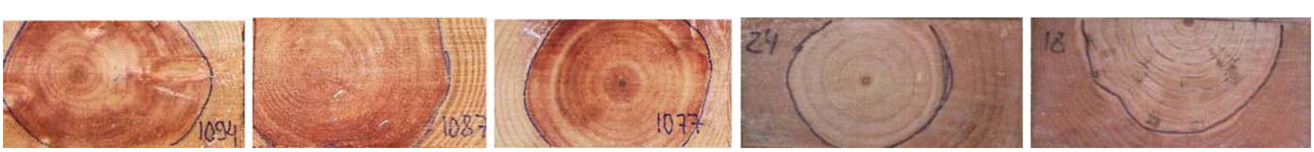
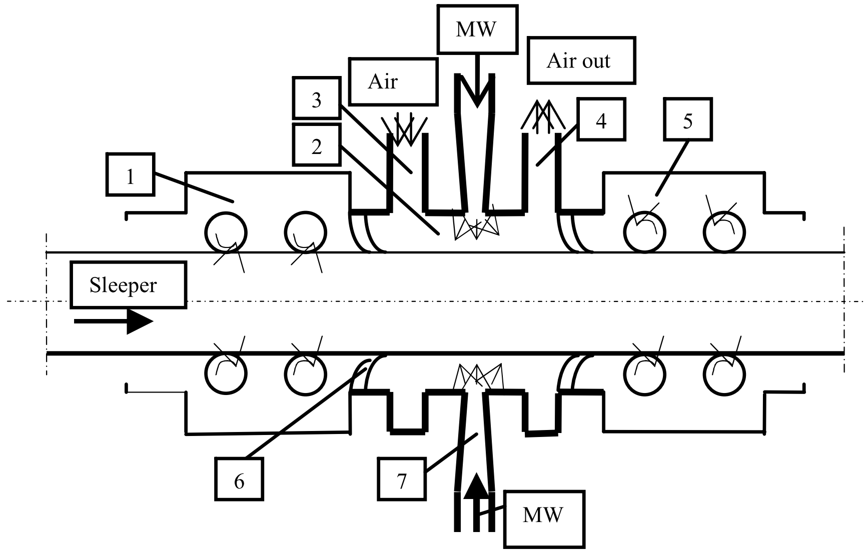


Fig. 1 Heartwood position in Radiata pine railway sleeper cross section. Central part of the sleeper cross section is heartwood (MC = 25–40%), the rest—sapwood (MC = 70–120%)

Abb. 1 Lage des Kernholzes im Querschnitt von Radiatakiefernschwellen. Der innere Bereich des Schwellenquerschnitts ist Kernholz (*u* = 25–40%), der Rest ist Splintholz (*u* = 70–120%)

Fig. 2 300 kW MW plant diagram. *1*—in-feed mechanism, *2*—MW applicator, *3*—air supply inlet, *4*—air outlet, *5*—out-feed mechanism, *6*—MW suppressor, *7*—MW radiator for energy supply to the applicator
Abb. 2 Schema einer 300 kW Mikrowellenanlage. *1* Zufuhrvorrichtung, *2* Mikrowellenapplikator, *3* Luftzufuhr, *4* Luftaustritt, *5* Auslaufvorrichtung, *6* Mikrowellenabschirmung, *7* Mikrowellenradiator zur Energiezufuhr zum Applikator



wood modification for sleeper processing prior to preservative treatment.

A 300 kW MW plant (frequency 0.922 GHz) was used for experiments (Fig. 2). It is capable of: handling timber with cross sections up to 200×300 mm^2 and 4700 mm in length; output—0.5–2.5 m^3/h; MW power—30–300 kW; feed speed—up to 8.5 m/min. The key part of every MW plant is the applicator which must provide the required energy distribution within the timber. A four port MW applicator (Fig. 3) was used for sleeper processing. It has a stainless steel rectangular body $200 \times 340 \times 500$ mm^3 and four radiator inlets (waveguides with open ends 124×200 mm^2) through which MW energy was supplied to the applicator from three generators G1, G2, and G3 with maximum 100 kW each. Generator G1 supplied power P1 to the applicator top, G2 supplied power P2 to the applicator bottom, and G3 supplied power P3 via a power divider (50% by 50%) to applicator sides (full power $P = P1 + P2 + 2P3/2$). Generators G1 and G2 provided electric field strength vector E orientation parallel or perpendicular to wood grain, generator G3—perpendicular to the grain.

During experiments, timber is held rigid in the applicator and can be transported through the applicator at controllable speeds. Energy distribution within the timber was determined by measuring the temperature at different points across the timber cross section and along the sleeper by means of thermocouples after MW heating of the wood up to 80–100°C.

MW power applied to the sleepers was in the range of 110 to 209 kW measured by power meters during timber processing. MW energy applied to the sleepers was in the range of 70 to 153 kWh/m^3. The average MW intensity (flux) in the radiator cross section 124×200 mm^2 was in the range of 0.15–0.28 kW/cm^2. Specific MW power released in the modification sleeper zone was in the range of 5000 to 8800 kW/m^3. The required log speed was provided through a variable speed drive in the range of 12 to 24 mm/s. Vapours and water released from the wood during the modification were removed from the applicator by high speed 90–110°C air flow. MW wood modification schedules used in experiments are displayed in Table 1. 72 sleepers were MW treated using two passes via applicator. During the first pass the sleepers were heated up to 80–90°C with applied power of 90–100 kW. During the second pass the sleepers were modified with applied power of 140–150 kW.

Three types of preservatives were used in the experiments: Copper Naphthenate solution, creosote and CCA (copper-chrome-arsenic). A Copper Naphthenate solution (density 0.93 kg/l) was used for the sleeper preservative treatment using two schedules. Schedule 1 parameters: initial air pressure 40 kPa for 6 min, treatment pressure 600 kPa—1 min, final vacuum—85 kPa—15 min were determined from preliminary experiments and found optimal for sleeper Hazard Class 4 solution retention. Schedule 2 parameters: initial air pressure 150 kPa for 5 min, treatment pressure 240 kPa—15 s, final vacuum—85 kPa—15 min.

Creosote (density 1.08 kg/l) treatment of the sleepers was done using commercial schedules on site at a treatment plant at Carter Holt Harvey's Mt Gambier mill. Treatment was afforded using a schedule that consisted of an initial air pressure of 350 kPa (6 min), an impregnation pressure of 1400 kPa (12 min) and a final vacuum of −75 kPa (35 min). For CCA treatment the following schedule was used: initial vacuum −85 kPa for 20 min, pressure 1300 kPa for 20 min, final vacuum −85 kPa for 20 min. Preservative uptake was used as an indicator of the wood permeability for liquids.

Preservative distribution in the sleeper cross section must answer to Australian Standard 1604.1 (2000) Hazard class 4 (H4): the preservative shall penetrate all the sapwood; unpenetrated heartwood shell be permitted, provided that it

Table 1 MW sleeper modification schedules (frequency 0.922 GHz)
Tab. 1 Mikrowellenbehandlungsprogramme der Schwellen (Frequenz 0,922 GHz)

Sleeper size, mm; preservative	Sleeper weight, kg	Timber green density, kg/m^3	MW power of every generator, kW	Applied MW power, kW	Sleeper speed, mm/s	MW energy, kWh/m^3
130 × 225 × 2100 Copper Naphthenate	35–45	570–730	64.6	194	24	75
			56.9 × 2 + 80	194	24	75
			36.6	110	12	85
			44.2	133	14	88
			49.4	148	14	98
130 × 260 × 2700 Copper Naphthenate	59–63	650–690	67	201	22	75
			54.8	164	18	75
			58.4	175	18	80
			69	207	20	85
			62	186	18	85
			65.7	197	18	90
			51	153	14	90
	73–77	800–850	69.5	209	18	95
			65	195	16	100
			62.3	187	14	110
130 × 260 × 2700 Creosote	56–60	620–660	30 46.7	Heating 90 + modification 140	14–16	135
			33.3 50	Heating 100 + modification 150	14–16	153
130 × 260 × 2700 CCA (copper-chrome-arsenic)	56–60	620–660	30 46.7	Heating 90 + modification 140	14–16	135
			33.3 50	Heating 100 + modification 150	14–16	153
Copper Naphthenate	53	580	30 46.7	Heating 90 + modification 140	14–16	133

comprises less than 20% of the cross section of the piece and does extend more than halfway through the piece from one surface to the opposite and does not exceed 50% of the width of the surface on which it occurs.

The following MW process variables were used for MW sleeper processing: MW power and intensity, MW energy consumption, electric field strength vector E orientation to wood grain, speed of timber in the applicator. Sleeper modification quality was determined by examining: preservative distribution in cross section, preservative uptake, check distribution in cross section and along the length, sleeper shape changes, strength properties, and adequacy to Australian Standards 1604.1 (2000) and Australian Standards 3818.2 (2004).

Sleeper bending strength and stiffness were tested by Salisbury Research Centre (Queensland, Australia) according to the methods specified in Australian Standard (AS/NZS 4063 1992). Details for the testing were as follows: load was applied and measured with a Shimadzu 30 tonne universal testing machine; deflection was measured at centre span with a Type MLT displacement transducer; bending test span—2070 mm with load applied at third points: specimens were loaded on the minor axis; localised crushing was avoided by placing 100 × 300 mm^2 bearing plates between each loading roller and the test specimen.

3 Results and discussion

3.1 MW processing

Experiments with the four port MW applicator on sleepers with uniformly distributed MC = 31–35% enabled the estimation of energy distribution within sleeper cross sections and along the length. After MW heating of the sleepers the maximum temperature was found in the central zone of the sleeper opposite the centre of the radiators (Fig. 4). And the

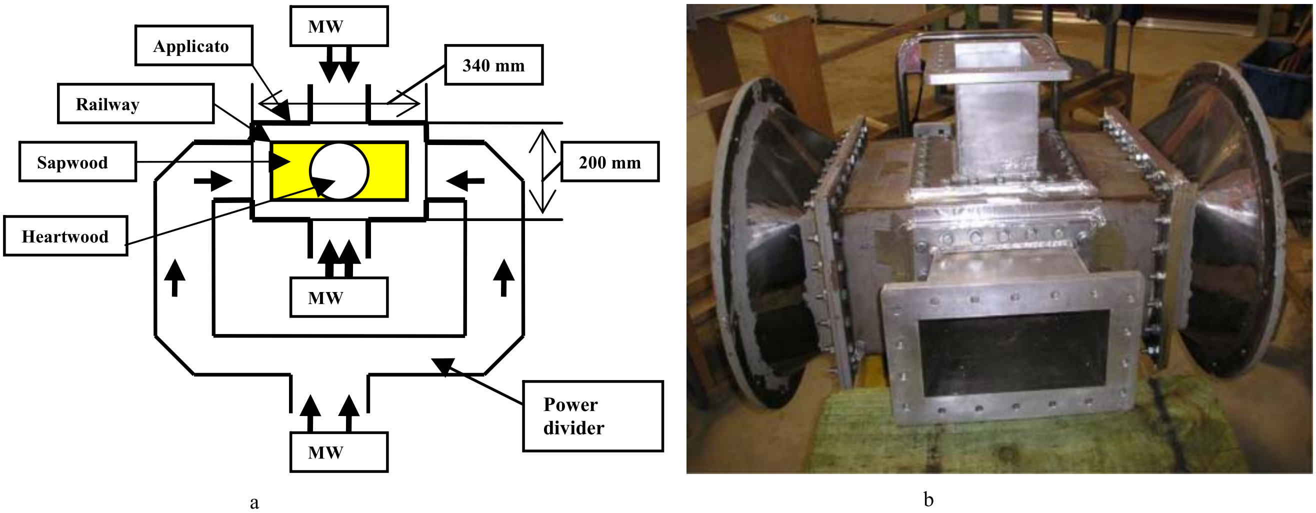


Fig. 3 MW applicator for railway sleepers with power supply to the applicator via four ports (radiators). (**a**) Diagram, central part of the sleeper cross section is heartwood (MC = 25–40%), the rest—sapwood (MC = 70–120%), (**b**) applicator photo
Abb. 3 Mikrowellenvorrichtung für Eisenbahnschwellen mit Energiebeaufschlagung über vier Kanäle (Radiatoren). (**a**) Schema, der innere Bereich des Schwellenquerschnitts ist Kernholz ($u = 25$–40%), der Rest ist Splintholz ($u = 70$–120%), (**b**) Foto der Vorrichtung

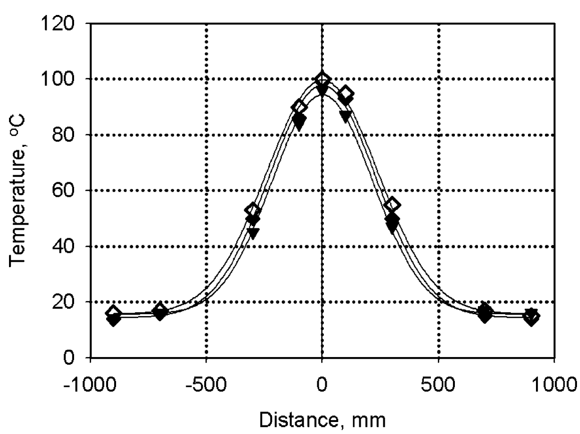


Fig. 4 Temperature distribution along the sleeper (size 130 × 260 mm^2, MC = 34%, oven dry density 480 kg/m^3) after heating for 20 seconds in the MW applicator. MW power of 90 kW was supplied via 4 radiators (from top and bottom 25 kW each and 20 kW from every side, vector E orientation is perpendicular to the wood grain in all ports. 0—plane of the radiator centres)
Abb. 4 Temperaturverteilung in Schwellenlängsrichtung (Querschnitt 130 × 260 mm^2, $u = 34\%$, Darrrohdichte 480 kg/m^3) nach 20-sekundiger Erhitzung in der Mikrowellenvorrichtung. Mikrowellenleistung 90 kW, Zuführung über 4 Radiatoren (von oben und unten jeweils 25 kW und von jeder Seite jeweils 20 kW, die Orientierung des Vektors E ist in allen Radiatoren rechtwinklig zur Faserrichtung. 0 = Mitte der Radiatoren)

heated zone spreads along the sleeper up to 700 mm in both directions from the centre of the radiators.

Study of the temperature distribution within the sleepers with uniform moisture content showed that practically all applied energy was absorbed in a 1400 mm sleeper length. The central 200 mm zone absorbs 32% and the 400 mm zone absorbs 57% of supplied MW energy. MW modification takes place mainly in the 200 mm zone with highest energy concentration. Temperature measurements showed that the applicator can provide a uniformity of energy release within the sleeper cross section with variation of 5–7% in sleepers with uniform MC distribution (31–35%) (Fig. 5). The change of the vector E orientation from perpendicular to parallel to the wood grain in top and bottom ports of the applicator allows for reducing the length of the absorption zone by 17%. This is an advantage because it reduces energy dissipation along the sleeper and increases energy release in the modification zone. The measurements of the temperature in the sleeper cross section and along the length showed that the designed applicator can provide good uniformity of the MW energy distribution and concentration required for wood modification.

The main factor effecting increase of wood permeability is MW energy applied to the wood. The change of the vector E orientation to wood grain in top and bottom radiators from parallel to perpendicular did not show any perceptible effect on wood modification estimated by solution distribution in sleeper cross section after impregnation. Appreciable effect of the sleeper speed on the degree of wood modification at the same applied energy and specific power release in the range of 5000 to 8800 kW/m^3 was not found. These can be explained by high variability of sleeper properties: heartwood/sapwood ratio, different moisture content and density in timber cross section, different dielectric properties of heartwood and sapwood. In order to produce good modification, sleepers required a specific power release in wood of at least 5000 kW/m^3.

During MW modification every sleeper lost moisture by evaporation and water removal in liquid form by in-

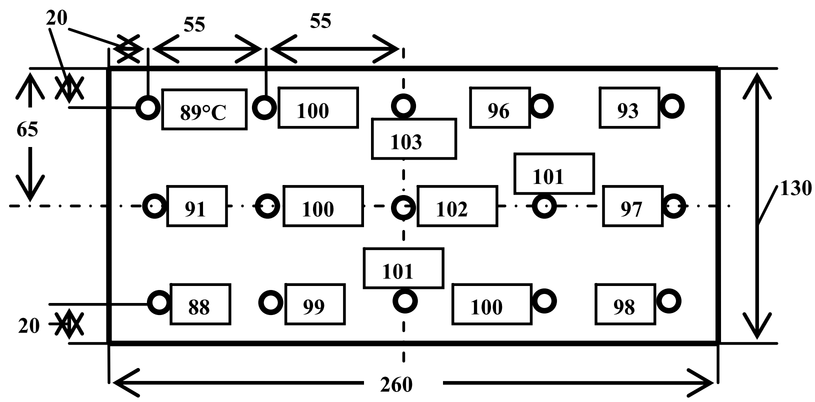


Fig. 5 Temperature distribution in the sleeper cross section (size 130 × 260 mm^2, MC = 34%, oven dry density 480 kg/m^3) after traveling via applicator. MW power of 90 kW was supplied via 4 radiators (from top and bottom 25 kW each and 20 kW from every side, vector E orientation is perpendicular to the wood grain in all ports; speed—14 mm/s. *Values in boxes*—temperature in °C measured in 15 points marked by *circles*)
Abb. 5 Temperaturverteilung im Schwellenquerschnitt (Abmessung 130 × 260 mm^2, u = 34%, Darrrohdichte 480 kg/m^3) nach dem Durchlauf durch die Mikrowellenvorrichtung (siehe Abb. 4) Geschwindigkeit—14 mm/s. Werte in Kästchen—Temperatur in °C, an 15 mit Kreisen markierten Stellen gemessen

Table 2 Sleeper moisture losses and Copper Naphthenate preservative uptake for different MW schedules and preservative treatment Schedule 1
Tab. 2 Feuchteverluste der Schwellen und Aufnahme von Kupfernaphtenatschutzmittel bei verschiedenen Mikrowellenprogrammen. Imprägnierprogramm 1

Sleeper size, mm	Sleeper weight, kg	Timber green density, kg/m^3	Applied MW power, kW	Sleeper speed, mm/s	MW energy, kWh/m^3	MC loss, %	MC loss variation coefficient, %	Solution uptake (Schedule 1), l/m^3	Uptake variation coefficient, %
130 × 225 × 2100	35–45	570–730	194	24	75	16.2	19.3	67	19
			194	24	75	20.2	20	62	27.6
			110	12	85	21	16.3	94	24.1
			133	14	88	22.7	12.2	102	21.6
			148	14	98	22.5	7.8	112	15.4
130 × 260 × 2700	59–63	650–690	201	22	75	17.8	15.9	38.7	30.3
			164	18	75	19.3	25.6	49.5	18.4
			175	18	80	21.3	14.8	51.6	16.1
			207	20	85	17.2	10.9	45.2	13.7
			186	18	85	22.1	18.7	52.7	23.3
			197	18	90	22.1	14.6	50.5	26.8
	73–77	800–850	209	18	95	27.7	27.4	32.2	31.7
			195	16	100	22.7	19.4	50.5	33.7
			187	14	110	25.4	14.6	46.2	14.5

ternal pressure via sleeper ends, surfaces and cracks and also in the form of small drops by small steam explosions. Sleeper MC losses depending on MW schedules are shown in Table 2 and Fig. 6. MC loss increased proportionally to the increase of the applied energy. During MW modification sleepers lost 16–28% of their moisture content and variation coefficient of MC values ranges between 8 and 27%. The quantity of MW energy spent for removal of 1 kg water from the sleeper was in the range of 0.79 to 1.03 kWh/kg. In the process of modification, resin is mobilized and may be released from the sleepers in vapor and liquid phases. The dry resin quantity measurement after modification of 104 sleepers showed that on average 12 g of resin is released from a sleeper 130 × 260 × 2700 mm^3 or 0.132 kg/m^3.

The MW energy consumption required for proper modification needs to be 75–110 kWh/m^3 depending on the sleeper green density (weight). Higher energy application increases wood permeability and uptake but leads to sleeper deformation and significant strength reduction.

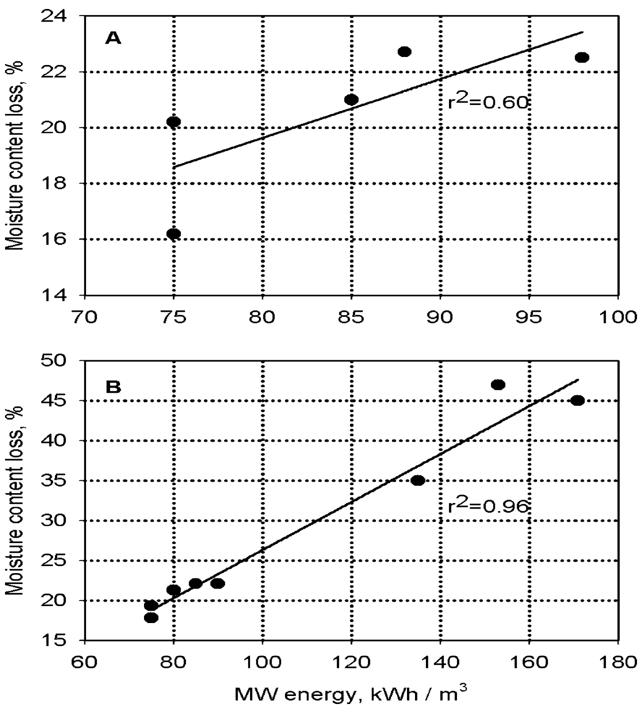


Fig. 6 Sleeper moisture content losses depending on applied MW energy. (**a**) sleeper size 130 × 225 mm^2 and wood green density range 570–730 kg/m^3, (**b**) sleeper size 130 × 260 mm^2 and wood green density range 650–690 kg/m^3

Abb. 6 Holzfeuchteverluste der Schwellen in Abhängigkeit der zugeführten Mikrowellenleistung. (**a**) Schwellenabmessung 130 × 225 mm^2 und Rohdichtebereich des frischen Holzes 570–730 kg/m^3, (**b**) Schwellenabmessung 130 × 260 mm^2 und Rohdichtebereich des frischen Holzes 650–690 kg/m^3

3.2 Sleeper quality

MW modification does not produce significant changes in the size and shape of the sleepers. The sleeper bow, spring and twist do not exceed the technical limit of 5 mm per meter length. According to the technical requirements for Grade 2 quality sleepers (Australian Standard AS 3818.2 2004) they cannot have end splits greater than 100 mm long, internal checks width larger than 2 mm whilst surface cracks sizes are not limited. 90–95% of MW modified sleepers meet these grading requirements and are suitable for the desired industrial use.

MW modification ruptures some elements of the wood structure and reduces the strength of the timber. Strength tests of 60 MW modified sleepers at 17% moisture content gave an average modulus of elasticity (MOE) value of 8.1 GPa with variation coefficient of 20.5% and a modulus of rupture (MOR) of 31.9 MPa with a variation coefficient of 31.5%. These MOE and MOR values mean that modified sleepers are strong enough to be used in railway lines.

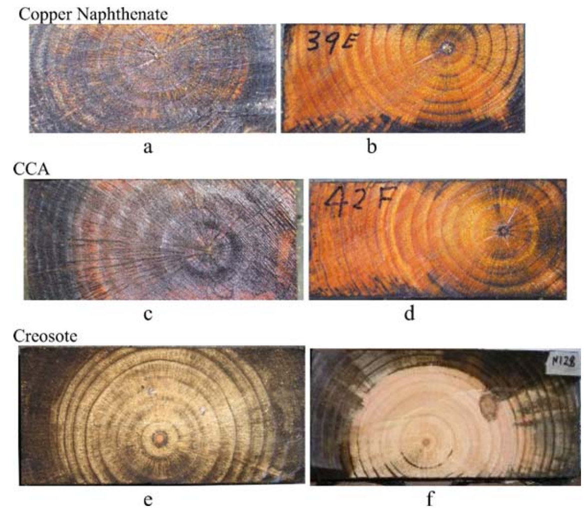


Fig. 7 Sleeper cross section impregnated by preservatives after MW modification and controls. Copper Naphthenate: (**a**) MW treated—full cross section preservative penetration, (**b**) control, solution penetrates only to some small areas. CCA: (**c**) MW treated—full cross section preservative penetration, (**d**) control, only some areas are preservative treated. Creosote: (**e**) MW treated—full cross section preservative penetration, (**f**) control, only sapwood is preservative treated

Abb. 7 Querschnitt von nach der Mikrowellenbehandlung mit Schutzmitteln imprägnierten Schwellen und Kontrollproben Kupfernaphtenat: (**a**) MW-behandelt—Schutzmittel dringt in ganzen Querschnitt ein, (**b**) Kontrollprobe, Schutzmittel dringt nur in kleine Bereiche ein. CCA: (**c**) MW-behandelt—Schutzmittel dringt in ganzen Querschnitt ein, (**d**) Kontrollprobe, nur in wenigen Bereichen ist Schutzmittel vorhanden, Teeröl: (**e**) MW-behandelt—Schutzmittel dringt in ganzen Querschnitt ein, (**f**) Kontrollprobe, nur im Splintholz ist Schutzmittel vorhanden

3.3 Preservative treatment

Experiments showed that MW modification can provide preservative penetration to heartwood and required distribution in timber cross section (Fig. 7). From the point of the preservative distribution 90–95% of the sleepers meet Australian Standard 1604 2000, Hazard Class 4, 5, and 6: the preservative shall penetrate all the sapwood; unpenetrated heartwood shell be permitted, provided that it comprises less than 20% of the cross section of the piece and does extend more than halfway through the piece from one surface to the opposite and does not exceed 50% of the width of the surface on which it occurs. Many sleepers had full cross section preservative penetration. Preservative uptake was used as an indicator of increasing the wood permeability for liquids. Compared to the control sleepers the MW modified samples had at similar conditions an uptake 1.8–4.5 fold higher (Table 3) for Copper Naphthenate, CCA and Creosote. It means that MW modification provides very significant wood permeability increase.

Applied to the sleepers 130 × 225 mm^2, MW energy increase from 75 to 98 kWh/m^3 leads to Copper Naphthenate solution uptake increase from 62–67 to 112 l/m^3 (1.7–1.8

Table 3 Sleeper uptake comparison of the MW modified and control samples impregnated at the same conditions
Tab. 3 Vergleich der Schutzmittelaufnahme in Mikrowellen behandelten Schwellen und Kontrollproben, die unter gleichen Bedingungen imprägniert wurden

Preservative	Impregnation process	Timber green density, kg/m^3	Initial MC, %	MW energy, kWh/m^3	MC after MW, %	Uptake of MW modified samples, l/m^3	Uptake variation coefficient, %	Uptake of the control samples, l/m^3	Uptake increase, times
Creosote	Initial air pressure 350 kPa (6 min), impregnation pressure of 1400 kPa (12 min) and a final vacuum −75 kPa (35 min)	620–660	64–76	135–153	29	139–160	14	51 (convent ionally seasoned)	2.7–3.1
Copper-chrome -arsenate (CCA)	Vacuum −85 kPa for 20 min, pressure 1300 kPa for 20 min, final vacuum −85 kPa for 20 min	620–660	64–76	135–153	29	275	16	149 (convent ionally seasoned)	1.8
Copper Naphthen-ate	Schedule 2. Pressure 150 kPa for 5 min, pressure of 240 kPa for 15 sec and vacuum −85 kPa for 15 min	580	52	133	17	125	22	28 (green)	4.5

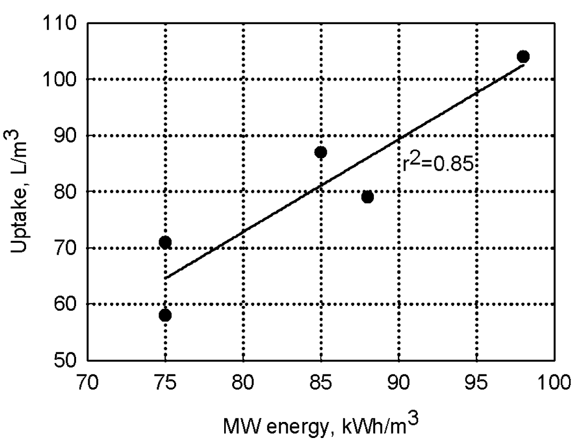


Fig. 8 Dependence of Copper Naphthenate uptake on the applied MW energy, impregnation Schedule 1. Radiata pine sleepers 130 × 225 mm^2, average initial MC = 35%, heartwood occupies 70–100% of cross section area, OD density 480 kg/m^3
Abb. 8 Kupfernaphtenataufnahme in Abhängigkeit der zugeführten Mikrowellenleistung, Imprägnierprogramm 1. Radiatakiefernschwellen 130 × 225 mm^2, durchschnittliche Anfangsholzfeuchte = 35%, Kernholz nimmt 75–100% der Querschnittsfläche ein, Darrrohdichte 480 kg/m^3

fold increase) (Table 2). Figure 8 illustrates a similar tendency in uptake increase at different sleeper wood properties. So, to get required uptake of about 50 l/m^3 for sleepers with a weight of 35–45 kg (green density 570–730 kg/m^3) it is necessary to apply MW energy of 70–75 kWh/m^3. Energy increase from 75 to 98 kWh/m^3 applied to the sleepers 130 × 260 mm^2 with a weight of 59–63 kg (green density 650–690 kg/m^3) did not show significant difference in uptake increase in this energy range. The uptake fluctuated in the range between 38.7 and 52.7 l/m^3 (variation coefficient ranged between 14 and 30%) with a tendency to grow with increases in applied energy. Sleepers with a weight of 73–77 kg (green density 800–850 kg/m^3) had a moisture content of 67–76%, therefore to obtain required uptakes it was necessary to apply 100–110 kWh/m^3.

Research results showed that MW modification can provide the required sleeper modification for subsequent preservative impregnation. The treatment increases wood permeability by 1.8–4.5 times, and allows for the required preservative uptake and distribution. The study of all sides of the MW sleeper modification allowed an estimate of the effect MW treatment has on sleeper impregnation and quality, to determine the rational MW process parameters and impregnation parameters, and demonstrate applicability of a four port MW applicator for commercial use. On the basis of the research results, a 400 kW commercial MW plant has been designed capable of an output of 100,000 sleepers per annum.

The economic calculations of the MW modification of Radiata pine railway sleepers for commercial plant output of 16,000–24,000 m^3 per annum show costs of AU\$26.4–42.6/m^3 assuming electricity charges ranging from AU\$0.06–0.12/kWh. These costs include capital (equipment) costs, labor, electricity, maintenance, magnetron replacement, floor space costs, but do not include electrical connections, mechanical installation and taxes.

4 Conclusion

The diameter of plantation Radiata pine logs allows only one sleeper from a sleeper length log, therefore the overwhelming majority of the sleepers has a percentage of heartwood of more than 60–70%. The heartwood has low permeability and is very difficult for impregnation. MW sleeper modification increases heartwood permeability enabling the treater to achieve the required quality of sleeper preservative treatment with different preservatives.

Experimental study of the energy release in sleeper cross section after processing by a four port MW applicator showed uniform temperature distribution (variation 5–7%) in the sleepers at uniform wood moisture content 31–35%. All applied MW energy was absorbed in a 1400 mm sleeper length. The central 400 mm length zone absorbs 57% of supplied MW energy. The change of the vector E orientation from perpendicular to parallel to the wood grain in top and bottom ports of the applicator reduces the length of the absorption zone by 17%.

MW modification ruptures some elements of wood structure and leads to timber strength reduction. Strength tests of 60 MW modified sleepers at 17% moisture content showed modulus of elasticity (MOE) value of 8.1 GPa and modulus of rupture (MOR) value of 31.9 MPa. These MOE and MOR values meet the allowable limits for the use of sleepers in railway lines. According to the technical requirements for sleepers Grade 2 quality (Australian Standard AS 3818.2 2004) they cannot have end splits more than 100 mm, internal checks width more than 2 mm and surface cracks sizes are not limited. 90–95% of MW modified sleepers answer to these requirements.

The MW energy required for modification depends on sleeper wood density and moisture contents. The amount can range from 75 to 110 kWh/m^3 at a green density between 600 and 800 kg/m^3. In this density range the application of more than 110 kWh/m^3 can lead to sleeper damage. During the MW modification the sleepers loose 16–28% of MC. Also during MW processing the sleepers loose 0.132 kg/m^3 of resin.

Experiments showed that sleepers with a high percentage of heartwood will have a dramatically increased wood permeability and solution uptake after MW modification. Preservative distribution in sleeper cross sections corresponds to the Australian Standard AS 1604.1. 2000 Hazard Classes 4, 5, and 6. MW energy increase from 75 to 98 kWh/m^3 supplied to the sleepers 130 × 225 mm^2 leads to Copper Naphthenate solution uptake increase from 62–67 to 112 l/m^3 (1.7–1.8 fold increase) at the same impregnation Schedule 1. To get the required uptake of about 50 l/m^3 for sleepers with a green density of 570–730 kg/m^3 it is necessary to apply MW energy of 70–75 kWh/m^3 and use impregnation Schedule 1. Sleepers with a green density of 800–850 kg/m^3 require the application of 100–110 kWh/m^3 to get a similar uptake. Preservative treatment Schedule 1 provides the required uptake of the Copper Naphthenate solution after sleeper MW processing and can be recommended for commercial use.

The study of railway sleeper MW modification for preservative treatment demonstrated the applicability of a four port MW applicator for sleeper processing and allowed rational MW process parameters to be determined, along with the effect that MW has on sleeper quality. On the basis of this research, a 400 kW commercial MW plant has been designed capable of an output of 100,000 sleepers per annum. Economic calculations showed that the costs of railway sleeper modification are in the range of AU\$27–43/m^3 at electricity cost range of AU\$0.06–0.12/kWh. These costs of MW sleeper processing are acceptable for industry and provide good opportunities for commercialization of the new MW technology.

5 Conflict of interest

The authors declare that they have no conflict of interest.

References

Australian Standard AS 1604.1 (2000) Specification for preservative treatment, part 1: sawn and round timber

Australian Standard AS 3818.2 (2004) Timber—heavy structural products—visually graded, part 2: railway track timber

Australian Standard AS/NZS 4063 (1992) Timber-stress-graded. Ingrade strength and stiffness evaluation

Sugiyanto K, Torgovnikov G, Vinden P (2008) Microwave wood modification of timber surfaces for preservative treatment (Congress paper). In: Proceedings of the global congress on microwave energy applications, Otsu, Japan, 4–8 August 2008, pp 229–232

Torgovnikov G, Vinden P (2009) High intensity microwave wood modification for increasing permeability. For Prod J 59(4):84–92

Vinden P, Romero J, Torgovnikov G (2004) A method for increasing the permeability of wood. US Patent No 6,742,278