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MICROWAVE CONVERSION OF PLANTATION GROWN BLUE GUM (*Eucalyptus globulues L'Herit*) WOOD TO TORGVIN AND IMPREGNATION WITH A METAL ALLOY

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Abstract

Microwave modification converts wood into a highly porous material *Torgvin* with numerous cavities and dramatic changes to the physical and mechanical properties of wood including very high permeability. Impregnation of *Torgvin* with a low melting point metal alloy fills the voids with metal. Strength property values of the newly formed *Vintorg*-metal range between the property values of wood and *Torgvin*. *Vintorg*-metal has new properties compared to natural wood: high electro-conductivity, high thermo-conductivity, very high density, and other physical properties that require further study. New specific properties of the *Vintorg*-metal opens up new fields of potential application.

Keywords and phrases: metal alloy, microwave wood modification, microwave applicator, Torgvin, Vintorg-metal.
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1. Introduction

A number of wood species have a very low permeability causing problems during timber processing. Plantation grown Blue gum (*Eucalyptus globulues*) is a fast growing species with variable wood properties including refractory (difficult to impregnate) heartwood. Microwave modification [2, 4, 5] can change Blue gum wood properties and open new potential applications for this species.

Green wood readily absorbs microwave (MW) energy because of its high moisture content. The passage of MW energy through wood results in a very high release of energy from within the material. When intense levels of MW energy are applied to wood, steam is generated within the wood cells. Under high internal steam pressure, the pit membranes in cell walls, tyloses in vessels and the weak ray cells rupture to form pathways for easy transportation of liquids and vapours. Increases in the intensity of applied microwave further increases internal steam pressure, resulting in the formation of narrow voids in the radial-longitudinal planes [5]. A several thousand-fold increase in wood permeability in the radial, tangential, and longitudinal directions can be achieved in species previously found to be impermeable to liquids and gases [2]. MW wood modification improves liquid impregnation and uptake. It is possible to use microwave wood modification to enhance existing processes and to develop entirely new processing and product options for wood.

High degrees of MW modification can convert wood into a highly porous material with numerous cavities mainly in the radial – longitudinal plane. The highly porous material was named "*Torgvin*™" [3]. *Torgvin* can be used as intermediate material for the production of new composite materials, for example, "*Vintorg*™" [6] by impregnation with resins, plastics, and metal alloys.

The research objectives include:

- a study of the effects of MW modification on Blue gum wood structure and properties;
- characterisation of the effect of impregnating MW modified wood with a metal alloy.

2. Material and Methods

2.1. Material

Forty boards of plantation grown Blue gum green sawn timber measuring $42 \times 84 \times 2500$mm with an initial moisture content ranging from 78-108% were used for experimentation. Wood density (for wood moisture contents of 8-12%) ranged from 532 to 858kg/m^3.

2.2. Equipment and experimental procedure

2.2.1. MW wood modification

A 60kW MW experimental installation (Figure 1) was used for wood modification. It includes an MW power supply, waveguides, tuners, Y-type applicator (Figure 2), tunnel, roller feeding system, and air dynamic system for the removal of vapours from the applicator and prevention of water condensation on the walls of the applicator.

Technical data of MW installation:

- MW power – 6-60kW.
- Frequency – 2.45GHz.
- Max dimensions of timber -50×100mm.
- Feed speed – 6-50mm/sec.
- Air heating power – 13kW.
- Air temperature – 20-150°C.

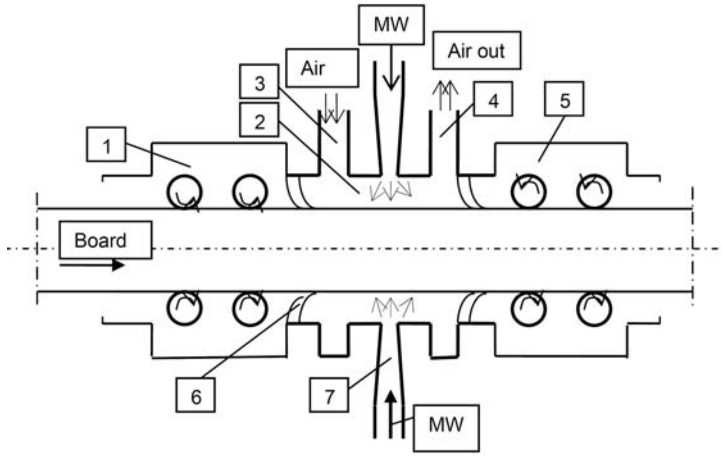


Figure 1. Diagram of MW experimental plant for wood modification: (1) in-feed mechanism; (2) MW applicator; (3) air supply inlet; (4) air outlet; (5) out-feed mechanism; (6) MW suppressor; and (7) MW radiator for energy supply to applicator.

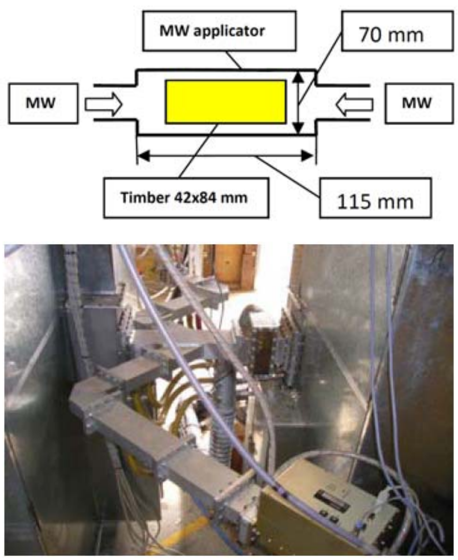


Figure 2. Diagram and photo of MW applicator for wood modification (cross-section $70 \times 115\text{mm}$). MW power at frequency 2.45GHz is supplied from two sides of the applicator.

During preliminary tests, the required parameters and schedule of MW wood modification for *Torgvin* manufacturing were determined:

MW power – 32.5kW supplied from two sides of the applicator.

Applied MW energy – 275kWh/m^3 (990MJ/m^3).

Specific MW power applied to wood in applicator – 46W/cm^3.

Electric field strength vector E orientation – perpendicular to the wood grain.

Board position – in the middle of the applicator, size 42mm is vertical.

Roller conveyor speed – 9.3mm/sec.

Ventilation air temperature – 110ºC.

The boards were processed during the movement through the MW applicator. The criteria for the evaluation of the degree of MW wood modification was the uniformity of the void distribution through the cross-section of the material. More than 85-90% of cross-section area had visible checks, meaning that the sample had good degree of modification.

2.2.2. Sample impregnation with alloy

Dry Blue gum *Torgvin* (10 samples measuring $20 \times 20 \times 340\text{mm}$) were used for impregnation with the metal alloy (Company Belmont alloy No. 2431, bismuth/lead/tin/cadmium). The alloy included a mixture of metals comprising bismuth 42.5%, lead 37.7%, tin 11.3%, and cadmium 8.5%. The alloy melting point was 74ºC and density – 7400kg/m^3. Technical specifications for the alloy included a Brinell hardness of 51MPa, and short term tensile strength of 37.2kPa.

A pressure vessel with heater was used for *Torgvin* sample impregnation. Wood samples were submerged into the metal alloy at a temperature of approximately 120ºC. The container containing the samples were then placed into a pressure vessel for impregnation. After preliminary testing, the following schedule was applied for impregnation of the samples with alloy:

Vacuum	− 85kPa	5 min
Pressure	1200kPa	20 min
Temperature in vessel		120°C.

2.2.3. Sample strength tests

MOR (modulus of rupture), MOE (modulus of elasticity), and surface hardness were used to characterise the strength properties of Blue gum wood, Torgvin, and Vintorg-metal. Australian standards wood testing procedures [1] were applied using universal strength testing machines (Hounsfield HK10-C) and Instron Materials Testing System (Model No. 5569, load capacity 50kN) (see Figure 3).

Samples for strength testing measuring $20 \times 20 \times 340$mm were made from wood (56pc), *Torgvin* (71pc), and *Vintorg*-metal (10pc). During the tests, the load was applied to the samples in the radial (R), tangential (T), and 45° angle in the radial and tangential (CR) directions. The moisture content of samples during testing ranged from 8-12%.

Figure 3. Instron materials testing system (Model No. 5569, load capacity 50kN) and Vintorg-metal samples.

3. Result and Discussion

3.1. Torgvin structure

Conversion of Blue gum wood to *Torgvin* provided macro-changes in wood structure: rupturing of wood cell pore membranes, resin boiling and replacement, destruction of tyloses, rupturing of ray cells, rupturing of libriform fibre walls and walls of vessels, and the formation of cavities (micro-voids) primarily in radial-longitudinal planes. Figures 4 and 5 illustrate Blue-gum / *Torgvin* structure.

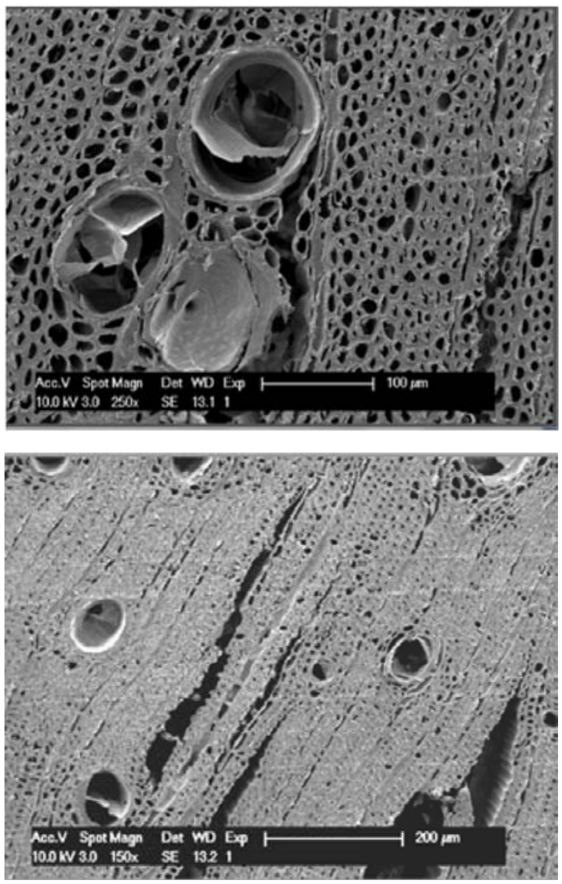


Figure 4. Blue-gum after high degree MW wood modification. Top - broken tyloses in vessels: bottom- checks and broken rays (thin dark lines).

High degrees of MW modification result in the formation of different sized voids in the wood. Voids form on the base of ruptured rays that then extend in the tangential, radial, and longitudinal directions. The number of voids depend on the number of rays in the specific wood volume. The higher the percentage ray tissue the greater the number of cavities formed.

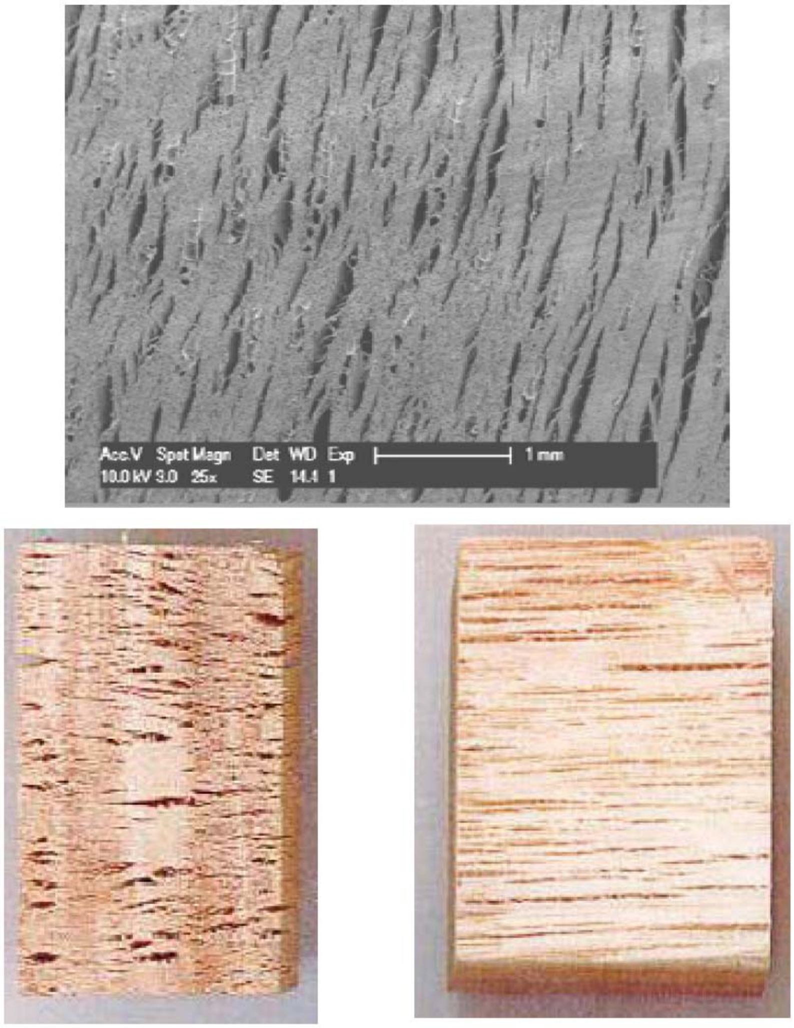


Figure 5. Voids in *Torgvin* manufactured in Blue gum.

The sizes of voids and their distribution in *Torgvin* are shown in the Table 1.

Table 1. Sizes of voids and their distribution in *Torgvin* from plantation grown Blue gum

Void width in tangential direction in the range	Percent of void number in tangential direction	Void length in radial direction	Percent of void number in radial direction	Void length in longitudinal direction	Percent of void number in longitudinal direction	Distance between voids in tangential direction	Percent of distances between voids in tangential direction
mm	%	mm	%	mm	%	mm	%
< 0.5	81.54	< 1.0	8.0	< 5	9.5	< 2	67.3
0.5-1.0	14.31	1-5	62.5	5-10	26.9	2-5	26.7
1-2	3.98	5-10	22.5	10-20	39.1	5-10	4.9
2-4	0.11	10-20	6.0	20-30	15.7	10-20	1.0
4-6	0.06	> 20	1.0	30-40	6.3	> 20	0.1
				40-50	1.5		
				> 50	1.0		

About 96% of voids have widths less than 1.0mm; 93% of voids have lengths in the radial direction less than 10mm, and 76% of voids in longitudinal direction have lengths up to 20mm. Distances up to 5mm between voids in the tangential direction form 94% of all visible distances. There are many "invisible" or very narrow checks (for example, partly destroyed rays) in the wood. However, their assessment requires a special study.

MW Blue gum modification converts wood into a highly porous material with altered properties compared to unmodified wood: improved permeability, reduced density, reduced heat conductivity (better heat insulation), reduced shrinkage and swelling, and improved acoustic properties (better sound insulation). 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 *Vintorg*. *Vintorg* is manufactured from *Torgvin* by impregnating with resin, followed by pressing and curing [4].

3.2. Vintorg-metal structure

During pressure impregnation, a liquid alloy penetrates and fills the voids, cracks, broken rays, and vessels in *Torgvin* to form a wood-metal composite structure. Figure 6 illustrates radial and tangential cuts in *Vintorg*-metal samples. Figure 7 illustrates cross-cut samples. Light colour dots in Figure 7 are vessels filled by metal, light colour lines are broken rays and voids filled with metal.

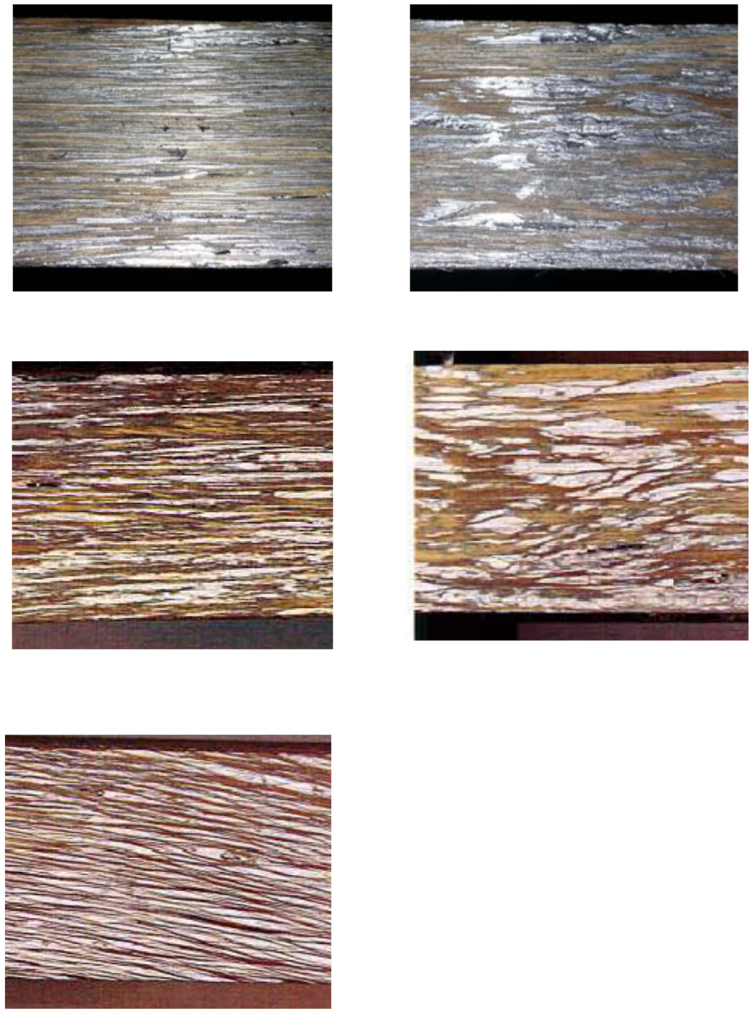


Figure 6. *Vintorg*-metal sample tangential (left) and radial (right) cuts. Vertical size 20mm.

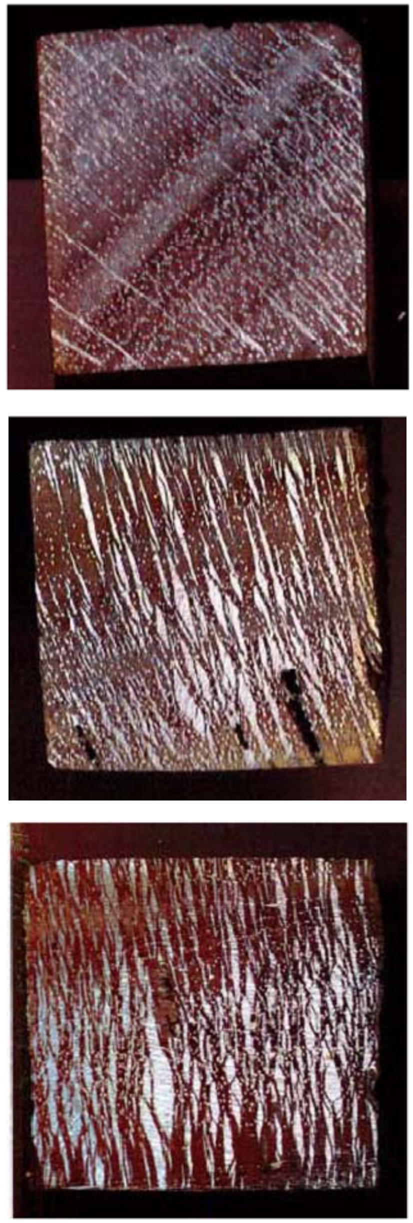


Figure 7. *Vintorg*-metal sample cross cuts. Sample size 20×20mm. Light colour dots are vessels filled by metal, light colour lines are broken rays and voids filled by metal.

3.3. Material properties

(a) Torgvin density

Density is one of the most important wood properties which determines other properties. MW wood modification reduces wood density depending on the species and the degree of modification. *Torgvin* manufactured from Blue gum has an average density 637kg/m^3 (CV 11.6%) at a moisture content 8-12% compared to an original wood density of 697kg/m^3 (CV 10.7%). Density reduction after MW modification is approximately 8.6%.

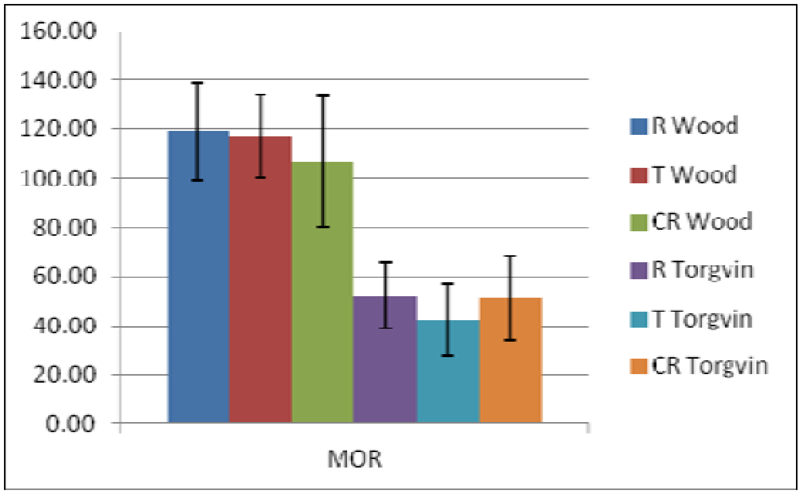
Voids in *Torgvin* occur in the radial and longitudinal planes while size increases mainly in the tangential direction. The level of density reduction is a function of MW energy applied to the wood.

(b) Torgvin strength

MW modification of Blue-gum results in a significant loss of mechanical strength. Conversion of wood to *Torgvin* leads to substantial loss in MOR, MOE, and hardness depending on the applied MW processing schedule. MW treatment at an applied energy of 275kWh/m^3 (990MJ/m^3) shows (Table 2, Figure 8) a reduction in MOR in the radial direction of 2.3 times and in the tangential direction, 2.8 times compared to natural wood. Loss of MOE in the radial direction is 1.6 and in the tangential direction 1.9 times the original wood. *Torgvin* hardness is reduced in the radial direction by 2.8 and in the tangential direction by 2.3 times compared to the original wood.

Table 2. Comparison of mechanical properties Blue gum *Torgvin* and wood

	MOR, MPa			MOE, MPa			Hardness, MPa		
Load application directions	Wood	Torgvin	Wood/ Torgvin ratio	Wood	Torgvin	Wood/ Torgvin ratio	Wood	Torgvin	Wood/ Torgvin ratio
Radial (R)	119	52	2.29	12390	7560	1.64	47	17	2.76
Tangential (T)	117	42	2.79	9150	4740	1.93	45	20	2.25
Under the angle 45^{o} to the radial and tangential directions (CR)	107	51	2.10	11110	6090	1.82	43	19	2.26
Transverse – average of the radial (R), tangential (T) and under the angle 45^{o} (CR) directions	114	48	2.38	10880	6130	1.77	45	19	2.37



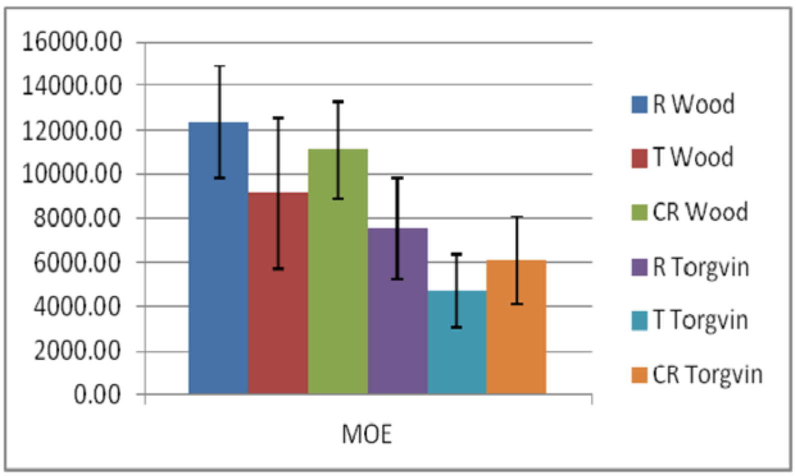


Figure 8. Modulus of rupture (MOR, MPa) and modulus of elasticity (MOE, MPa) of Blue gum wood and *Torgvin* in the radial (R), tangential (T), and 45° angle in the radial and tangential directions (CR). Average wood density: 697kg/m^3, Torgvin: 637kg/m^3 (at MC = 8-12%).

The more significant reductions in MOR and MOE in tangential compared to radial grain directions is due to the fact that voids occur in the radial-longitudinal planes. Variation in *Torgvin* mechanical properties is significantly higher compared to wood. The coefficient of variation (CV) of *Torgvin* MOR is 31.9%, compared to the original wood (CV = 19.9%). *Torgvin* MOE is 37.3%, compared to the original wood (CV = 20.8%). More significant surface hardness reductions in the radial direction compared to the tangential face is explained by the easier penetration of indentation ball into surfaces with checks compared to surfaces without checks.

Whilst the rupture of wood structural elements reduces the strength properties of *Torgvin*, the subsequent porous structure of *Torgvin* and high permeability for liquids provides opportunities for impregnation the material with resins, plastics, and low melting temperature alloys to get composite materials with desirable properties.

(c) Vintorg-metal

After impregnation of *Torgvin* with metal alloy, the voids and vessels are filled with metal, increasing the density of the subsequent *Vintorg* up to $2520 - 4020 \text{kg/m}^3$ (with an average density of 3275kg/m^3) and density variation (CV%) of 17.6%. Density variation arises from the high variation in void volumes and vessels. The mass of wood in *Vintorg*-metal ranges from 15.8 to 28.4% (average 19.5%) of the total material mass. The pure alloy has a density of 7400kg/m^3.

Results of *Vintorg*-metal strength tests in comparison to wood and *Torgvin* are shown in Table 3. *Vintorg*-metal MOR is 1.54 times higher compared to *Torgvin* and 1.59 times weaker than the original wood. *Vintorg*-metal MOE is 1.63 times higher than *Torgvin* and 1.08 times weaker than the original wood. *Vintorg*-metal hardness is 2.21 times higher than *Torgvin* and 2.42 times weaker than the original wood.

Table 3. *Vintorg*-metal strength in comparison to wood and *Torgvin*

	MOR, MPa			MOE, MPa			Hardness, MPa		
Load application directions	Wood	Torgvin	Vintorg - metal	Wood	Torgvin	Vintorg - metal	Wood	Torgvin	Vintorg - metal
Radial (R)	119	52	79	12390	7560	10300	47	17	31
Tangential (T)	117	42	68	9150	4740	9710	45	20	52
Transverse (CR) – average of the radial (R) and tangential (T)	118	48	74	10770	6150	10005	46	19	42

Vintorg-metal density increases from 2520 to 4020kg/m^3 (by 1.6 times) leading to average MOR and MOE increases of only 10%. Hardness is increased in the radial direction by 70% and in tangential direction only by 14%.

The alloy fills voids and vessels in *Torgvin* and forms a metal-wood structure, where the material skeleton is essentially wood (Figure 7). Alloy provides some strength to the voids and vessels but the wood skeleton carries the main load. Therefore, an increase in alloy quantity in *Vintorg*-metal by 1.6 times does not significantly improve the MOR and MOE. The alloy used in this study is very soft compared to other low melting temperature metal alloys. Therefore, it can be expected that the use of other alloys can make *Vintorg*-metal stronger then wood.

Vintorg-metal has new properties compared to natural wood: high electro-conductivity, high thermo-conductivity, very high density, different shrinkage and swelling properties, and different acoustic properties. Assessment of these properties requires a special study. *Vintorg*-metal has original surface patterns due to wood-metal structure, which is significantly influenced by the original technological attributes of the wood species. This provides opportunities for using *Vintorg* metal as a decorative material or perhaps for specialised jewellery.

4. Conclusion

MW modification of Blue gum converts wood into a highly porous material *Torgvin* with numerous cavities mainly in the radial – longitudinal planes. MW modification of the wood structure significantly changes the physical and mechanical properties of wood. *Torgvin* strength properties (MOR, MOE, and surface hardness) are reduced by 1.8 to 2.4 times compared to natural wood. More significant MOR and MOE reductions arise in the tangential compared to radial direction. The very high permeability of *Torgvin* facilitates its use as an intermediate material for *Vintorg* manufacture by impregnating the material with suitable resins, plastics or metal alloys.

Blue-gum *Torgvin* impregnated with metal alloy (Company Belmont alloy No. 2431, bismuth/lead/tin/cadmium) converts the material to *Vintorg*-metal. The alloy fills the voids and vessels in *Torgvin* and forms a metal-wood structure, where the material skeleton consists of wood. Alloy changes the physical properties of *Torgvin*. *Vintorg*-metal MOR and MOE are increased by about 1.6 times compared to *Torgvin* but are still weaker compared to the original wood.

Vintorg-metal has new properties compared to natural wood: high electro-conductivity, high thermo-conductivity, very high density, different shrinkage and swelling properties, and different acoustic properties. Characterization of these properties requires a special study. A study of material properties of *Vintorg* manufactured using different alloys and new physical properties should potentially open up new fields of applications. *Vintorg*-metal has original decorative surface patterns due to the wood-metal structure which provides opportunities for using the material in decorative applications.

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