Adhesiveless Bonding of Wood – A Review with a Focus on Wood Welding

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Most industrially used synthetic wood adhesives release formaldehyde, which is carcinogenic for humans. Adhesiveless bonding of wood can be achieved using heat treatment by either hot-pressing method, suitable mainly for wood particles and fibres or by wood welding. Welding of wood, which relies on the heat generated *via* friction, can be used for bonding two or more solid wood pieces together. The process can be carried out either by linear or rotational wood welding. This review first considers the manufacturing of binderless wood-based panels by hot-pressing. Then this is followed by an in-depth outlook of wood welding and its application in the wood industry. The effects of varying wood welding parameters, such as applied pressure, vibrational frequency and amplitude, holding pressure, holding time, welding time in linear wood welding, and relative diameter difference between the substrate and the dowel in rotational wood welding to obtain joints with optimal mechanical and physical properties is reviewed and discussed. Wood products made by heat treatment (hot-pressing and wood welding) are environmentally friendly, and the brief curing times needed for their manufacture represent a great advantage compared with the usage of wood adhesives to bind pieces of wood.

Keywords: Wood welding; Dowel welding; Linear friction welding; Vibrational welding; Rotational welding; Binderless bonding

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INTRODUCTION

Different types of wood synthetic adhesives, many of which release toxic compounds, are used to bond solid wood pieces or wood particles and fibre together in the wood engineering industry. Such bonding can also be achieved without using any adhesives in a greener and non-toxic way. This can be done by applying heat treatment either externally (hot-pressing method), which is used to bond wood particles and fibres, or internally by wood-welding (*via* friction), which is used to bond solid wood pieces. There are two main techniques to weld solid wood pieces together, and these are rotary and linear friction welding. Both during the hot-pressing method and the wood welding process, the lignin contained in wood melts and solidifies, making durable bonds. In this way, greener, non-toxic and renewable binderless wooden products can be manufactured, especially when the wood particles and the fibres used in the process are by-products of the agricultural industry.

BINDERLESS BONDING BY HOT-PRESSING

Binderless particleboard panels are currently being manufactured using sugar-containing lignocellulosic materials (particles and fibres), such as flax, sunflower, corn, sugar-cane bagasse, and stalks of sorghum, utilising the residual sugars as bulking and bonding agent without using any type of adhesive resins. The process involves self-bonding *via* chemical components that are activated during hot pressing (Nasir *et al*. 2019). This cuts the production cost and avoids the use of harmful chemicals utilised as adhesives (Shen 1986). The mechanical and physical properties of binderless boards depend on the divergence of different wood material (Tajuddin *et al*. 2016). The bonding mechanism of binderless boards, which has been reviewed by others (Pintiaux *et al.* 2015; Zhang *et al.* 2015; Tajuddin *et al*. 2016; Hubbe *et al.* 2018), mostly involves one or more of the following factors:

1. Hygroscopic hemicellulose degradation to form soluble sugars that may undergo reactions to become less hygroscopic, and polysaccharides that are highly branched;
2. Forming free sugar from the degradation of hemicelluloses that can undergo polymerisation during the period of hot pressing resulting in the formation of an adhesive;
3. Mainly in lignin, the thermal softening of the cell wall matrix to allow to reform a new, less stressed matrix after pressing;
4. Cross-linking between lignin and carbohydrate polymers and/or between carbohydrate polymers (Lamaming *et al*. 2013).

The oil palm industry proportionately generates large amounts of biomass residues such as oil palm fronds, trunk, empty fruit bunches, ash, and shell (Abdul Khalil *et al*. 2015). The chemical composition of the waste of oil palm biomass consists of starch, lignin, high holocellulose, and sugar that are required for the self-bonding adhesion (Hashim *et al*. 2011a). The optimal press temperature and press time for manufacturing binderless particleboard from the biomass of oil palm trunk are given in Table 1. The properties (internal bond strength: IB and modulus of rupture MOR) of all the panels produced in the optimal conditions, also shown in Table 1, satisfy the standard JIS A 5908 (2003).

Table 1. Optimal Processing Conditions from Numerical Optimisation (Baskaran *et al*. 2015)

	Thickness (mm)	Temperature (°C)	Time (S)	IB * (MPa)	MOR * (MPa)	Thickness Swelling (%)	Water Absorption (%)
Sample 1	5	191	23	7.957	5.3	13.363	59.241
Sample 2	10	196	24	2.564	7.1	15.938	56.970
Sample 3	15	195	30	1.245	9.8	18.702	63.742
* Note: IB = internal bond strength; MOR = modulus of rupture							

During the hot-press treatment, steam is generated inside the composite board. The steam treatment modifies lignin and degrades hemicelluloses (Pintiaux *et al*. 2015). Table 2 shows the wood fibre or particles that can be used to manufacture binderless composites and the procedure/mechanism/properties of the boards.

Table 2. Wood Particles or Fibres Used in Binderless Boards

Wood fibre or particle	Mechanism/properties/procedure, *etc*.	References
Coconut husk	Glucose worked as the self adhesive.	van Dam *et al*. 2006
Rhizophora spp particles	Larger particles showed better adhesion strenghth.	Marashdeh *et al*. 2011
Finely ground powders of Kenaf	180 °C, 5.3 MPa, 10 min press time satisfied Japanese industrial standard JIS A 5905.	Okuda and Sato 2004; Okuda *et al*. 2006a,b
Powdered moso bamboo	High internal bond (IB) values were achived.	Saito *et al*. 2013
Bagasse	Showed better mechanical properties than using of polymeric mechyl diphenyl diisocyante (pMDI).	Nonaka *et al*. 2012
Refined black spruce bark	Hot-pressed at 260 °C for 6 min	Gao *et al*. 2011
The fronds, mid-parts, and the core-parts of oil palm	Acceptable bending strength (MOR) and IB strength were achieved.	Hashim *et al*. 2012
Oil palm trunk waste	Hot press for 120 °C for 46 min or 215 °C for 29 min gives IB of 0.49 MPa, MOR of 8.18 MPa, thickness swelling (TS) of 22%.	Nadhari *et al*. 2013
Steam-exploded oil palm frond	Boards satisfied the S-20 grade requirements according to JIS at a density of 1.2 g/cm^3 for 6-mm boards.	JIS A 5905 1994; Laemsak and Okuma 2000
Fine particles of oil palm trunks	MOR and IB values of 4.04 MPa and 0.49 MPa	JIS A 5908 2003; Hashim *et al*. 2010
Strands of oil palm trunks	MOR and IB values of 24.95 MPa and 0.95 MPa	JIS A 5908 2003; Hashim *et al*. 2010
Oil palm trunks	Increasing the hot press time reduced the thickness swelling and resulted in better dimensional stabilities.	Aidawati *et al*. 2013
Oil palm trunks	MOR increases with the pressing temperature, but insufficient to meet the JIS A 5908 (2003).	Hashim *et al*. 2011b
Wheat straw	Hydrogen peroxide and calcium chloride were added.	Halvarsson *et al*. 2009
Rice straw	Showed good thermal and fire resistance.	Ferrandez-Garcia *et al*. 2017
Treated wood fibre	Laccase enzyme was introduced to create phenoxy radicals in the fibre lignin.	Álvarez *et al*. 2011
Rubber wood fibre	Lignins were oxydized by laccase enzymes.	Nasir *et al*. 2013, 2015

During the mechanism of bonding wood particles in binderless boards, heat treatment is applied externally to melt wood components such as lignin prior to the solidification. Another technique to bond wood pieces together is wood welding, where instead of applying the heat treatment externally, the heat needed to melt the lignin is generated internally. This is done by mechanically applying frictions between the surfaces of the two wood pieces that can then bond together in a non-toxic and greener way.

WOOD WELDING

Wood welding is a novel process of joining wood pieces without the use of adhesives or any other material. The wood welding technique has been provoking a growing interest in academic and industrial environments due to the eco-friendly and non-toxic nature of binding wood pieces in a very short period of time.

General Principles of Wood Welding

The wood welding process is performed by applying mechanical linear or rotational friction on the wood interfacial regions without the use of any adhesives (Pizzi *et al*. 2006). Figure 1 illustrates linear friction (vibratory) welding of wood. With this technique, the top piece of the two wood samples that need welding vibrates horizontally with a certain frequency, an amplitude of *a*, and a pressure of *PZ* for a period of *VZ* time. During this process, the lignin of the wood surfaces melts due to the heat generated. Once the vibration stops, the melted lignin solidifies, bonding the two pieces of wood together (Gfeller *et al*. 2003; Horman *et al*. 2016). The temperature of the welding surface should be in between lignin's melting temperature and its thermal decomposition temperature (170 °C to 280 °C). Lignin enhances the internal bond strength and surface density by melting with heat (Zor 2020). A study revealed that welded wood joints showed stronger bonds compared to when the joints were glued (Buck *et al*. 2015).

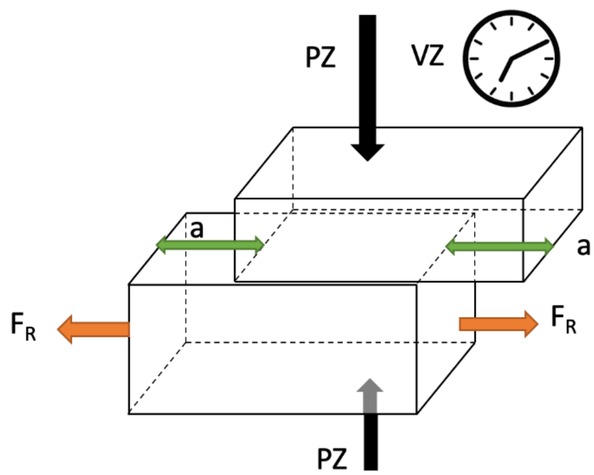

Fig. 1. Methods of wood welding where *PZ* is welding pressure, *VZ* is welding time, F_R is friction force, and *a* is amplitude of vibratory movement (Horman *et al*. 2016)

The same mechanism takes place when a rotating wood dowel is inserted into a pre-drilled hole on a wood piece, as shown in Fig. 2. The diameter of the hole should be around 1 mm smaller than the diameter of the wood dowel to establish a good friction, which is necessary to melt lignin when the dowel is inserted. The same concept of rotational wood welding (so-called wood nail concept) is used to fasten wood nails without pre-drilled holes (Ganne-Chédeville *et al*. 2005).

The solder layer of interface joint produces a dark amorphous compound that acts as an adhesive that consists of a network of interlaced cells immersed in an array of molten lignin polymers (Müller *et al*. 2010). Only a few minutes are required to achieve a successful wood welding process. The mechanical performance of welded wood joints has been reported to be as good as wood joints glued with conventional wood adhesives (Sandberg *et al*. 2013). In a study by Ganne-Chédeville and co-workers, the experimental cooling speed of the wood welding process was shown to be higher than a numerical model prepared. This temperature discrepancy between the experimentally measured values and the predicted values was attributed to the chemical reactions involved in the process, such as hydrolysis, pyrolysis, and gas generation (Ganne-Chédeville *et al*. 2008a).

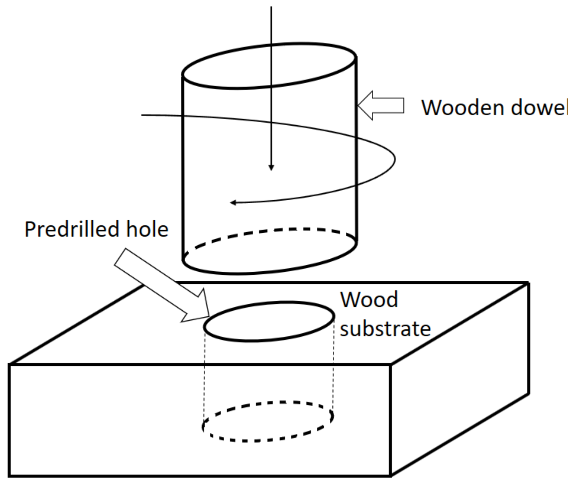

Fig. 2. Rotational dowel welding

It has been demonstrated that the joint strength occurring *via* cross-linking chemical reactions during wood welding can be improved by applying longer holding times (Pizzi *et al*. 2003). Lignin, in addition to hemicelluloses, represents the most important wood constituent for successful wood welding (Gfeller *et al*. 2004a; Sun *et al*. 2010). Depolymerisation and repolymerisation reactions of lignin are occurring during wood welding (Peña *et al*. 2016). Characterisation of lignin after thermal treatments can be performed by using Fourier-Transform Infrared Spectroscopy (FTIR) (Windeisen and Wegener 2008). FTIR can provide evidence of the varying proportion of functional groups, particularly it can highlight a decrease of aryl-ether and acetyl groups, as well as an increment of newly formed carbonyl groups that undergo dehydration reactions by making bonds between wood particles (Stamm *et al*. 2006).

Effect of Grain Orientation

Microfibrils of cellulose, in both crystalline and amorphous states, tear off from the wood surface during the welding process, and this can be seen by scanning electron microscopy (SEM) coupled with nuclear magnetic resonance (NMR) analysis (Pizzi *et al*. 2006). When studied, the grain orientation on linear wood welding did not seem to influence the average shear strengths, with differences not exceeding 10% (Milena *et al*. 2005; Omrani *et al*. 2010). However, the tensile strength of a tangential grain orientated maple was 6.5 ± 1.6 MPa, while that of radial grain orientation was 9.0 ± 0.9 MPa (Ganne-Chédeville *et al*. 2006). Therefore, it seems that the grain orientation plays an important role on the mechanical properties of the welded wood joints (Belleville *et al*. 2016a).

The welded interface of end-grain-to-end-grain of spruce has shown equivalent or better strength than glued finger joints (Amirou *et al*. 2016). End-grain-to-end-grain butt joint wood welding using Sidney blue gum (*Eucalyptus saligna*), spotted gum (*Eucalyptus* *maculata*, *Corymbia maculata* spp.), and Blackbutt (*Eucalyptus pilularis*) woods showed an average welded joint strength of 6.6 MPa, 8.6 MPa, and 5.3 MPa, respectively, yielding good joint strengths (Mansouri *et al*. 2010b). Moso bamboo also showed better experimental results compared to oak, beech, and spruce end-grain butt joints that were obtained by friction welding (Zhang *et al*. 2017). The vibration amplitude has shown an important effect on the bond strength of moso bamboo welded in an outer-to-inner orientation (Zhang *et al*. 2014).

End-grain-to-end-grain welded beech and oak wood yielded a much better strength compared to the Type A and Type B grain at 45° joints (Omrani *et al*. 2009b). Three high-density (800 to 900 kg/m^3) Australian eucalyptus woods welded to end-grain-to-end-grain yielded a satisfactory joint strength (Mansouri *et al*. 2010b). A minimalist Z chair was built by rotational dowel welding without using any wooden or metallic angular supports. The dowels were welded at two different angles to minimise the leverage action on the joints (Renaud 2009).

The most important factors of wood dowel welding are the ratio between rotation rate/dowel moisture content, followed by rate of rotation and 20 min soaking into ethylene glycol. The least important factors have been found to be the ratios between rotation rate/dowel temperature, dowel temperature/wood species, and wood grain direction/wood species (Ganne-Chédeville *et al*. 2005).

Accelerated dowel insertion rates has been shown to yield better results than constant dowel insertion rates (Auchet *et al*. 2010).

Mechanically induced vibrational wood welding has been used for different types of wood panels, namely particleboard, oriented strand boards (OSB), medium density fireboards (MDF), and plywood, by welding them in edge-to-edge and face-to-face orientations. In general, the strength of edge-to-edge panels welding is better than the face-to-face ones (Ganne-Chédeville *et al*. 2007).

Effect of Welding Time

An optimal tensile shear strength was achieved for birch (*Betula pendula* L.) wood welding performed by linear vibratory welding with a time of 3.5 s (Ruponen *et al*. 2015). A similar tensile shear strength could be obtained with an even shorter welding time using higher linear vibration frequencies. Linear friction (*i.e.*, vibratory) welding specimens (20 × 10 × 150 mm^3) were welded at an amplitude of 2 mm, frequency of 100 Hz, welding pressure of 1.9 MPa, holding pressure of 1.9 MPa, and holding time of 7 s by varying welding times (2.5 s, 3.0 s, 3.5 s, and 4.0 s).

Mansouri *et al*. (2009) revealed that when using a vibration frequency of 150 Hz, a displacement of 2 mm, and a welding time of 1.5 s, no fibres were expelled out from the interface edges during the wood welding. Additionally, there was no darkening, and an improved water-resistance in the welded joints was observed (Mansouri *et al*. 2009). Computed tomography (CT) scanning revealed that crack formation of welded Scots pine wood can be delayed by applying a pressure of 1.3 MPa instead of 0.75 MPa, a 1.5 s welding time instead of 2.5 s, and by using heartwood (Vaziri *et al*. 2012). In addition, the water-resistance of welded Scots pine could be enhanced using a pressure of 1.3 MPa and 1.5 s welding time (Vaziri *et al*. 2010). The degree of densification of weld lines (weld line density divided by the non-welded wood density) for the heartwood specimens was lower than that for the sapwood samples of Scots pine. Furthermore, the water-resistance of weld lines seemed to be independent of the density of weld lines (Vaziri *et al*. 2011b), which is usually twice the density of the wood pieces welded (Ruponen *et al*. 2015).

Vaziri *et al.* (2011a) showed that with the use of heartwood, a welding pressure of 1.3 MPa, and 1.5 s of welding time, the water absorption in the weld line can be decreased, water-resistance can be increased, and an enhanced performance of welded wood upon exposure to highly varying air humidity (Vaziri *et al*. 2011a) can be obtained. The addition of a small quantity of a native mixture of terpenoic acid was shown to give an enhanced water-resistance to the welded wood joints (Mansouri *et al*. 2011; Vaziri 2011). Joining wood by either linear vibration welding or rotational dowel welding can remarkably enhance the water-resistance of the welded wood joints (Pizzi *et al*. 2011). Enhancement of cold water-resistance of vibration-welded wood bondline was obtained by using naturally derived additives, such as furfural and tannins, which were promoting polymerisation autocondensation (Wieland *et al*. 2005). In theory, a reduced moisture content of the wood to be welded can lead to a decrease in scaled effects (welding occuring homogeneously over the whole surface – the central parts of the interface normally does not show a good weld when wood pieces are larger) and can produce a much higher mechanical joint strength (Hahn *et al*. 2014b). However, the weld strength of hydrothermolysed wood is poor (Boonstra *et al*. 2006). This is due to the increase in the rigidity and brittleness of the wood cells during the solidification of the melted lignin that occurred during the hydrothermolysis process when the wood was exposed to the elevated temperature of 240 °C (Ståhl *et al*. 2018).

Poplar wood hydrolyses at 200 °C into hydrolysable polysaccharides and then at 260 °C into polysaccharides that are more difficult to hydrolyse (Bonn *et al*. 1983). Wood veneers can be welded at a temperature between 225 and 250 °C and a pressure of 40 bar for 1 h without vibration or rotation. However, shorter times (less than 1 hout) seemed to yield poor welding (Mansouri *et al*. 2010a). A developed three-dimensional heat transfer model can predict the thermal behaviour of welded wood (Vaziri *et al*. 2014).

An analysis of anatomical deformations has confirmed that when 'long' welding times are used, after a certain period, the specific structure of entangled wood fibres disappears (Ganne-Chédeville *et al*. 2008c).

Water Resistance

The water-resistance of welded wood joints depends on the wood species. Vaziri and co-workers have reported that Magnetic Resonance Image (MRI) was able to visualise that the water-resistance of welded beech was lower than welded pine (Vaziri *et al*. 2011c). Improved shear strength and water-resistance were shown with the incorporation of wollastonite particles (Vaziri *et al*. 2020). The addition of citric acid was also shown to improve the water-resistance of welded wood joints (Amirou *et al*. 2017). Pre-oiling the dowels with sunflower oil can ease insertion into the pre-drilled substrate. Pre-lubricating the dowels for a better depth, which would allow more layers of wood to be joined together, was also shown to provide improved water-resistance to the welded joints (Segovia *et al*. 2013).

Dark Colour Formation in Weldlines

The steam generated during the wood welding process comes out as smoke, generating quinones, which make the weldlines dark in colour. This formation of dark colour quinones in weld lines is one of the disadvantages of wood welding. The formation of dark colour quinones in weld lines (Fig. 3) is a common issue in the process of wood welding when this is carried out by both vibratory and rotational welding. Nevertheless, wood welding performed by linear vibratory motion with a frequency of 150 Hz yielded colourless weld lines making the dark coloured quinones disappearing (Delmotte *et al*. 2009).

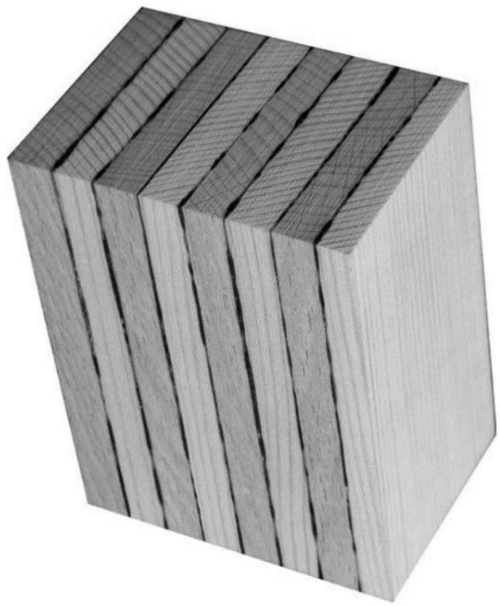

Fig. 3. Cuboid composed of alternating layers of spruce and beech wood (Stamm *et al*. 2005b)

Chemistry of Wood Welding

It is important to have an in-depth knowledge of wood chemistry to understand the thermochemical reactions occurring during the welding process leading to the adhesion mechanism and ultimately the weld line strength (Belleville *et al*. 2018). The chemical mechanisms related to wood welding are shown in Figs. 4, 5, 6, and 7. It is possible to observe the ether bond splitting mechanism shown in Fig. 4 using FTIR by following the increase of the peak at 1335 cm^{-1} in the spectrum. The thermal degradation of lignin during the welding process is shown in Fig. 5. Depolymerisation and repolymerisation reactions of lignin (route 1 and route 2, respectively) are illustrated in Fig. 6. Figure 7 shows the possible ways of formation of formaldehyde and water during and after the curing of wood welding. The quantities of formaldehyde released during wood welding are considerably lower compared to the formaldehyde emitted by the synthetic resins used as adhesives (Schäfer and Roffael 2000).

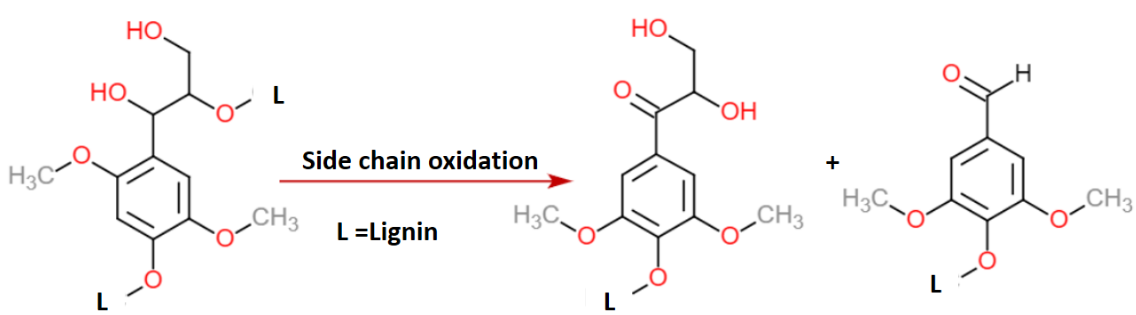

Fig. 4. Changes in lignin after side chain oxidation (Scott *et al*. 2005)

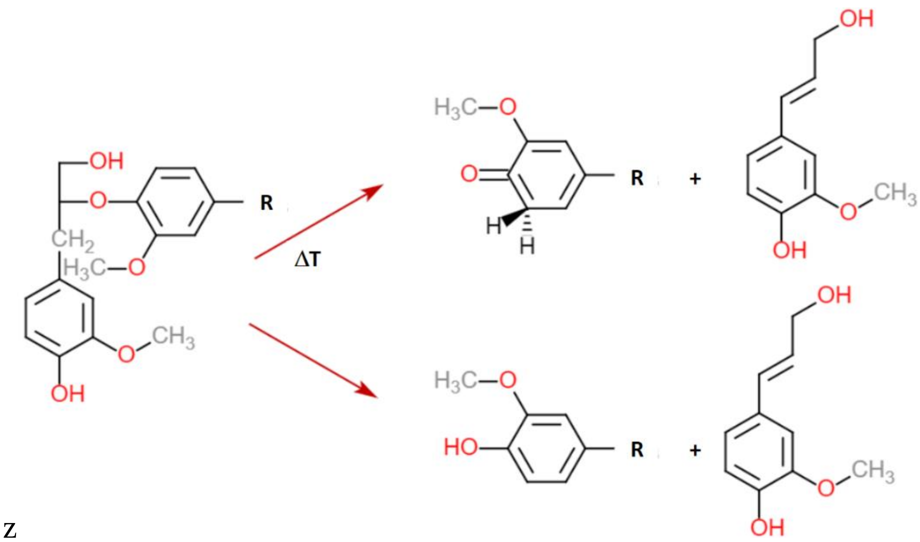

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Fig. 5. Free radical thermal degradation pathways of β-O-4-bonded lignin structures (van der Hage *et al*. 1993)

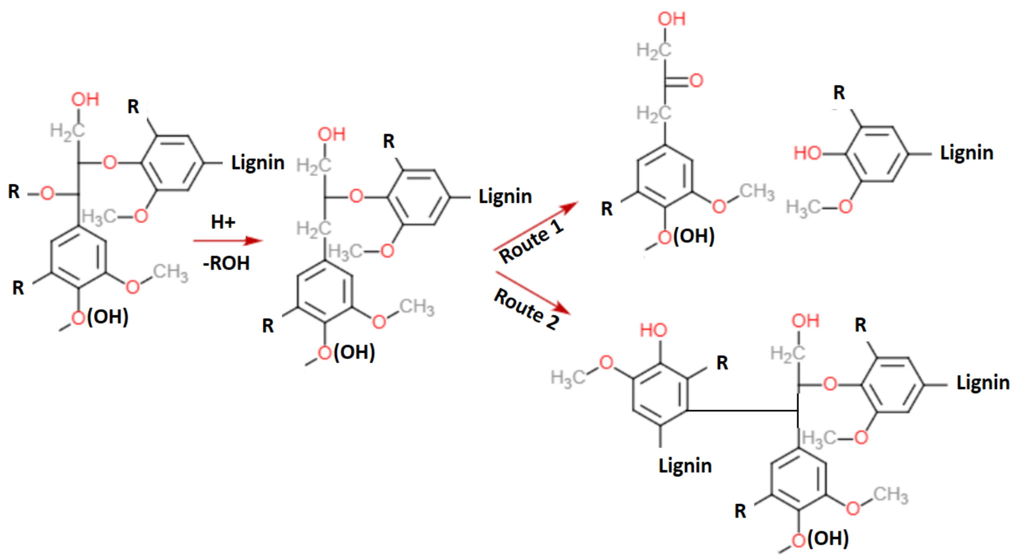

Fig. 6. Depolymerisation (route 1) and condensation (route 2) reactions of lignin (Li *et al*. 2007)

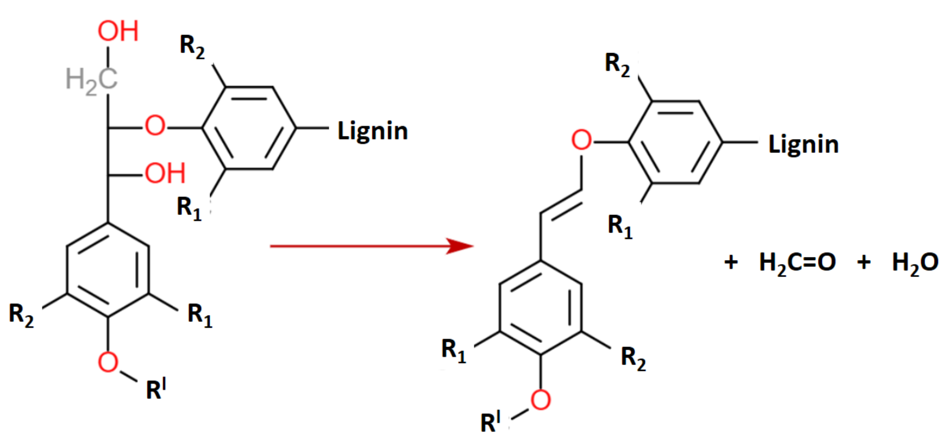

Fig. 7. Formation of formaldehyde from lignin units (Schäfer and Roffael 2000)

Temperature of Wood Welding

The temperature of the wood welding interface (T_0) can be expressed using Eq. 1,

$$T_0 = T_i + \frac{2\beta u\tau\sqrt{\alpha}}{h\sqrt{\pi}}\sqrt{t} \quad (1)$$

where T_i is the initial temperature (K) of the wood, t is time (s), τ is the friction stress (Pa), u is the rate of rotation or vibration (W m^{-2} Pa^{-1}), β is the fraction of mechanical energy convertible into thermal energy, (it is 0.080 ± 0.01 for both the rotation welding and linear welding systems), and α (m^2 s^{-1}) and h (W m^{-1} K^{-1}) are the diffusivity and thermal conductivity of the wood, respectively (Zoulalian and Pizzi 2007).

Optimisation of Wood Welding

Wood dowel welding is an ecologically friendly alternative to glued or nailed wood connections (Leban *et al*. 2005). Rotational welding of wood dowels can result in joints with considerable strength. Wood dowels immersed in $CuCl_2$ and welded for 3 s showed a high pull-out resistance and data reliability (Zhu *et al*. 2017a, 2018, 2019). In addition, the highest pull-out resistance was achieved when the moisture contents of the wooden dowels and the substrate were 2% and 12%, respectively (Zhu *et al*. 2017b).

A rotational speed of 1230 rpm gave the optimal results for the wood species *Eucalyptus saligna*, *Corymbia maculata*, *Ochroma pyramidale*, *Eucalyptus pilularis*, and *Tectona grandis* (Belleville *et al*. 2016b). Nonetheless, for sugar maple and yellow birch, the optimal rotational speed was found to be 1000 rpm (Belleville *et al*. 2013).

A study by Rodiguez and co-workers showed that Canadian sugar maple and yellow birch wood could be successfully welded. The joints of birch were comparable to those obtained by gluing using polyvinyl acetate (PVAc) adhesives, whereas the maple joints were superior to those obtained with the synthetic adhesive (Rodriguez *et al*. 2010).

Beechwood dowels with a diameter of 10 mm and with the radius of the ends chamfered by 0.6 mm were inserted into holes of 9 mm diameter to achieve good wood bonding (Ebner *et al*. 2014). The critical parameter to obtain an optimised joint strength was the relative diameter difference between the substrate hole and the dowel. A smaller difference between the two improved the joint strength (Kanazawa *et al*. 2005). Beechwood has been found to be the best material for welding dowels regardless of fibre orientation (Župčić *et al*. 2014). The shear strength of welded spruce wood samples reached 70% of its ultimate value after 20 s from the termination of the welding process. This showed to help welding several layers of wood without generating damages in the already formed joints (Stamm *et al*. 2005a).

Laminated composites of wood-bamboo-wood lumber bonded by linear vibration friction welding showed mechanical properties suitable for the application in the furniture industry as well as in the wood construction industry (Hu and Pizzi 2013). Alternating layers of beech and spruce wood were welded having an interval of approximately 1 min to make a cuboid (Fig. 3). During the process of frictional vibration, smoke was generated at 593 K, and the maximum temperature reached was approximately 713 K (Stamm *et al*. 2005b).

Linear vibration wood welding of grooved surfaces seemed to increase the welded surface and showed better results than non-grooved surfaces (Omrani *et al*. 2009a).

An interface of butt joints between two wood planks joined using rotationally welded dowels in a zig-zag pattern resulted in joints sufficiently strong that there was no need to use any adhesive. The joint could even resist after immersion in boiling water for

2 h as well as subsequent oven drying (Omrani *et al*. 2007). When wood dowels were welded at 45°, the joints showed a lower maximum failure stress than glulam joints bonded either with PVAc or urea-formaldehyde (UF) adhesives. In addition, they seemed to have lower slippage than the PVAc bonded joints (Bocquet *et al*. 2007a).

When the dowel insertion angle of the rotationally welded dowels of blockboard panels was 20°, the best results for both tensile and bending strengths were achieved, compared with the angles of 10° and 0° (Belleville *et al*. 2012). It has been reported that wood planks strong enough to be used in suspended floors could be obtained by high-speed dowel rotating welding (Bocquet *et al*. 2007b). When the maximum rotational rate value was decreased, the suspended floor made using the resulting dowel-welded planks were better performing than traditional floors (Pizzi *et al*. 2006; Pizzi 2007). In fact, this made it possible to obtain a high degree of rigidity of the suspended floor with a minimal number of timber planks needed to build it (Bocquet *et al*. 2006). Combining dowel welding with shrink-fitting using mortise and tenon wood joints has shown better joint strength than individual techniques alone (Mougel *et al*. 2011).

Thin wood pieces can be welded with good strength using an ultrasonic wood welding process that is also known as microfiction stir welding. Even though microfriction stir welding can be done for any length of wood pieces, the limited depth of the weld line is the main disadvantage (Tondi *et al*. 2007).

Generally, multi-axial mechanical behaviour of welded wood assemblies can be taken from a modified Arcan device by varying the tensile shear loading angle (Gineste *et al*. 2012). Such a device can be used to determine a large database of experimental results under compression or tensile shear loads. It can be used to develop numerical tools to predict complex assemblies of welded wood joints.

The partial unplugging (detaching) of long wood fibres forms a network of entanglement drowned in a melted material matrix during the first phase of wood fusion welding. During the solidification of melted material, a wood cell entanglement network composite lignin matrix is formed (Gfeller *et al*. 2004b). Welded wood dowels have been shown to possess comparable mechanical and physical properties of wood dowels glued with PVAc adhesive, but with the glued dowels being cured for 24 h. Preheating the dowels and substrate at 100 °C prior woold welding were shown to yield a better outcome than that obtained by PVAc gluing (Pizzi *et al*. 2004).

Resch *et al.* (2006) have shown that through-welded dowel assemblies were stiffer than assemblies of steel-nailed of the same design (Resch *et al*. 2006).

The morphological discrepancies of different types of welded wood joints depend on the density and the evenness of the bondline (Leban *et al*. 2004). The density of welded interphase of high-density *Eucalyptus benthamii* (590 kg/m^3) is relatively large (740 to 750 kg/m^3), indicating that the mechanical strength of the joint appears to be high (Martins *et al*. 2013).

When the outcome of a numerical modelling used to predict the strength of welded wood double lap joints was compared with experimental data, the results showed that the experimental mean values could be accurately predicted by the probabilistic joint strength method (Vallée *et al*. 2011).

Ganne-Chédeville *et al* (2008b) have reported that the energy release rate of the wood welded joints can be measured using a double cantilever beam test. The test revealed that the crack propagates only in the joints, enabling a good mechanical property of the welded segment (Ganne-Chédeville *et al*. 2008b).

Experiments have revealed that circular vibrational movement during wood welding is more advantageous than linear vibration welding, and the strength of wood welded specimens was 40% higher than the corresponding adhesive glued connections (Hahn *et al*. 2014a). In addition, experimental evidence showed that the large variabilities of the strength of wood welded bonds can be described using Weibull statistics (Hahn *et al*. 2011; Vallée *et al*. 2012).

The compounds in the smoke emitted from the welding interface during linear vibration welding of oak and beech wood were identified as water vapour, CO_2, as well as degradation compounds from amorphous lignin such as volatile terpenes and wood polymeric carbohydrates. However, there was no emission of degradation volatiles or gases detected after the welding was done (Omrani *et al*. 2009c). The main carbohydrates of volatile compounds are glucomannans (for a softwood such as Norway spruce) and xylan hemicelluloses (for hardwood such as beech wood) (Omrani *et al*. 2008). Wood carbonisation starts increasing during cross-linking of the lignin network even after stopping of welding the wood surfaces (Delmotte *et al*. 2008).

The hardness of the wood surface can be measured using the Brinell hardness number (BHN) by applying a load of 500 N on a 10 mm diameter hardened steel sphere on the tested wood surface, as shown in Eq. 2 below,

$$\text{BHN} = \frac{F}{\pi/2D\sqrt{D^2 - d^2}} \qquad (2)$$

where d (mm) is the diameter of the indentation left on the surface to be tested, D is the diameter of the striking steel ball (10 mm), and F is the force exercised (500 N). The surface hardness of wood pieces prepared using mechanically induced vibration wood welding technique has shown that applying unsaturated oil gives harder surfaces due to the heat generated from vibrational welding treatment (Pizzi *et al*. 2005).

A confocal laser-scanning microscope was used to visualise the heat affected zone of a welded wood joint shown in Fig. 3. An image of one of the weld lines is reported in Figs. 8. Figure 9 depicts enlarged interface areas, indicated with picture A and picture B in Fig. 8. The cell structure of the interface in zone B seems to be destroyed and densified by thermomechanical action, whereas the interface in A has thicker late wood cell walls with smaller voids. The less porous annual rings of Fig. 8 lead to an undulated structure, creating an angle in the welding interface (Stamm *et al*. 2005b).

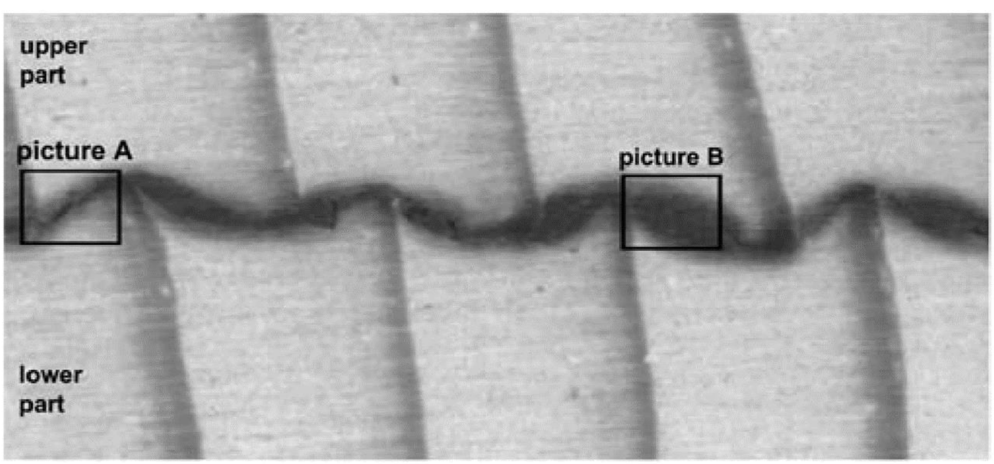

Fig. 8. Varying thickness of undulated structure of the interfacial layer; zones labelled with pictures A and B are presented enlarged in Fig. 9 (Stamm *et al.* 2005b)

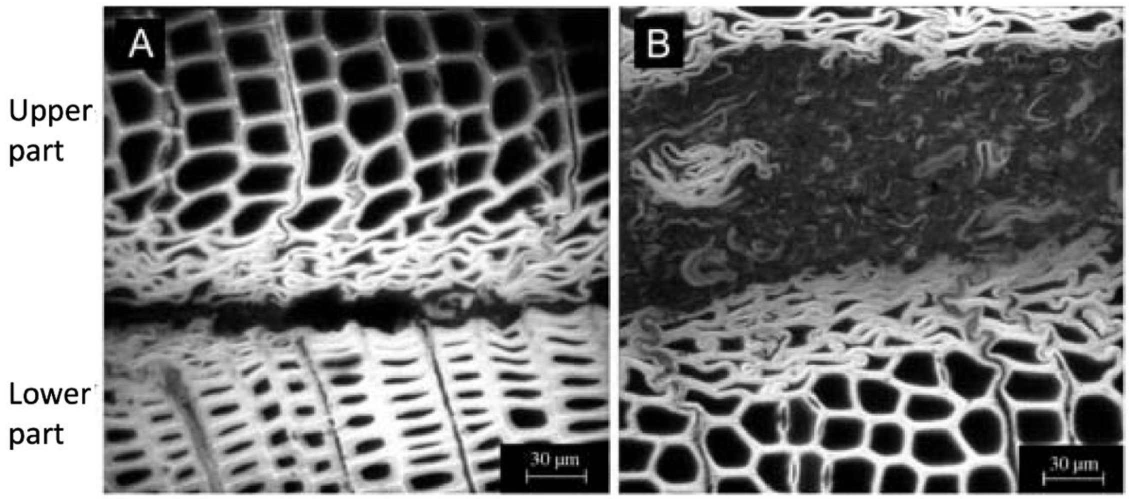

Fig. 9. Microscopic pictures of the zone affected by heat and the adjacent regions (Norway Spruce, transverse plane); picture A shows the thicker late wood cell walls with smaller voids are nearly intact and picture B shows that the cell structure of wood is destroyed at the interface (Stamm *et al*. 2005b)

Linear friction welding of wood can minimise and even eliminate the use of adhesives such as PVAc in the furniture and the interior wood joinery industry due to its economic and ecological benefits. In addition to this, the time required to weld wood is a few seconds, while, for example, PVAc gluing requires curing for at least 24 h after its application. Therefore, the use of wood welding would shorten dramatically the time required to manufacture the final products. Furthermore, welding of wood reduces the usage of synthetic and oil-derived adhesives with both environmental and financial benefits. Cutting boards can be manufactured using linear friction wood welding without the need of utilising any adhesives even in a small backyard workshop. Goods made by wood welding could be added to the existing market as environmentally friendly, non-toxic, and reliable final products.

OUTLOOK AND FUTURE WORK

Mostly binderless boards are made by using agricultural waste as the raw material. Therefore such wastes, instead of being disposed of into a landfill, is reutilized. This moves it into a circular economy, with great environmental benefits. Binderless boards can be considered as one of the best alternatives for wood-based panels which are commonly made using toxic formaldehyde yielding wood adhesives.

Wood-to-wood friction vibratory welding has a high potential for future applications due to its fast-curing time, no requirement for expensive adhesives, and its eco-friendlessness. The ecological and renewable nature of the process and the absence of volatile organic compounds emission, as well as lack of formaldehyde and residual vinyl monomers release, makes wood welding an environmentally friendly procedure for bonding wood within a circular economy framework, as wood welded products could be easily recycled. In addition, wood dowel welding can be taken as one of the best alternatives for using wood fasteners, nails, screws, and glue. Although wood is not a homogeneous material, it is possible to adjust several influential parameters during the welding process to achieve the optimal mechanical and physical properties even when different types of woods are used. Nevertheless, future studies are needed to minimise the unpleasant odours and the dark colour formation in the welded interface to achieve a more pleasant appearance of the final product.

Other advantages of wood welding include a good water-resistance of the welded wood joints and the possibilities of welding wood veneer sheets by altering the grain orientation without using glues in the plywood manufacturing process. Because of the excellent moisture resistance of welded wood joints, these can compete with the conventional joint gluing process. However, for a real impact in the wood market, the mechanical and physical properties of welded wood-based panels need to be fully characterised and compared with those of welded virgin wood. In addition, the strength of welded wood joints should be tested and analysed over time. Finally, strategies to scale up laboratory experiments into an industrial scale need to be identified and proposed.

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