Wood Material Science & Engineering
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/swoo20

Influence of pressing parameters on mechanical and physical properties of self-bonded laminated beech boards

Carmen Cristescu[a], Dick Sandberg[a], Mats Ekevad[a] & Olov Karlsson[a]
[a] Department of Wood Science and Engineering, Luleå University of Technology, Skellefteå, Sweden
Published online: 27 Jan 2015.

Wood Material Science & Engineering, 2015
http://dx.doi.org/10.1080/17480272.2014.999703

Taylor & Francis
Taylor & Francis Group

ORIGINAL ARTICLE

Influence of pressing parameters on mechanical and physical properties of self-bonded laminated beech boards

CARMEN CRISTESCU, DICK SANDBERG, MATS EKEVAD, & OLOV KARLSSON

Department of Wood Science and Engineering, Luleå University of Technology, Skellefteå, Sweden

Abstract
Five-ply self-bonded boards were obtained by pressing beech veneers parallel to the grain without additional adhesives, steam or pre-treatment. Fifteen different combinations of pressing parameters were tested, including temperature (200°C, 225°C and 250°C), pressure (4, 5 and 6 MPa) and pressing time (240, 300 and 360 seconds). Due to severe pressing conditions, the new product showed a higher density and different properties compared to a conventionally glued laminated wooden board. The self-bonding quality was assessed through dry shear strength tests, through a three-point bending test and a water-soaking test at 20°C. The dimensions in the cross section of the boards were measured after soaking in water. Results show that the choice of pressing parameters affects all the mechanical and physical properties tested. A statistical analysis revealed that the pressing temperature is the most influential parameter. Boards pressed at 200°C delaminated rapidly in water, whereas boards pressed at 225°C delaminated only at core-positioned layers after 48 hours and boards pressed at 250°C did not delaminate at all in water. Compared to panels pressed at lower temperatures, boards pressed at 250°C had the highest density, a higher shear and bending strength and a lower water absorption.

Keywords: *Pressing, veneer, absorption, bending, tensile, shear, strength, Fagus sylvatica, self-bonding, swelling*

Introduction

Environmental concerns as well as the rising cost of adhesives based on fossil-oil derivatives have led to an interest in environment-friendly methods for bonding wood. Decreasing and even avoiding formaldehyde emissions from adhesives have become a target for wooden product manufacturers worldwide. One way to produce laminated wooden boards without adhesives is simply to press the veneers together under high heat and pressure. The process uses only heat and mechanical compression in an open system, and no other treatment of the veneer is necessary (Cristescu 2006, 2008).

Technologies for self-bonding veneers without any type of binder or chemical activation prior to pressing were introduced in Germany in the 1940s by Runkel and Jost (1948) and in the USA by Boehm (1951). These processes were developed as extensions of the fibreboard and chipboard processes. The Runkel and Jost's technology is called the Thermodyn process. Nine veneers at a moisture content (MC) of 10–17% were subjected to 15 MPa pressure at a temperature of 170°C in a gas-tight pressure mould and compressed to a laminate with a density of 1300–1400 kg/m^3. After hot-pressing, a re-cooling phase to a temperature below 100°C was necessary to obtain a shape-stable product.

The Masonite plywood production process described in a patent by Boehm (1951) does not require a closed pressing system, but the veneers must undergo a steaming (hydrolysis treatment) process in an autoclave prior to pressing. Boehm emphasises the strong inter-dependence of the steaming and pressing parameters e.g. if the veneers are hydrolysed in the autoclave at a high temperature and pressure, as for example steam at a temperature of 285°C and a pressure of 7 MPa for 30 seconds, then the lignin will be activated to a relatively high degree, and under such conditions, the pressing temperature and pressure should not exceed 220°C and 5 MPa, in order to avoid excessive flow of the wood

Correspondence: Carmen Cristescu, Department of Wood Science and Engineering, Luleå University of Technology, SE-931 87 Skellefteå, Sweden. Tel: 46 910 58 53 71. E-mail: carmen.cristescu@ltu.se

(*Received 27 October 2014; revised 4 December 2014; accepted 15 December 2014*)

material. However, if the veneers are hydrolysed at a relatively low steam temperature and pressure, the press temperature and pressure need to be higher.

During the 1970s, progress was made in non-conventional bonding technologies for small-size and waste wood (Stofko 1974), but there was little interest in the auto-adhesion for joining veneer or solid wood. One reason for this low interest was the new, (at that time), synthetic resins that started to be dominant on the market after the 1940s because of their ease of handling, adjustable viscosities, good moisture durability and low price (Müller *et al.* 2007). The new non-conventional bonding technologies included various methods of bonding through surface activation, radically different from the conventional phenol-formaldehyde and urea-formaldehyde adhesive systems. According to Zavarin (1984), the progress of these methods was limited by insufficient knowledge of the chemical composition of wood and fibre surfaces as well as of processes involved in bonding. The more recent technique for welding solid wood is a self-bonding process where the friction between the wood surfaces to be joined plays a decisive role (Suthoff *et al.* 1996, Sandberg *et al.* 2013).

One important issue when joining wood surfaces without adhesive is their poor resistance to water. In wood welding, water resistance was achieved by using species with a high resin content, such as pine, in which rosin melts and surrounds the weld line (Vaziri 2011), or Paduk wood (Ganier *et al.* 2013), where the extractives have a protecting influence on the welded interphase, due to their inherent water repellence. Applying a mixture of rosin in ethanol on beech wood surfaces and letting it dry for two days prior to welding is another way of obtaining water-resistant bonds (Pizzi *et al.* 2011).

Wood powder placed as a binder between veneers prior to hot-pressing leads to a water-resistant bond, as shown by Ando and Sato (2010), who pressed cross-laminated sugi (*Cryptomeria japonica* D. Don) veneers at 200°C for 20–30 minutes or 220°C for 10 minutes. This process gave a board that met the second grade of JAS (Japanese Agricultural Standard) for plywood, i.e. for use in applications where it is occasionally exposed to wet conditions. Ando and Sato (2010) determined the tensile shear strength of the bond-line under dry conditions and in wet conditions after soaking in 60°C water for 3 hours. They considered that the pressing temperature and time were important factors in the manufacture of sugi plywood bonded with sugi powder, and these parameters contribute not only to compacting the powder but also to reducing the thickness recovery and water absorption of the veneers.

Ruponen *et al.* (2014) obtained water-resistant boards from parallel-laminated 1.5 mm thick birch (*Betula pendula* L.) veneer. Their technique involved three steps: soaking the veneers in water at 20°C for 24 hours, pressing for 4 hours at 160°C and 6 MPa, and treating for a further 4 hours in superheated steam at a temperature of 200°C.

Cristescu and Karlsson (2013) analysed the differences in the chemical composition of boards pressed at 200°C, 225°C and 250°C aiming an explanation for their different behaviour in water. It was shown that the monosugars accumulated at the surface of the veneer were transformed during hot-pressing into hydroxymethyl-furfural which, at temperatures higher than 225°C, was transformed further into other products, including furfural. It was also suggested that degraded lignin migrated towards the bond-line where a condensation reaction might occur, especially at 250°C.

The purpose of the present study was to investigate the impact of the pressing parameters (temperature, pressure and time) on the quality of beech laminated boards pressed using the technique shown in Cristescu (2006). One important aim was to screen and determine the temperature-pressure-time combination necessary to achieve a water-resistant board and to analyse the type of relation between water-related properties and strength.

Material and method

Experimental design

In this study, three variables were considered: the temperature of the press plates, the pressure and the pressing time. Previous results presented by Cristescu (2006, 2008) showed that the parameter region of interest is cuboidal and this guided the selection of parameter values for this study. The temperature selected were 200°C, 225°C and 250°C; the pressures were 4, 5 and 6 MPa; and the pressing times were 240, 300 and 360 seconds.

Twelve replicates were pressed at the centre point of the parameter region (225°C, 5 MPa, 300 seconds) while two replicates were pressed at the other points (Figure 1), assuming that the information concerning the error estimate obtained from the centre point can be extended to the other points (Montgomery 2005).

The order in which the pressings were performed was generated randomly, established by a response surface design matrix from Minitab 17 statistical software (Minitab Inc. 2014), and this was followed not only when pressing the veneers but also when performing the shear and bending tests.

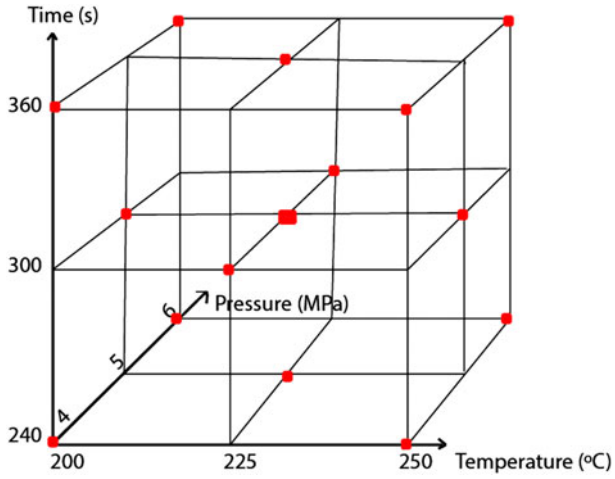

Figure 1. Parameter region and selected parameter combinations used when pressing the boards. Each dot in the figure represents one test group in Table I.

The SIMCA (Umetrics, 2014) software was used to analyse the entire set of data and parameter responses, and the MODDE software (Umetrics, 2014) was used to study whether there was a strong correlation between the responses.

Boards manufacturing

Defect-free rotary-cut 2.2 mm thick veneers of beech (*Fagus sylvatica* L.) from Romania were used for this study. Prior to cutting, the logs were plasticised by steaming them at 80°C, and they were then rotary-cut at 40–50°C, followed by drying at 140–170°C to reach a MC of 7–10%. The veneers were conditioned to an equilibrium MC (EMC) of 9% before sample preparation. The oven-dry density (EN-323, 1993) of the veneers ranged from 580 to 605 kg/m^3.

Veneers with dimensions of 2.2 × 140 × 140 mm (thickness × width × length) were prepared. The fibre orientation was controlled in the plane of the veneers (LT-section) but not in the other directions and only straight-grained veneers were used. Five-ply boards with parallel-orientated veneers were pressed in a laboratory press (Fjellman®, No. 2032, Mariestad, Sweden) at different temperatures, pressures and times according to the parameter combinations presented in Figure 1 and Table I.

Thermocouples were placed between the veneers to measure the temperature in the bond-lines during pressing. The plates' temperature and pressure levels were continuously displayed on the press display. When the set time was reached, the pressure was released. The boards were then taken out of the press and allowed to cool freely at room temperature.

Sample preparation

Figure 2 shows how the samples were prepared from each board. Samples for density measurement (EN-323), shear, bending and water-resistance testing (absorption and swelling according to EN-317) were prepared from all replicates. From each laminate, a sample was cut and then conditioned.

The MC of the samples before soaking was the EMC at a temperature of 20°C and 60% relative humidity. The EMC was between 2% and 4%, depending on the pressing conditions. The variation in EMC is due to the well-known fact that thermal treatment of wood affects the sorption–desorption isotherms of the material; see e.g. Hill (2006).

Water absorption and swelling

Samples with dimensions of 50 × 50 mm were used for a water absorption and swelling test, according to EN-317 (1993).

The water absorption value is the amount of water taken up by the samples after they had been soaked in water at a temperature of 20°C for 48 hours, and is expressed in relation to the initial mass at EMC, calculated as:

$$w_a = \frac{m_f - m_i}{m_i} \quad (1)$$

where w_a is the water absorption, m_f is the final mass and m_i is the initial mass.

The dimensional changes in length (L), width (W) and thickness (T) directions of each sample were determined, and the swelling coefficients were calculated according to:

$$S_{L,W,T} = \frac{t_f - t_i}{t_i} \quad (2)$$

where $S_{L,W,T}$ is the swelling coefficient in the different directions of the sample, t_f is the final dimension and t_i is the initial dimension in each direction.

Longitudinal tensile shear testing

Samples with dimensions of 130 × 25 mm were subjected to the shear strength test. The length direction of the sample was aligned in the longitudinal direction of the veneer. Notches were cut according to the instructions in EN-314 (2004). The samples were not soaked in water prior to the shear strength test as prescribed in the standard, since it was seen in previous studies (Cristescu 2008) that boards pressed at 200°C would delaminate and it would thus be impossible to compare these samples with samples pressed at higher temperatures.

Table I. Results of density, water absorption, swelling, shear and three-point bending test (average values of all samples in a group and standard deviation in brackets).

									Three-point bending test			
Group no.	Temp. (°C)	Press (MPa)	Time (s)	Density (kg/m3)	Thickness (mm)	Water absorption (%)	Swelling coefficient thickness (%)	Shear strength(MPa)	Span (mm)	Maximum load (*N*)	Type of failure	Strength according failure type stress
1	200	4	240	615 (18.5)	8.5 (0.0)	73.1 (0.9)		1.7 (0.6)	100	357 (22.0)	Int.shear[b]	1.3 (0.9)
2	200	4	360	650 (6.2)	8.3 (0.1)	72.8 (1.5)		1.6 (0.6)	95	835 (25.0)	Int.shear	1.8 (1.5)
3	200	5	300	670 (20.4)	8.2 (0.1)	72.2 (0.0)		2.0 (0.2)	100	912 (51.5)	Int.shear	1.9 (0.0)
4	200	6	240	680 (29.1)	8.1 (0.3)	72.5 (1.9)		2.5 (0.0)	100	1156 (6.0)	Int.shear	2.5 (0.9)
5	200	6	360	690 (22.1)	7.7 (0,1)	70.0 (1.2)	26.0 (1.3)	2.8 (0.1)	95	1124 (56.5)	Int.shear	2.6 (1.2)
6	225	4	300	700 (12.3)	8.0 (0.0)	68.7 (0.8)	25.3 (1.8)	3.3 (0.1)	100	1115 (89.5)	Int.shear	2.6 (0.4)
7	225	5	240	710 (16.1)	7.9 (0.1)	64.9 (0.4)	25.0 (2.6)	3.2 (0.7)	90	1231 (69.0)	Int.shear	4.5 (0.8)
8[a]	225	5	300	744 (39.1)	7.5 (0.4)	61.5 (1.5)	22.7 (3.2)	5.1 (0.4)	90	1897 (73.5)	Int.shear	4.9 (1.9)
9	225	5	360	750 (28.0)	7.3 (0.3)	60.8 (2.1)	23.2 (3.4)	4.9 (0.1)	85	1917 (16.5)	Int.shear	4.7 (2.1)
10	225	6	300	765 (27.2)	7.0 (0.4)	57.2 (1.7)	22.8 (2.0)	4.1 (0.1)	85	2101 (47.3)	Tension	164 (3.9)
11	250	4	240	828 (28.1)	6.7 (0.2)	48.8 (1.6)	16.0 (0.9)	4.1 (0.0)	90	2065 (89.1)	Tension	154 (10.6)
12	250	4	360	866 (17.2)	5.7 (0.2)	43.8 (2.0)	16.3 (1.5)	5.0 (0.2)	80	2180 (41.1)	Tension	222 (4.2)
13	250	5	300	901 (19.1)	5,7 (0.5)	40.9 (0.8)	16.0 (2.8)	4.6 (0.0)	80	2148 (38.5)	Tension	198 (3.8)
14	250	6	240	973 (20.3)	5.6 (0.1)	39.6 (0.3)	16.5 (0.9)	5.8 (0.0)	80	2199 (72.1)	Tension	206 (9.3)
15	250	6	360									

[a]Mean value and standard deviation for 12 replicates.
[b]Int.shear, interlaminar shear.

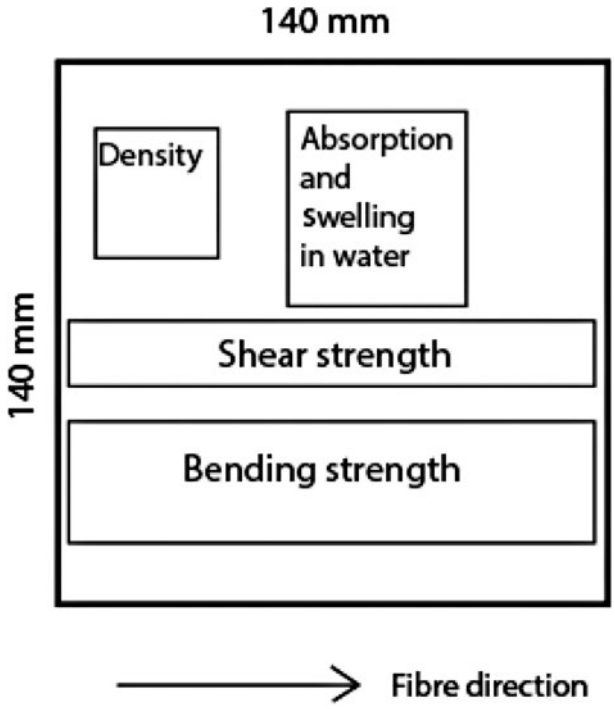

Figure 2. A schematic view of a hot-pressed board showing how samples were taken for density measurement, shearing, bending and water-resistance testing (absorption and swelling).

Bending test

The length direction of the bending test specimens was parallel to the fibre direction in all the tests. The board thickness differed from 8.3 mm for a board pressed at 240°C, 4 MPa, 240 seconds to 5.8 mm for a board pressed at 250°C, 6 MPa, 240 seconds.

A three-point static bending test was performed. The length of all samples was 130 mm, and the span was between 80 and 100 mm, depending on the thickness (the span-thickness ratio ranged from 12 to 18). In an attempt to have a fair response from all samples and taking into account their moment of inertia as well as the dimensions indicted in EN-310 (1993), the width varied according to sample thickness following Euler–Bernoulli equation. It was desirable for the load to act in the same manner on all the samples, so the loading rate was decided after testing with different speeds on similar samples; in order to reach failure within 30–90 seconds, the loading rate should, according to EN-310 (1993), be up to 1 mm/s for the samples pressed at 200°C and up to 3 mm/s for samples pressed at 250°C.

The test measured the maximum load that the samples could support in a three-point bending. Some of the samples broke because of inter-laminar shear, and in this case, the formula used to calculate the rupture strength was:

$$\tau = \mu \frac{F}{A} = 1.5 \frac{F}{2bt} = \frac{3F}{4bt} \quad (3)$$

where:

τ = interlaminar shear strength
μ = coefficient that takes into account the shape of the sample
F = maximum load
A = area subjected to shear stresses
b = sample width
t = sample thickness,

while other samples broke due to tension in the lower layer, and in their case, the formula used to calculate the modulus of rupture (MOR) was:

$$\sigma = \frac{Fl6}{4bt^2} \quad (4)$$

where:

σ = tension strength
F,b,t = as in Equation (4)
l = span.

Results and discussion

A summary of all the test results is presented in Table I. An important observation is that pressing at the maximum levels for all the parameters (250°C, 6 MPa, 360 seconds) led to a failed board, i.e. these samples suffered damage by a light inner explosion when the press was opened. The reason of the explosion was the excessive internal pressure produced by the increasing amount of gaseous degradation products. The colour of the laminate in this case was extremely dark, indicating a severe degradation of the wood material. All responses for this sample were excluded from the analysis since the structure had deteriorated in an uncontrolled way and the thickness within a single board varied.

Density

Table I shows that a thermo-densification process took place during the hot-pressing. The density increases by 7% for Group No. 1 and by 67% for Group No.14 (the degree of thermo-densification is defined here as the difference between the board density and density of veneers before pressing).

Water absorption

Soaking in water for 48 hours was sufficient for all samples to achieve a constant mass.

The results in Table I show that the samples pressed at 200°C absorbed the largest amount of

water and that the absorption decreased with an increase in all the pressing parameters.

The liquid absorption capacity of a material can be divided into at least two components, one of which is capillary absorption. Some species (especially hardwoods) that undergo thermal treatment above 200°C show a reduced capillary absorption (Johansson *et al.* 2006), but Scots pine shows a different trend when immersed in water (Metsä-Kortelainen *et al.* 2006). Another factor affecting the absorption is wettability, which decreases for thermal-treated beech at 240°C, as shown by Hakkou *et al.* (2005). One explanation of this tendency is that, during thermal treatment, the degradation of hemicelluloses significantly reduces the amount of free reactive hydroxyl groups, and thus decreases the ability to bind water (Inari *et al.* 2007). Another explanation is that there is a decrease in sugars concomitant with the increase in furfurals at the surface of pressed thermal-treated spruce boards, as reported by Karlsson *et al.* (2012). A similar behaviour was shown to take place in the hot-pressing of beech wood (Cristescu and Karlsson 2013). Monosaccharides in the untreated veneer, especially large quantities located at the surfaces, are transformed into dehydration products such as furfurals when heated, possibly due to caramelisation. On the other hand, Hill (2006) notes that during severe thermal treatment the possibility of cross-link formation in the lignin increases, and this can also be a factor contributing to water repellence. For example, when beech, aspen and Douglas fir were thermally treated by mild pyrolysis at temperatures between 220°C and 260°C, the most hydrophilic species became the most hydrophobic, and the decrease in hydrophilic character increased with increasing temperature and increasing duration of the treatment (Böhnke 1993).

Swelling in water

Figure 3 shows the swelling of the samples in water in the thickness, width and length directions. The swelling was lowest in the direction with no densification of the veneers during pressing. As expected, swelling in the thickness direction was especially high because of the compression of the cells, as described by Navi and Sandberg (2012).

The thickness swelling of samples pressed at 200°C is not shown in Figure 3, as these samples delaminated in less than 12 hours on immersion in water.

Ordinary untreated compressed wood is subject to a large amount of spring-back when used under moist conditions, but pressing at high temperatures appreciably reduces the swelling (Stamm 1964). In Figure 3, it can be seen that increased temperature, pressure and time led to a decrease in the swelling, in accordance with the decreasing absorption. The

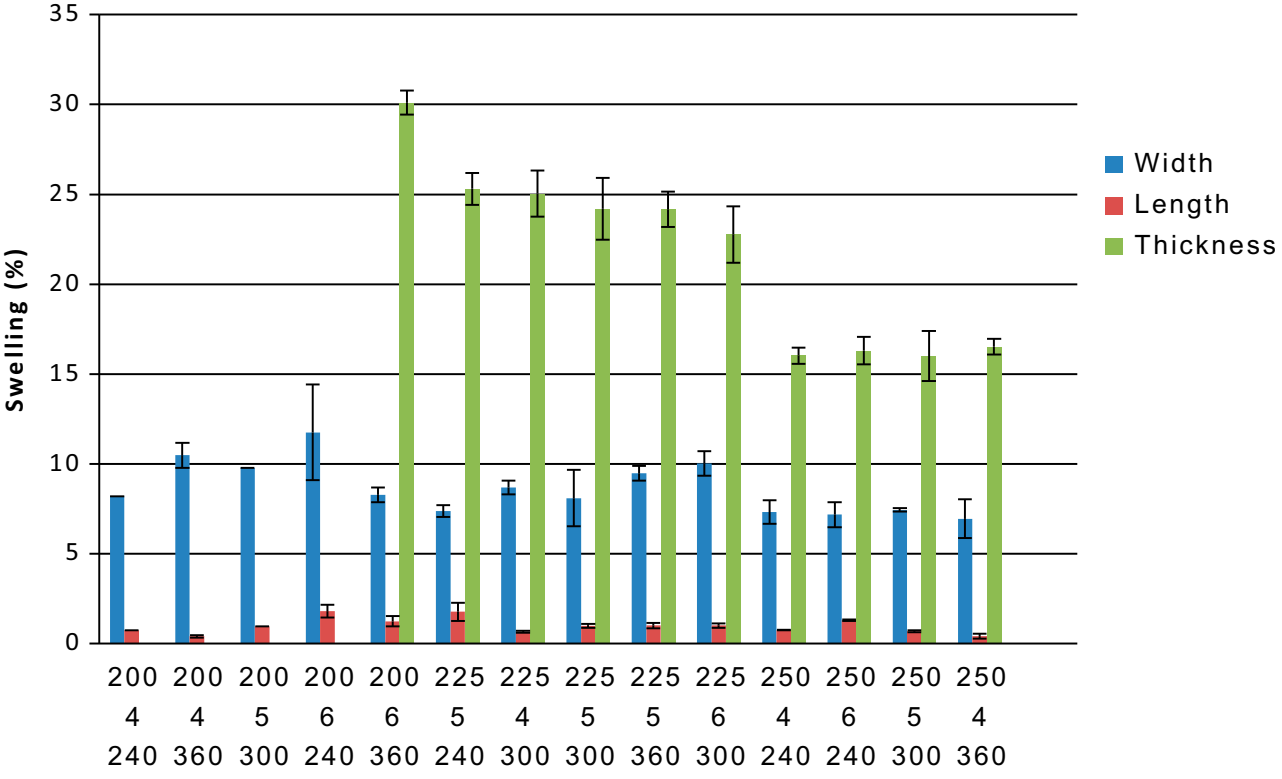

Figure 3. Swelling in the main directions of boards immersed in water for 48 hours. Mean value and standard deviation indicated as bars.

increased dimensional stability at higher temperatures can be considered the result of a decomposition of hemicelluloses into different types of sugars that further react between themselves, forming a water-insoluble polymer (Navi and Heger 2005).

Repellin and Guyonnet (2005) also reported a gradual reduction in the volumetric swelling in beech when solid wood boards were heated at 200°C, 220°C, 240°C and 260°C for 5 minutes. The species, temperature and duration of treatment are similar to the parameters in our experiment. Their conclusion was that heat does affect the chemical structure to the extent of reducing the sites that can react with water in untreated wood. Repellin and Guyonnet (2005) suggested that the reduction in the swelling in beech wood cannot be explained only in terms of the disappearance of hemicellulose adsorption sites but that other phenomena such as structural modifications and chemical changes in lignin may also play an important role.

Bond-line temperature and bonding quality

Figure 4 shows a cross section of a specimen pressed at 225°C, 5 MPa and 300 seconds. The four bond-lines can be divided in two groups, outer and inner bond-lines according to their position within the board. The temperature in the bond-lines during hot-pressing was measured with thermocouples, and it was found that the inner bond-lines needed a longer time to achieve the same temperature as the outer bond-lines.

Monitoring this interlaminar temperature with thermocouples in the bond-lines should be introduced as a standard procedure whenever self-bonding behaviour of laminated boards is studied. It could be considered as an input variable and, as demonstrated in this study, it might determine the water resistance of a self-bonded laminated board.

The water-swelling test provided information concerning board bonding quality. Figure 5 shows a selection of six samples belonging to different test groups after the water-resistance test. The samples are representative of their respective temperature

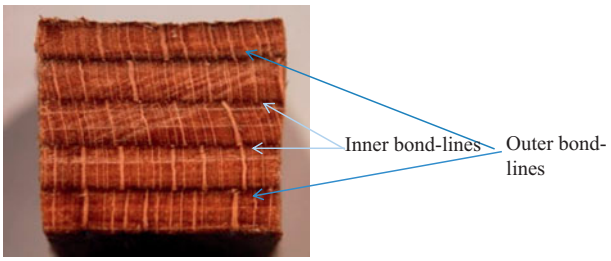

Figure 4. Image of a board pressed at 225°C, 5 MPa and 300 seconds. The thickness after pressing was 6.5 mm.

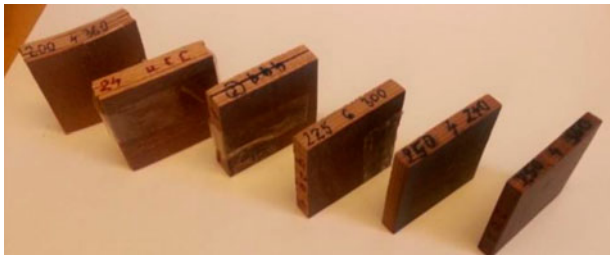

Figure 5. Samples after 48 hours immersion in water at 20°C and subsequent drying. The samples (left to right in picture) are from Groups No. 2, 5, 8, 10, 11 and 12 (Table I).

levels. All the samples pressed at 200°C delaminated because the temperature within the bond-line was not sufficiently high to ensure a strong bond. The samples pressed at 225°C, 5 MPa and 300 seconds delaminated in one or both of the inner bond-lines, but the outer bond-lines were water resistant. The samples pressed at 225°C, 6 MPa and 300 seconds did not delaminate at all, and this shows the important role of pressure for the heating of the bond-line: a high pressure ensures that the targeted temperature can be quickly reached, and this allows the internal bond-lines to be pressed and simultaneously heated enough to create water-resistant bonds. None of the samples pressed at 250°C delaminated.

Shear strength

The inner bond-lines are the weakest bond-lines, and all shear strength tests were therefore performed on samples with notches cut up to the inner bond-lines.

The highest shear strength was obtained when the samples were pressed at 250°C, 4 MPa and 360 seconds, which suggests that a longer pressing time and a lower pressure provide a better bonding. The temperature reached in the bond-line during pressing may however be the decisive factor, as shown in Cristescu and Karlsson (2013). It is obvious that the higher the plate temperature, the shorter is the time to heat up the inner bond-line. It has previously been shown that pressing for as short time as 80 seconds is sufficient to achieve a good adhesion if the plate temperature is 300°C (Cristescu 2006). Although this study showed that pressing at 250°C, 4 MPa and 240 seconds or 360 seconds resulted in boards with a dry shear strength of 4. 1 or 5 MPa respectively, a different result than that obtained by Mansouri *et al.* (2010) under similar pressing conditions.

Two models were used considering pressing parameters as input variables and shear strengths as responses, one using Minitab and one model using SIMCA software. Both models showed that, although the shear strength is related to all three

parameters (temperature, pressure and pressing time), it is the temperature that is, by far, the most influential factor. The boards tend to increase in shear strength with increasing pressing conditions until the samples crack at 250°C, 6 MPa and 360 seconds.

Bending strength

Bending test is complex because it actually involves a combinations of tensile, compressive and shear stresses, causing rotational distortion or flexure (Winandy and Rowell 2012). Failure is the results of the lowest strength being exceeded when considering all the three stresses. Although MOR refers to the tensile stresses of the specimen, in laminated composites, it is often the weak interlaminar shear stress that causes the samples to fail when subjected to a bending test (Reeder and Rews 1990, Lopes *et al.* 2008).

In this study, the samples broke according to two alternative patterns, as seen in Figure 6 and in Table I, due to interlaminar shear in the horizontal plane (Figure 6, top) or to longitudinal tensile-based fracture in the lower layer (Figure 6, bottom).

Testing samples pressed at 200°C and 225°C resulted in a lower maximum load than samples pressed at 250°C. The lower density of samples pressed at 200°C and 225°C than at 250°C may explain this behaviour and the codependency of density and bending strength often mentioned in the literature (Stamm 1964, Hoffmeyer and Pedersen 1995, Tabarsa and Chui 1997, Blomberg *et al.* 2005). Nevertheless, density is not the only factor in the case of self-laminated boards, since the failure in the three-point bending test in this study was of two main types. In the samples pressed at 200°C and 225°C, rupture occurred because of the weak bonding between the adjacent layers, where the combination of temperature, pressure and time of Group No. 1–10 was not sufficient to achieve chemical changes necessary to create a compact self-bonded board.

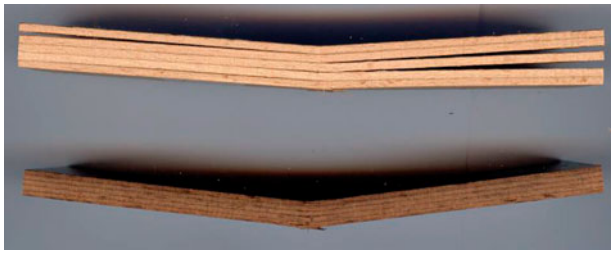

Figure 6. Side view after bending test of samples pressed at 200°C, 4 MPa and 240 seconds (top) and at 250°C, 6 MPa and 240 seconds (bottom).

All the samples pressed at 250°C, on the other hand, showed failure caused by longitudinal tension combined with cross-grain tension. The samples pressed at 250°C were those that resisted soaking in water. The explanation of why samples break differently may be found at the microscopic level as well as the chemical level. Samples pressed at 250°C have a more homogeneous structure in a cross-plane, and they have smaller pores and thicker bond-lines (Cristescu 2008). Samples pressed at 250°C contain more furfural and lignin-like condensation products in the bond-line (Cristescu and Karlsson 2013).

According to the data in Table I, the boards that failed in tension (with no interlaminar shear at the moment of fracture) were also the boards that resist water-soaking. It can be concluded in the case of self-laminated boards that the overall strength is related to the type of chemical bonds formed within the bond-line.

Statistical analysis

The PLS model described 88.2% (R^2) of the variation and the predictive ability was 77.7% (Q^2). The results of the PLS analysis showed that temperature has, by far, the strongest impact. The PCA (Principal Component Analysis) showed that all responses are interrelated according to a simple model, positively influenced by density.

The data show that interactions have a great influence since similar responses are obtained with different combinations of two of the parameters when the third is kept constant. For example, a change in pressing time from the lowest to the highest level significantly improves the bonding strength. The interaction might be expressed through an additional predicting parameter: the inner temperature in the bond-line.

Although the anatomical and chemical structures of wood are complicated and uneven, it might be interesting to compare the self-bonding of wooden veneers to laminated products of other materials. In such a case, other dependent factors such as porosity could be studied as this is generally known to highly affect the interlaminar shear strength of a composite (Lopes *et al.* 2008). The porosity of the material might be influenced by the pressure and the temperature used during the pressing process and should receive attention in future studies.

Conclusions

1. The physical and mechanical properties of the type of board produced in this study depend on all

three pressing parameters (temperature, pressure and pressing time), but temperature is by far the most influential factor.

2. This study marked the lower and upper limits of the pressing parameter combination: a beech board with good mechanical and esthetic properties can be obtained at pressures of 4–6 MPa, for temperature 200–250°C and at a pressing time of 4–6 minutes.

3. It is possible to create water-resistant bonds between five rotary-cut 2.2 mm thick beech veneers by pressing them in a simple hot press using a pressing temperature of at least 250°C combined with a pressure of 4 MPa up to 6 MPa to a pressing time of 240–360 seconds.

4. The resistance to water absorption and swelling is enhanced by more severe pressing conditions.

5. A higher overall quality of the product was obtained with increasing density. The boards with the highest density (above 800 kg/m^3) had the lowest water absorption (below 40%), the lowest thickness swelling (16%), the highest dry shear strength (around 5 MPa) and the highest bending strength (above 200 MPa). In this study, such boards were obtained only when pressing at 250°C.

Acknowledgement

The authors are grateful for the support of the Ske-wood research programme, Sparbankstiftelserna Norrland and the Frans och Carl Kempe Foundation, Sweden.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Ando, M. and Sato, M. (2010) Evaluation of the self-bonding ability of sugi and application of sugi powder as a binder for plywood. *Journal of Wood Science*, 56, 194–200.

Blomberg, J., Persson, B. and Blomberg, A. (2005) Effects of semi-isostatic densification of wood on the variation in strength properties with density. *Wood Science and Technology*, 39, 339–350.

Boehm, R. B. (1951) *Process of Making a Plywood Product*. US Patent 2557071.

Böhnke, I. (1993) *Etude Expérimentale et Théorique des Traitements Thermiques du Bois. Caractérisation Physico-Mécanique des Bois Traités* [Experimental and Theoretical Study of Thermally Treated Wood. Physico-Mechanical Properties of Treated Wood]. Ph.D. Thesis (St. Etienne: Ecole des Mines).

Cristescu, C. (2006) Bonding laminated veneers with heat and pressure only. In: *Proceedings of the 2nd International Conference on Environmentally-Compatible Forest Products "Ecowood"*, 20–22 September (Porto), pp. 339–348.

Cristescu, C. (2008) *Bonding Veneers Using Only Heat and Pressure. Focus on Bending and Shear Strength*. Licentiate Thesis (Luleå: Luleå University of Technology).

Cristescu, C. and Karlsson, O. (2013) Changes in content of furfurals and phenols in self-bonded laminated boards. *BioResources*, 8, 4056–4071.

EN-310 (1993) *Determination of Modulus of Elasticity in Bending and of Bending Strength* (Brussels: European Committee for Standardization).

EN-317 (1993) *Determination of Swelling in Thickness after Immersion in Water*. (Brussels: European Committee for Standardization).

EN-323 (1993) *Determination of Density*. (Brussels: European Committee for Standardization).

EN-314 (2004) *Plywood – Bonding Quality*. (Brussels: European Committee for Standardization).

Ganier, T., Hu, J. and Pizzi, A. (2013) Causes of the water resistance of welded joints of Paduk wood (*Pterocarpus soyauxii* Taub.). *Journal of Renewable Materials*, 1, 79–82.

Hakkou, M., Pétrissans, M., El Bakali, I., Gérardin, P. and Zoulalian, A. (2005) Wettability changes and mass loss during heat treatment of wood. *Holzforschung*, 59, 35–37.

Hill, C. A. S. (2006) *Wood Modification: Chemical, Thermal and Other Processes*. (Chichester: John Wiley & Sons).

Hoffmeyer, P. and Pedersen, J. G. (1995) Evaluation of density and strength of Norway spruce wood by near infrared reflectance spectroscopy. *Holz als Roh- und Werkstoff*, 53, 165–170.

Inari, G. N., Petrissans, M. and Gerardin, P. (2007) Chemical reactivity of heat-treated wood. *Wood Science and Technology*, 41, 157–168.

Johansson, D., Sehlstedt-Persson, M. and Morén, T. (2006) Effect of heat treatment on capillary water absorption of heat-treated pine, spruce and birch. In Lagana, S. Kurjatko and J. Kudela (eds.) *Proceedings of the 5th IUFRO Symposium Wood Structure and Properties* 3–6, 251–255, Sila, Sielnica, Slovakia.

Karlsson, O., Yang, Q., Sehlstedt-Persson, M. and Morén, T. (2012) Heat treatments of high temperature dried Norway spruce boards: Saccharides and furfurals in sapwood surfaces. *BioResources*, 7, 2284–2299.

Lopes, C. S., Remmers, J. J. and Gürdal, Z. (2008) Influence of porosity on the interlaminar shear strength of fibre-metal laminates. *Key Engineering Materials*, 383, 35–52.

Mansouri, H. R., Leban, J. M. and Pizzi, A. (2010) High density panels obtained by welding of wood veneers without any adhesives. *Journal of Adhesion Science and Technology*, 24, 1529–1534.

Metsä-Kortelainen, S., Antikainen, T. and Viitaniemi, P. (2006) The water absorption of sapwood and heartwood of Scots pine and Norway spruce heat-treated at 170°C, 190°C, 210° C and 230°C. *Holz als Roh- und Werkstoff*, 64, 192–197.

Minitab (2014) (State College, PA: Minitab).

Modde (2014) (Umeå: MKS Umetrics AB).

Montgomery, D. C. (2005) Design and Analysis of Experiments. (New York, NY: John Wiley & Sons).

Müller, C., Kües, U., Schöpper, C. and Kharazipour, A. (2007) Natural Binders. In: U. Kües (ed.) *Wood Production, Wood Technology, and Biotechnological Impacts* (Göttingen: Universitätsverlag).

Navi, P. and Heger, F. (2005) *Comportement Thermo-Hydrome´ Canique du Bois: Applications Technologiques et Dans les Structures* [Thermohydro-Mechanical Behaviour of Wood: Technological and Structural Applications] (Lausanne: PPUR Presses Polytechniques).

Navi, P. and Sandberg, D. (2012). *Thermo-Hydro-Mechanical Wood Processing* (Lausanne: PPUR Presses Polytechniques).

Pizzi, A., Mansouri, H. R., Leban, J. M., Delmotte, L. and Pichelin, F. (2011) Enhancing the exterior performance of wood joined by linear and rotational welding. *Journal of Adhesion Science and Technology*, 25, 2717–2730.

Reeder, J. R. and Rews, J. H. (1990). Mixed-mode bending method for delamination testing. *AiAA Journal*, 28, 1270–1276.

Repellin, V. and Guyonnet, R. (2005) Evaluation of heat-treated wood swelling by differential scanning calorimetry in relation to chemical composition. *Holzforschung*, 59, 28–34.

Rowell, R. M. (ed.). (2012) *Handbook of Wood Chemistry and Wood Composites*. (London: CRC Press, Taylor and Francis Group).

Runkel, R. and Jost, J. (1948) *Verfahren und Vorrichtung zur Herstellung von Formungen aus Holz, Holzabfällen oder verholzten Pflanzenteilen unter Druck, bei höheren Temperaturen*. [Method and Apparatus for the Production of Mouldings from Wood, Wood Waste or Vegetable Origin under Fibres under Pressure at Elevated Temperatures]. Deutche Patent DE841055.

Ruponen, J., Rautkari, L., Belt, T. and Hughes, M. (2014) Factors influencing properties of parallel laminated binderless bonded plywood manufactured from rotary cut birch (*Betula pendula* L.). *International Wood Products Journal*, 5, 11–17.

Sandberg, D., Haller, P. and Navi, P. (2013). Thermo-hydro and thermo-hydro-mechanical wood processing: An opportunity for future environmentally friendly wood products. *Wood Material Science and Engineering*, 8, 64–88.

Simca (2014) (Umeå: MKS Umetrics AB).

Stamm, A. J. (1964). *Wood and Cellulose Science*. (New York, NY: Ronald Press Company).

Stofko, J. (1974). *The Autoadhesion of Wood*. Doctoral dissertation, Ph.D. Thesis (Califonia: University of California).

Suthoff, B., Schaaf, A., Hentschel, H. and Franz, U. (1996) *Verfahren zum reibschweißartigen Fügen von Holz*. [Method for Joining Wood]. Offenlegungungsschrift DE 196 20 273 A1. Deutsches Patent und Markenamt.

Tabarsa, T. and Chui, Y. H. (1997) Effects of hot-pressing on properties of white spruce. *Forest Products Journal*, 47, 71–76.

Vaziri, M. (2011) *Water Resistance of Scots Pine Joints Produced by Linear Friction Welding*. Doctoral Thesis (Luleå: Luleå University of Technology).

Zavarin, E. (1984). Activation of wood surface and nonconventional bonding. In: Rowell (ed.). *Chemistry of Solid Wood*. (Washington, DC: American Chemical Society), pp. 349–400.